PhD THESIS

in

Environmentally Sustainable Construction by Reducing Embodied Carbon Emissions in the Construction of Large-Scale Projects: *a study on high-rise buildings.*

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Submitted to the University of Hertfordshire in Partial Fulfilment of the

Requirement of the

Degree of Doctor of Philosophy

School of Civil Engineering

March 2024

Acknowledgement

I dedicate this work to the cherished memory of my beloved father, Dr. Khalaf Raqqad.

I appreciate my supervisor efforts Dr. Antonios Kanellopoulos.

I am grateful for my mother and wife's support.

Abstract

This research aims to comprehensively evaluate and quantify the impact of construction processes and practices in large-scale projects, focusing mainly on high-rise buildings. Employing Life Cycle Assessment (LCA) methodologies, the study measures and analyses the reduction of embodied carbon emissions throughout the construction phase. The goal is to identify and promote strategies that minimise climate change impacts associated with these projects, thereby advancing the development of environmentally sustainable high-rise buildings.

The thesis addresses the urgent issue of carbon emissions in construction, explicitly examining embodied carbon from material delivery to project completion—the gate-to-use phase. Unlike extensively studied operational emissions, the effects of material selection and construction methods on embodied carbon are less understood. This research fills these gaps through rigorous investigation.

Modular construction practices, such as off-site construction (OSC) and on-site techniques, can solve environmental problems and achieve sustainability in several ways; OSC or (Prefabrication) could be a successful strategy to eliminate environmental impacts caused by construction, also solving the world's population rapid increase and housing associated issues. However, construction assessment methods like LCA must accompany multiple actions and assessment criteria.

Using bibliometric analysis, case studies, and industry surveys, the research explores how strategic decisions can effectively lower the carbon footprint of high-rise buildings. It aims to enhance understanding and awareness of embodied carbon, gathering insights into current knowledge levels and identifying misconceptions. Highlighting iconic structures such as the Burj Khalifa and The Shard, the research showcases how materials such as steel and concrete, alongside advanced construction techniques, substantially reduce emissions.

Surveys with construction professionals reveal a growing awareness of environmental impacts, particularly greenhouse gas emissions. However, a notable challenge persists: the need for standardised measurement units for embodied carbon, hindering comparisons across projects. To address this, the thesis proposes adopting $kgCO_2/m^2$ as a standard metric to enhance clarity and comparability within the industry.

The study underscores the importance of integrating sustainability from design through on-site activities. Key strategies such as prefabrication, optimised material use, and efficient waste management are critical in reducing embodied carbon. Customised sustainability approaches tailored to local climates and regulatory frameworks are also advocated.

Interviews with industry stakeholders underscore a shared recognition of the need for coordinated sustainability efforts and clear guidelines for lifecycle carbon assessments. They emphasise the potential of innovative construction methods like off-site manufacturing and renewable energy integration to mitigate environmental impacts further.

This research contribution to knowledge identifies practical pathways to reduce embodied carbon in high-rise construction and provides actionable recommendations for their implementation. The study advocates a holistic sustainability approach, delivering crucial insights for policymakers and industry leaders. These contributions are pivotal in advancing sustainable practices within the construction sector and fostering a greener future.

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Acronyms

Term	Definition
ACM	Association for Computing Machinery
AEC	Architecture, Engineering, and Construction
AGT	Amman Gate Towers
AI	Artificial Intelligence
AM	Additive Manufacturing
BIM	Building Information Modelling
BOQ	Bill of Quantities
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BSRIA	Building Services Research and Information Association
BREEAM	Building Research Establishment Environmental Assessment Method
CABE	Chartered Association of Building Engineers
CEM	Construction Engineering Management
CH_4	Methane
CO_2	Carbon Dioxide
CCS	Carbon Capture and Storage
CPR	Collaborative Practice Research
CTUe	Comparative Toxic Unit for eco systems
EAF	Electric Arc Furnace
EC	Embodied Carbons
EF	Environmental Footprint
EVs	Electric Vehicles
ESB	Empire State Building
EPA	Environment Protection Agency
GHG	Green House Gas
GGBS	Ground-Granulated Blast Furnace Slag
GM	General Motors
GPS	Global Positioning System
GW	Global Warming
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
ICE	Internal Combustion Engine
ICE	Institution of Civil Engineers
ICE	Inventory of Carbon and Energy
IBS	Industrialised Building Systems
IEEE	Institution of Electrical and Electronic Engineers
IPCC	Intergovernmental Panel on Climate Change
ISS	International Space Station
ISO	International Organization for Standardization
JCCA	Jordan Construction Contractors Association
JEA	Jordan Engineers Association
JIT	Just In Time
JGBC	Jordan Green Building Council
LEED	Leadership Energy and Environment Design
LCA	Life Cycle Assessment
LCCA	Life Cycle Carbon Assessment

LCIA	Life Cycle Impact Assessment
N_2O	Nitrous Oxide
NRDC	Natural Resources Defence Council
OC	Operational Carbons
OSC	Off-Site Construction
PFCs	Perfluorocarbons
PPVC	Prefabricated Prefinished Volumetric Construction
RAP	Reclaimed Asphalt Pavement
RC	Reinforced Concrete
RIBA	Royal Institution of British Architects
RPS	Rural Planning Services
TBS	Traditional Building Systems
SCF	Southern Construction Framework
SPECS	School of Physics, Computer Science, and Engineering
SO_2	Sulphur Dioxide
UNSDGs	UN Sustainable Development Goals
WLC	Whole Life Cycle
WSN	Wireless Sensor Networks
WMA	Worm Mix Asphalt
WBGC	World Building Green Council

Chapter 1 Introduction

1.1 Research Background

The research focuses on how large-scale construction projects, particularly high-rise buildings, can be more environmentally sustainable by reducing carbon emissions produced during construction. The significance of this research lies in the fact that it has the potential to generate substantial impacts and substantial cost savings by improving the design, engineering, and construction of skyscrapers, considering their immense scale.

Embodied carbon emissions refer to the amount of carbon dioxide and other greenhouse gases that are being released during the production and transportation of building materials, as well as during the construction process itself (Amiri and Sakeena, 2021; Pomponi and Moncaster, 2018; Röck et al., 2020). These emissions contribute to global warming and climate change, which have a range of negative impacts on the environment, including blizzards, hurricanes, ice melting, sea level rise, and drought (Hong et al., 2019; Röck et al., 2020; Schwartz, 2018).

The research aims to find ways to reduce these emissions and make construction more sustainable to mitigate the negative impacts of climate change. Sustainable construction is an essential study area, as the construction sector significantly contributes to carbon emissions and environmental degradation (Alotaibi et al., 2022). By finding ways to reduce these impacts, we can work towards a more sustainable future.

Few studies discuss the impacts and provide sustainable solutions in sustainable construction projects (Wu et al., 2017). Moreover, integrating sustainability in both academic and practice levels in construction project management was crucial for achieving balanced environmental, social, and economic targets (Yu et al., 2018).

The increase of risks associated with climate change is precisely within the buildings sector represented in large-scale projects such as high-rise buildings, where the construction industry has a significant contribution to climate change, as explained by (Hurlimann et al., 2018), despite (Lowe, 2001) claimed that climate change is the research focuses on how large-scale construction projects, particularly high-rise buildings, can be more environmentally sustainable by reducing carbon emissions produced during construction. The significance of this research lies in the fact that it has the potential to generate substantial impacts by improving the design, engineering, and construction of skyscrapers, considering their immense scale.

These emissions contribute to global warming and climate change, which have a range of negative impacts on the environment, including inevitable, and we must adapt to it.

According to (Vitale et al., 2018), the construction industry has great potential to reduce the environmental impacts caused by its activities.

The construction industry has significantly contributed to increased CO_2 emissions globally from 1990 to 2019. According to Crippa (2020), CO_2 emissions estimations were taken seriously during this period, and the construction industry had a significant proportion of them.

(Lee et al., 2018) stated that large-scale projects are responsible for about 30-40% of carbon emissions. However, Hu and Esram (2021) confirm that the construction industry contributes only 10% of global greenhouse gas (GHG) emissions. Sustainable construction has become a crucial issue in recent years, along with construction technology and building structures and systems (Zavadskas et al., 2017).

Despite the varying numbers, 10% and 30-40% are highly influential in terms of affecting the environment. The buildings and construction sector accounted for 36% of final energy use and 39% of energy and process-related CO_2 emissions in 2018, 11% of which resulted from manufacturing building materials and products such as steel, cement, and glass (International Energy Agency. and Global Alliance for Buildings and Construction., 2019). Environmental pollution and threats to natural resource depletion have made sustainable construction a growing concern (Bansal et al., 2017).

It is essential to address the issue of carbon emissions in the construction industry and work towards sustainable construction practices to reduce environmental impact. CO_2 emissions presumably have the most significant environmental impacts and are highly related to construction activities, where reducing carbon emissions in the building sector is urgent for sustainable development (Teng and Pan, 2019).

This research hypothesis suggests that large-scale projects, such as high-rise buildings, can be helpful for testing and implementing new construction technologies. These projects can also help address the challenges associated with population growth, particularly in urban areas, where space is often limited. Construction projects address such issues, and this research presents the best solutions to overcome the gaps in sustainable construction practices and measurements.

Despite Yang's (2008) raised concerns regarding high-rise buildings' complexity and resource consumption, the research argues that such buildings can be designed and constructed sustainably and environmentally. The research intends to challenge the notion that high-rise buildings are inherently unsustainable and explore ways to design and build them to minimise their environmental impact.

1.2 Research Motivation

The research motivations can be described as the expected needs of human beings nowadays and in the future, especially within the increased demand for energy, alongside the increased number of populations worldwide. The following summarises the motivations of this research:

- Predictions for the global population will increase to 9 billion in 2050 (Habert et al., 2020; Thakur et al., 2021)
- The European Union (EU) has set ambitious objectives for dealing with climate change by achieving a net zero greenhouse gas emissions by 2050 (Crippa, 2020), as UN Sustainable Development Goals (UNSDGs), Intergovernmental Panel on Climate Change (IPCC), UK net zero buildings 2050, Organization for Economic Co-operation and Development (OECD), Swiss engineers and energy (SIA 2040), Kyoto protocol, publicly available specification (PAS 2080) and many others
- Environmental sustainability and energy efficiency in the construction industry are the most important recently (Z. Wang et al., 2019), and the built environment is an essential target for researchers to study the associated emissions and consequences of greenhouse gases caused by construction projects (Harputlugil and de Wilde, 2021)
- The problem of implementing environmentally sustainable practices in construction projects, especially off-site construction, and prefabrication methods, is that OSC has no apparent benefits in the operation and demolition phase of buildings (Jin et al., 2018)
- The invention of modern, efficient, and renewable energy in the operational phase of buildings (Jin et al., 2020) increased the importance of focusing on embodied energy and embodied carbon emissions. Moreover, new energy-efficient buildings have remarkably reduced the operation's carbon emissions, which directed the focus on embodied carbon emissions (Röck et al., 2020)

The predicted increase in the global population up to nine billion in 2050, along with the ambitious objectives set by various organisations for climate change, has highlighted the importance of addressing the construction industry's environmental sustainability and energy efficiency. Researchers have recognised the built environment as a significant source of greenhouse gas emissions and consequences. However, implementing environmentally sustainable practices in construction projects, especially off-site construction, remains challenging due to the need for clear benefits in building operation and demolition phases.

The invention of modern, efficient, and renewable energy in the operational phase of buildings has shifted the focus on embodied energy and embodied carbon emissions, making it crucial to consider and mitigate environmental impacts caused by construction. Therefore, it is necessary to continue exploring and implementing effective strategies to promote sustainability and energy efficiency in the construction industry while meeting the demands of the growing population.

1.3 Research Rationale

Embodied carbon is the carbon emissions associated with building components' materials, manufacturing, and transportation during construction (Mckinsey, 2023). Operational carbon, conversely, refers to the carbon emissions related to the energy used to operate and maintain a building over its lifetime. While operational carbon has traditionally been the focus of efforts to reduce carbon emissions in buildings, embodied carbon is becoming increasingly important as the construction industry grows and contributes more to global emissions. Architecture, Engineering, and Construction (AEC) professionals must understand both types of carbon and their environmental impact to reduce the built environment's carbon footprint and meet climate goals.

R. Globally, explained that the carbon emissions from buildings constructed between now and 2050, before considering the decarbonisation of energy grids, are equivalent to the carbon emissions from their energy usage until 2050 (Globally, 2018). As energy grids become environmentally cleaner and buildings become more energy efficient, the significance of embodied carbon becomes even more significant. If energy grids are successfully decarbonised, the total embodied carbon of new buildings could surpass their operational carbon emissions.

This thesis aims to highlight the critical distinction between embodied and operational carbon in the context of the built environment and emphasise the growing significance of embodied carbon as the construction industry expands and contributes more to global emissions.

By providing a concise overview of embodied and operational carbon, the thesis aims to raise awareness about the need for a holistic approach to carbon reduction in the built environment and encourage AEC professionals to consider both carbon emissions in their practices. (Mckinsey, 2023) lends credibility to the information presented, highlighting the importance of these concepts in the current sustainability discourse.

Many factors and uncertainties should be considered in each stage of the life cycle of any building. For example, some of the uncertainties that primarily influence the use stage energy consumption (operational) are the climate, the occupant's behaviour, the building shape, the orientation, or the country's electricity mix, while the impacts generated during the pre-use stage (embodied) are only affected by the different materials used during construction stage or by the distances carried out for the transport of materials (Tumminia et al., 2018). These can be controlled and monitored during the project's planning, design, and construction phases.

Moreover, more technology and alternative energy or clean energy resources are being used extensively in the operation phases of buildings. That is why embodied carbon was chosen in this research, while high-rise buildings are assumed to be overgrowing to fill the urbanisation demand and population growth. (Gan et al., 2017) stated that:

"*For long-term sustainability, reducing energy consumption and GHG emissions in buildings, especially high-rise buildings, can be considered one of the most sustainable measures for reducing the human impact on the environment.*"

1.4 Research Question

The research's main questions contain qualitative, quantitative, and mixed questions based on the research methodology, which are:

Qualitative: How can sustainable construction methods mitigate embodied carbons and help achieve sustainable modern buildings during the construction of large-scale projects, particularly high-rise buildings?

Mixed: Can and how can modular construction practices help achieve carbon neutrality in the context of net zero high-rise buildings?

Quantitative: What is the level of standardising, awareness, and understanding in the construction industry for environmental sustainability topics and carbon emissions impacts, and what is the best unit to measure it?

The three proposed research questions focus on different aspects of sustainable construction practices and their impact on carbon emissions. Qualitative research can provide in-depth insights into how sustainable construction can mitigate embodied carbon, especially in high-rise buildings. Mixed research can combine qualitative and quantitative methods to examine the potential of off-site construction in achieving carbon neutrality in net-zero high-rise buildings.

Quantitative research can measure the construction industry's awareness and understanding of environmental sustainability and the impacts of carbon emissions. The choice of research method and unit of measurement will depend on the specific research question and objectives.

1.5 Research Problems and Challenges

The research area of sustainable construction is critical for addressing the environmental impact of the built environment. However, this field faces numerous challenges and problems that must be addressed to achieve sustainable outcomes.

In this research, key challenges and issues are identified in the literature, which includes a lack of innovation in the construction sector (Bailey et al., 2022), it has not progressed at the pace or to the extent that is often anticipated or required (Sawhney et al., 2020). The construction process often prioritises short-term goals, leading to limited consideration of embodied carbon emissions. Additionally, the absence of unified standards, claims of increased costs associated with sustainable practices, challenges in implementing multiple sustainability measures within a single project, and the intricacies of sustainability research delineated by various boundaries further compound these issues.

These challenges and issues are crucial to understanding the current state of research in sustainable construction. Furthermore, it can be summarised as the following main points:

- Lack of Innovation in the Construction Sector: The construction industry is often criticised for its lack of innovation compared to other sectors (X. Gan et al., 2018), or described by (Abioye et al., 2021) by the age-long culture of resistance to change. This lack of innovation can hinder the adoption of sustainable practices and technologies that could reduce the environmental impact of the built environment. Innovation is vital for driving change and finding new solutions to complex sustainability challenges in the construction sector
- Short Construction Process vs Building Lifetime: Another challenge in sustainable construction is the relatively short duration of the construction process compared to the expected lifetime of buildings. While buildings can last for decades, the construction process is relatively short-lived. These challenges prioritise sustainability in the design and construction phases and ensure that long-term environmental impacts are adequately addressed
- Limited Focus on Embodied Carbon Emissions: While operational carbon emissions have received significant attention in sustainability research, embodied carbon emissions, which

are associated with the materials, manufacturing, and transportation of building components, have received less focus (Feng et al., 2018). This lack of focus is even though embodied carbon emissions can account for a significant portion of a building's overall carbon footprint. More research and standardised approaches are needed to assess and reduce embodied carbon emissions in the construction industry

- Lack of Unified Standards: The absence of unified standards for measuring and evaluating sustainability in the construction industry presents a significant challenge. Organisations and countries have sustainability standards and certifications, leading to clarity and consistency in sustainability assessment and reporting. Harmonising standards and creating a unified framework for sustainability assessment in construction could streamline efforts and facilitate better decision-making
- Claims of Higher Costs for Sustainable Practices: There is a perception that adopting sustainable practices in construction projects may result in higher costs and longer durations (Feng et al., 2018). This perception can hinder the widespread adoption of sustainable practices, especially in regions or countries with limited resources. However, research has shown that the actual costs of sustainable practices can vary depending on various factors, and a holistic cost-benefit analysis is needed to evaluate the actual economic implications of sustainable construction
- Difficulty in Implementing Multiple Sustainable Measures in a Single Project: Sustainability in construction often involves implementing multiple measures and strategies to address various environmental, social, and economic aspects. However, integrating numerous sustainable measures in a single project can be challenging due to design conflicts, budget constraints, and limited stakeholder buy-in. Finding synergies and balancing different sustainability objectives in a project can be complex and require careful planning and coordination
- Complexity of Sustainability Research with Various Boundaries: Sustainability research in the construction industry involves dealing with diverse boundaries, such as technical, economic, social, and policy boundaries. These boundaries can affect the implementation and assessing sustainable practices in construction projects. Understanding and navigating these complex boundaries is essential for conducting effective sustainability research and achieving meaningful sustainability outcomes

The challenges and issues summarised in this section highlight the complexities and shades of the research area of sustainable construction, from the lack of innovation in the construction sector to creativity and reliability in applying rational practices and regulations. Figure 1-1 presents topics associated with sustainability during this research.

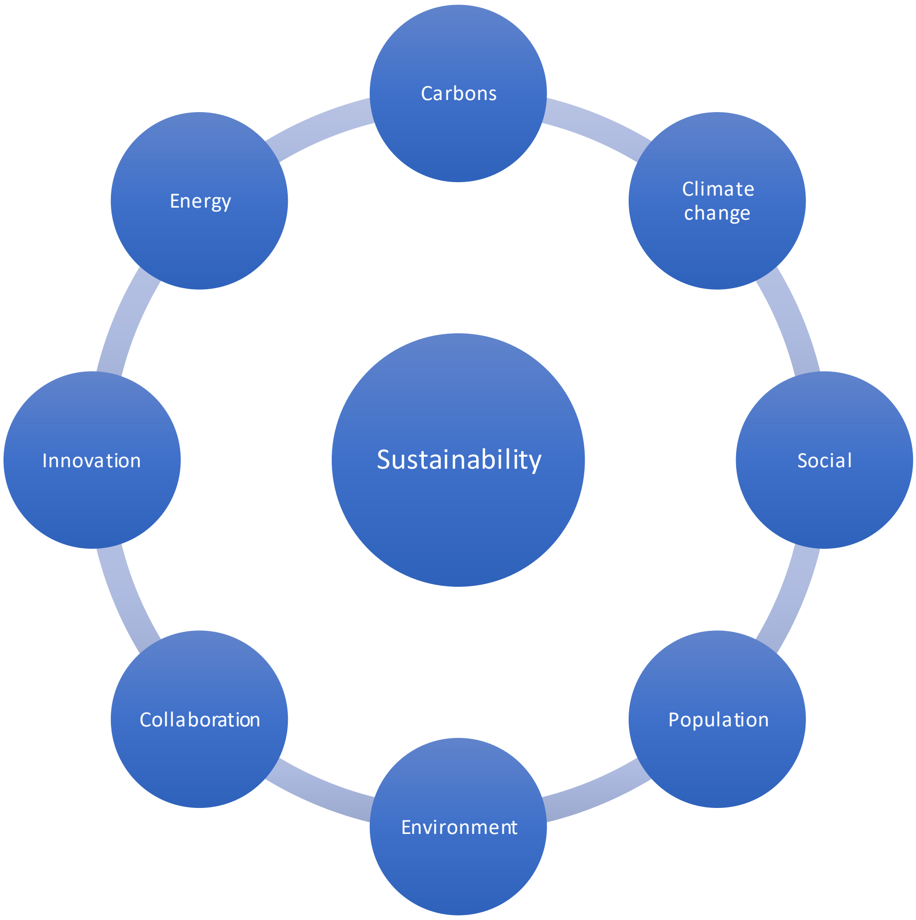

Figure 1-1 Research sustainability primary connections

It is challenging to provide a specific explanation of what sustainability includes. However, sustainability covers a broad range of interconnected topics and boundaries. These boundaries can include environmental factors such as carbon emissions, water and air quality, natural resource depletion, and ecosystem health.

Social factors can also play a significant role in sustainability, such as human rights, labour practices, and community well-being, despite (Bailey et al., 2022) stated that extensive research spanning over four decades has delved into construction innovation. However, the predominant focus has been on economic and technological advancements, leaving other aspects that could be explored more. Economic factors such as resource efficiency, supply chain management, and financial performance can also impact sustainability.

The boundaries of sustainability are often interdependent, meaning that changes in one area can affect others. Therefore, achieving sustainable practices requires a holistic approach that considers the interplay between all these factors. Figure 1-1 visually shows these boundaries and their interrelationships. All relations will be broken into the necessity and relevance of the objectives of this research.

1.6 Research Gaps

Research gaps include gaps of knowledge that can be filled within the research. Such gaps can be summarised as there was a lack of unified measurements and calculations of embodied carbon in construction projects, especially with more attention given to operational carbons.

Uncertainties such as transportation and storage proportions should be carefully explored, especially when considering off-site methods, which resulted in increased reinforced concrete emissions despite prefabrication methods. Moreover, life cycle assessments must provide accurate and holistic data when representing the environmental impacts of materials during the construction process.

A study by (Quale et al., 2012) considered the significant uncertainties associated with several input parameters when comparing conventional construction with modular construction. The errors related to each factory and building site were calculated. Percent uncertainties were estimated and propagated for variables such as on-site waste generation (±25%), transport distances to the modular facility (±25%), on-site trips (±25%), and on-site temporary heating (±50%). Although there may be uncertainties related to emissions factors, contractor surveys, and human error in reporting, these factors were not considered in this study.

Some certainties and factors are highly related to sustainable construction practices; finding the ‘theory of everything’ for construction projects would be impossible. However, these gaps or uncertainties could be narrowed down and filled to be adaptable to each type of project or a specific type of material.

Life Cycle Assessment (LCA) software plays a crucial role in evaluating the environmental impact of construction materials, such as steel and concrete. However, there is a recognised need for enhanced consistency within these software tools. This consistency pertains specifically to their assessment methods and calculations related to the environmental footprint of materials used in construction.

When analysing materials like steel and concrete, discrepancies or variations in LCA software outputs can arise due to differing data sources, calculation methodologies, or system boundaries. This lack of uniformity can lead to consistency in measuring environmental impacts across different software platforms.

Another gap is that optimising materials or production overlaps with the concept of sustainability; sometimes, they are considered the same, and at other times, they can be against each other. However, such investigation will be presented through data analysis chapters.

The research mission is to identify and pin out those or discovered knowledge gaps within the topic, find proposed or available solutions, and then analyse the findings. Moreover, the research gaps will be introduced at the end of each chapter. See Figure 1-2.

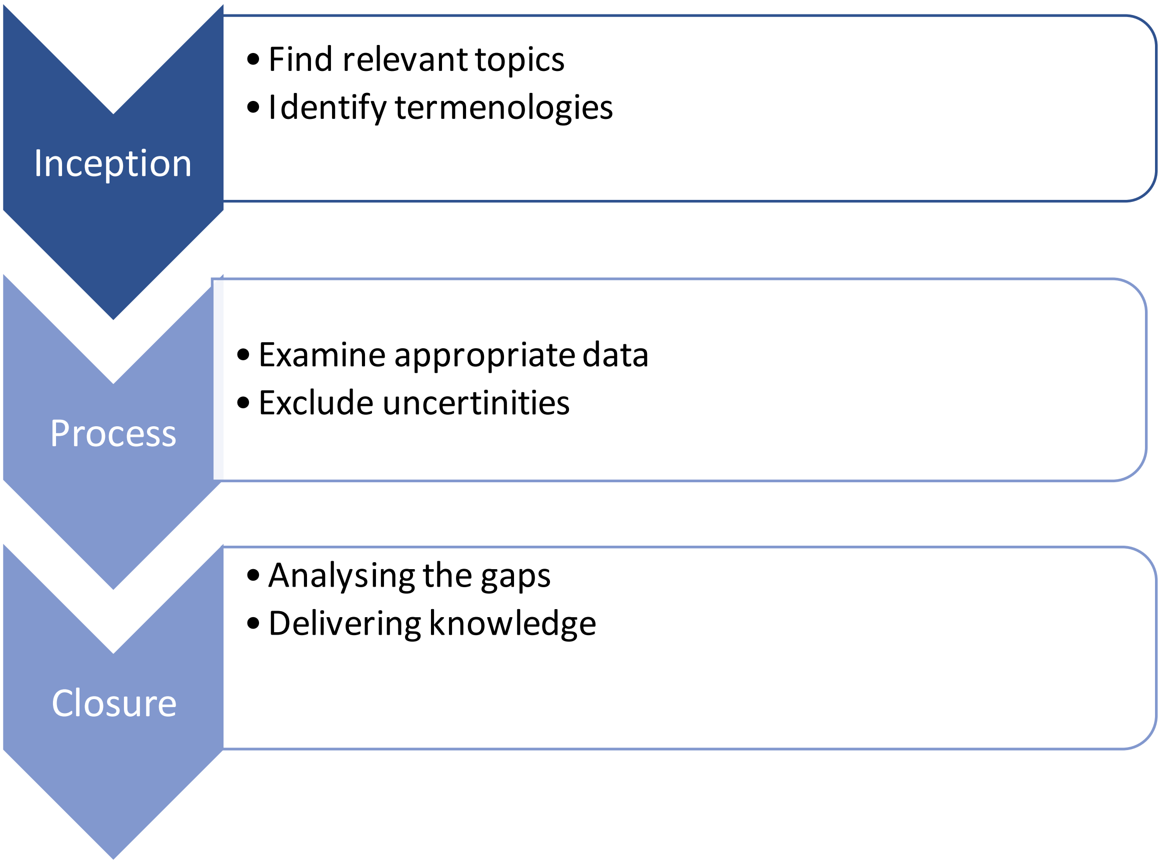

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Figure 1-2 Research gaps process

1.7 Research Aims and Objectives

This research aims to comprehensively evaluate and quantify the impact of construction processes and practices in large-scale construction projects, with a particular focus on high-rise buildings. By employing Life Cycle Assessment (LCA) methodologies, the study will measure and analyse the reduction of embodied carbon emissions throughout the construction phase. The goal is to identify and promote strategies that minimise the climate change impacts associated with these projects, thereby advancing the development of environmentally sustainable high-rise buildings. Through this investigation, the research seeks to contribute to the broader discourse on sustainable construction practices and provide actionable insights for reducing the carbon footprint of urban high-rise projects.

This research believes that sustainable large-scale projects, especially high-rise ones, can intensively help reduce environmental impacts, especially embodied carbon emissions, with more focus on the construction phase (cradle-to-site) as the world is soon directing to zero operational carbon emissions.

This environmental sustainability approach includes other construction project roles but suggests that priority should be given to high-rise projects due to urbanisation, population, economic, environmental, and social concerns.

The embedded aim is to conduct an assessment that delves into the topic's understanding and awareness, explicitly focusing on discerning the disparities between operational and embodied carbons. This endeavour intends to evaluate individuals' familiarity with these concepts and their ability to differentiate between the two distinct forms of carbon emissions.

Through this assessment, the aim is to gather valuable insights into the current level of knowledge, identify any knowledge gaps or misconceptions, and ultimately contribute to enhancing overall comprehension and awareness in this domain.

Primary bulk structural materials, steel, and concrete will be examined and explicitly evaluated since they are the ones that generate carbon emissions and affect the construction industry's climate change.

Objectives

1. Quantify and identify the environmental and carbon impact caused by the construction projects and propose mitigation strategies, especially for embodied and operational carbons, by collecting quantitative and qualitative data
2. Review modular construction practices, such as off-site practices and on-site methods, as carbon mitigating strategies in the construction industry by creating a database
3. Evaluating the role of embodied carbon emissions and life cycle assessments in construction projects
4. Examining construction projects of modern high-rise buildings in terms of environmental sustainability
5. Standardising the assessment criteria for decarbonising the construction industry

1.8 Research Limitations

Research limitations were primarily related to the availability of studies and solid databases. In contrast, other forms of constraints that might be encountered in the research are the limited number of case studies or professional people directly related to the subject of study, especially when knowing that there is a shortage of rigorous calculations of GHG emissions of prefabricated construction (Mao et al., 2013), and a lack of data during the construction stage of projects.

Time constraints should also be considered through the progress of the literature review, methodology, and data collection. While data collected from the questionnaire could suffer from biased or unreliable statements (Dillman et al., 2014), case studies should be investigated carefully to avoid misjudgements (Yin, 2018).

1.9 Contribution to Knowledge

The anticipated new findings and knowledge in this research explored the life cycle and construction process stages of construction projects, translated into the embodied emissions associated with it. They proved that practices such as on-site and off-site technologies can mitigate embodied and operational carbon emissions, especially when constructing large-scale projects, particularly high-rise buildings.

So, the research will focus on the construction process phase of construction buildings and its associated embodied emissions, which result from the manufacturing and transportation of materials and the construction process itself. The research will demonstrate that using innovative construction technologies, both on-site and off-site, can help mitigate embodied and operational carbon emissions associated with construction projects.

These technologies may reduce the energy and resources needed to construct large-scale or high-rise buildings, significantly reducing their environmental impact. The research highlights the benefits of incorporating sustainable design principles into the construction process, such as using renewable materials and energy-efficient building systems.

Overall, the anticipated research findings may provide valuable insights for the construction industry on how to design and construct large-scale projects, particularly high-rise buildings, in a more sustainable and environmentally friendly way. Most importantly, the research shall provide more consistency in standardising and evaluating environmental impacts and carbon emissions in the construction industry to make future net zero emissions possible.

1.10 Thesis Structure

Figure 1-3 outlines the research map in general description.

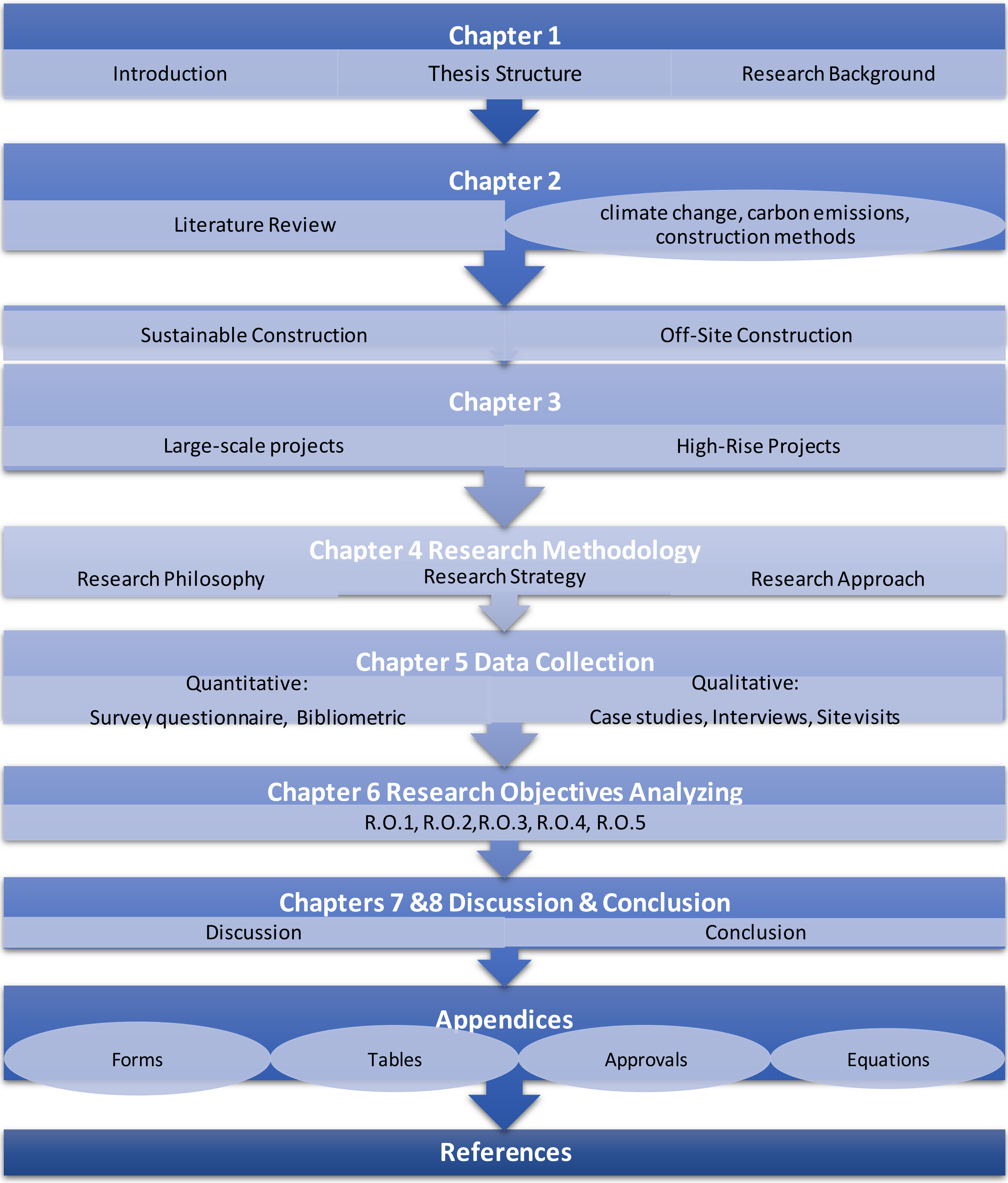


Figure 1-3 Thesis structure

1.11 Research Strategy

The research approach in collecting and analysing data will join the objectivist and subjectivist approaches, using a realistic pragmatic strategy, which is the most appropriate way when using the mixed methodology for data collection.

This realistic pragmatic approach was chosen mainly due to the nature of this research, which depends on both real-world projects and the environment rather than depending on purely academic data.

The research approach for collecting and analysing data will use a mixed methodology. This approach was chosen because it is the most appropriate way to collect and analyse data for a research project that relies on real-world projects and the environment.

Objectivism is a research approach that uses quantitative data and focuses on identifying universal laws and patterns that can be applied across different contexts. On the other hand, *subjectivism* focuses on individual experiences and perspectives, using qualitative data to gain insights into people's attitudes, behaviours, and beliefs (Creswell, 2013; Creswell and Clark, 2018).

According to (Almalki, 2016), mixed methods research is the type of research where researchers or a team combine elements of both qualitative and quantitative research approaches, incorporating qualitative and quantitative viewpoints, data collection, analysis, and inference techniques. This approach is used to achieve comprehensive and in-depth understanding, and to corroborate findings.

(Creswell and Clark, 2018) added to the defined mixed methodology approach combines these two approaches, allowing researchers to collect and analyse quantitative and qualitative data and providing a more comprehensive understanding of the research topic. The realistic pragmatic strategy is a mixed methodology approach that focuses on the practical application of research findings in real-world situations.

The mixed methodology approach would be appropriate for high-rise building construction and its environmental impact. This proportionate is because the research relies on quantitative data, such as material and energy consumption data, and qualitative data, such as the opinions and experiences of stakeholders involved in high-rise building projects. The approach will help ensure that the research findings are grounded in academic theory and real-world applications, providing a comprehensive and nuanced understanding of the topic.

This research, rooted in the industry, relied heavily on the close partnership between researchers and industry professionals. In this context, according to (Ellen Grist, 2014), it exemplifies Collaborative Practice Research (CPR), a methodology advocated by Mathiassen (2002) as a practical approach to research (Mathiassen and Sørensen, 2002). This research will integrate data from academic sources and professionals actively engaged in engineering practice.

Figure 1-4 illustrates the connection between the research question, objectives, and identified gaps in the study, while Table 1-1 presents the location of the research objectives throughout the thesis.

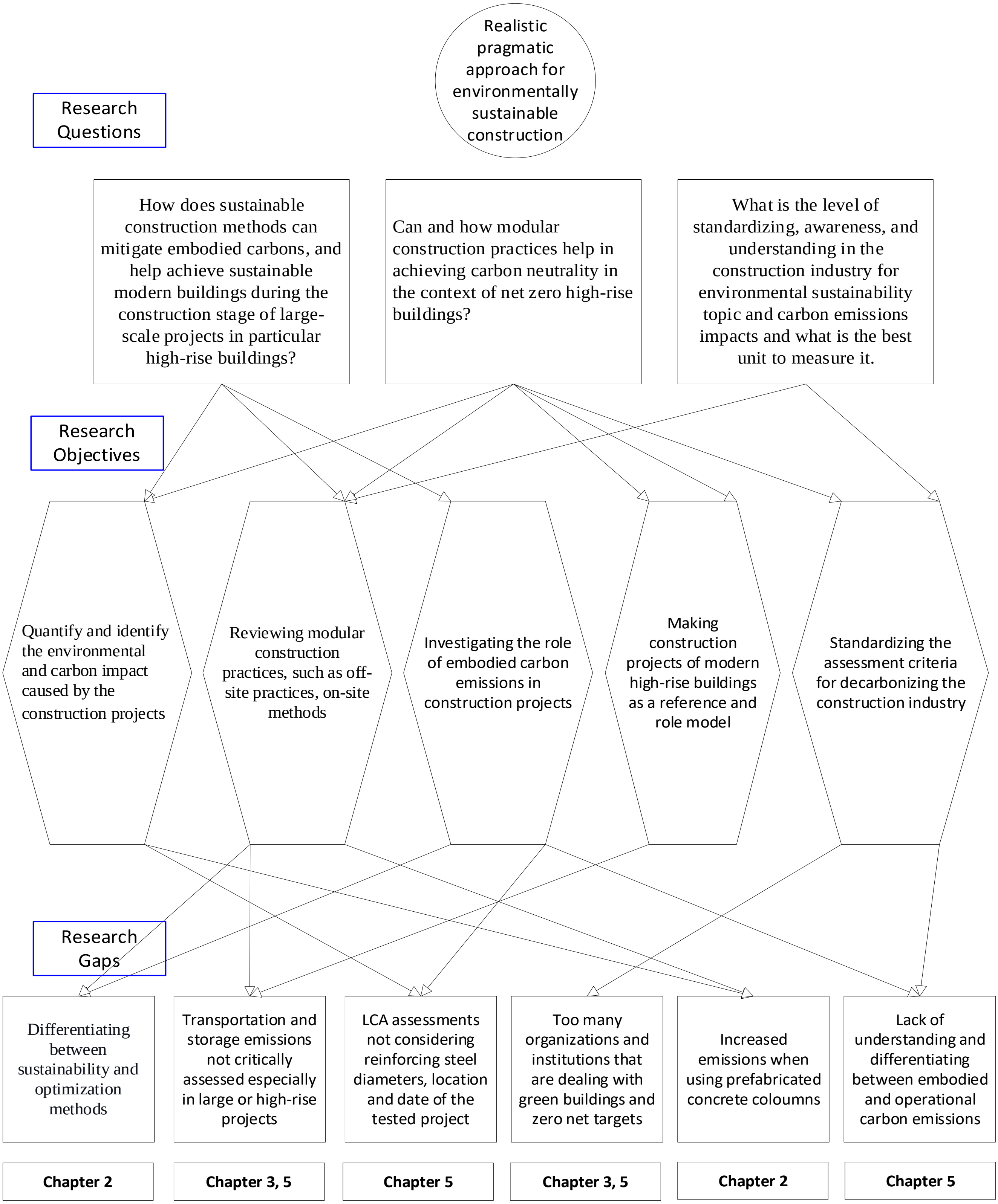


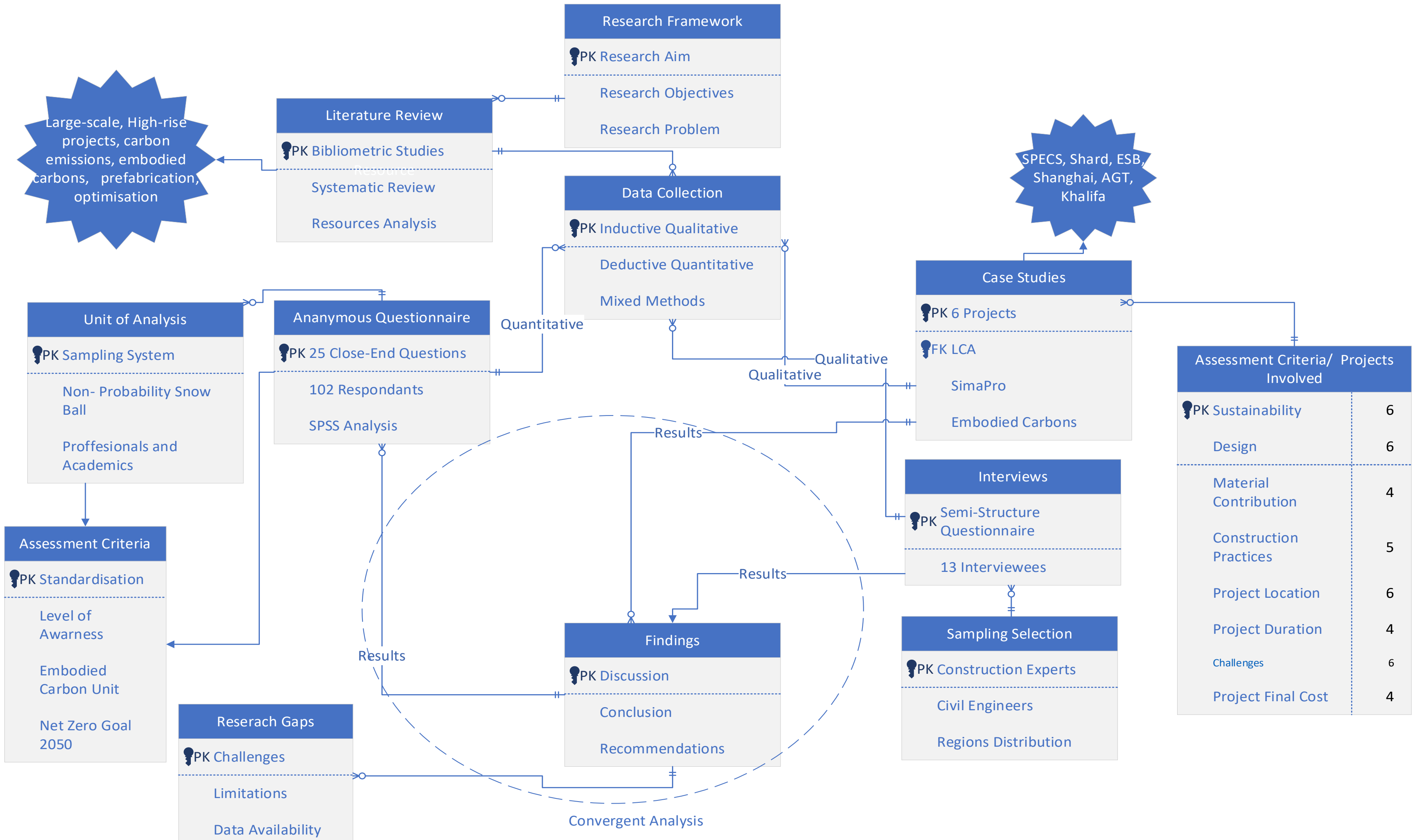
Figure 1-4 Research Strategy

Table 1-1 Research objectives analysis

Chapter 1 Introduction	Chapter 2 Literature Review	Chapter 3 Large-Scale Projects	Chapter 5 Data Collection	Chapter 6 Research Objective Analysing
	R.O.1. Quantify the environmental and carbon impact caused by the construction projects **R.O. 2.** Review modular construction practices, such as off-site practices and on-site methods, as carbon mitigating strategies in the construction industry by creating a database **R.O. 3.** Evaluating the role of embodied carbon emissions and life cycle assessments in construction projects **R.O.4**. Examining construction projects of modern high-rise buildings in terms of environmental sustainability **R.O.5.** Standardising the assessment criteria for decarbonising the construction industry	**R.O.1**. Quantify the environmental and carbon impact caused by the construction projects **R.O.3**. Evaluating the role of embodied carbon emissions and life cycle assessments in construction projects **R.O.4**. Examining construction projects of modern high-rise buildings in terms of environmental sustainability	**R.O.1**. Quantify the environmental and carbon impact caused by the construction projects **R.O.2.** Review modular construction practices, such as off-site practices and on-site methods, as carbon mitigating strategies in the construction industry by creating a database **R.O. 3.** Evaluating the role of embodied carbon emissions and life cycle assessments in construction projects **R.O.4**. Examining construction projects of modern high-rise buildings in terms of environmental sustainability **R.O.5.** Standardising the assessment criteria for decarbonising the construction industry	

1.12 Research Framework

The following figure presents the general research framework guidelines that will be adhered to throughout the thesis. It is important to note that there will be some deviations and adjustments as needed to address specific cases or issues effectively.



Research Framework
PK Research Aim
Research Objectives
Research Problem
Large-scale, High-rise projects, carbon emissions, embodied carbons, prefabrication, optimisation
Literature Review
PK Bibliometric Studies
Systematic Review
Resources Analysis
Data Collection
PK Inductive Qualitative
Deductive Quantitative
Mixed Methods
SPECS, Shard, ESB, Shanghai, AGT, Khalifa
Case Studies
PK 6 Projects
FK LCA
SimaPro
Embodied Carbons
Unit of Analysis
PK Sampling System
Non- Probability Snow Ball
Proffesionals and Academics
Anarnymous Questionnaire
PK 25 Close-End Questions
102 Respondants
SPSS Analysis
Quantitative
Qualitative
Qualitative
Assessment Criteria/ Projects Involved
PK Sustainability 6
Design 6
Material Contribution 4
Construction Practices 5
Project Location 6
Project Duration 4
Challenges 6
Project Final Cost 4
Results
Interviews
PK Semi-Structure Questionnaire
13 Interviewees
Results
Assessment Criteria
PK Standardisation
Level of Awarness
Embodied Carbon Unit
Net Zero Goal 2050
Results
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Chapter 2 Literature Review: The Environment and Sustainability

2.1 Introduction

This chapter presents the most relevant literature within the research topic, which contains definitions, explanations, rationalisation, analysis, and evaluation of the literature data used. Most recent research documents will be used, some of them might be old but precious, through different types of sources such as articles, books, conference papers, eBooks, thesis documents, and websites.

The chapter structure contains an introduction about the content and the type of sources being used. The body text is divided into sections and subsections in a tunnel metaphoric way, starting in general terms and then narratively reaching the desired research topic. The chapter ends with a summary section that summarises the headline of the literature.

Environmental and specific construction impacts will be introduced, then construction practices and techniques will be presented.

2.2 Environmental Impacts

Climate change is considered a global environmental phenomenon and the most critical environmental issue of the century in many aspects, such as economic, social, and political (Das, 2018). Climate change, global warming, and even recently, global cooling have become crucial to our lives (Letcher, 2021).

On a political scale, contradictions and disputes were presented in this subject in the political argument that made former US President George W Bush withdraw from the 1997 Kyoto Protocol and underestimate climate change. The USA even removed references from government websites (Garrett, 2017). However, the research will mostly remove any political agendas or business boundaries from the subject to eliminate bias and prejudice and deliver a neutral scientific study.

(Hossain and Poon, 2018) stated that global warming environmental impacts due to greenhouse emissions are undisputed, and this kind of consensus will be positive in the research, as fewer arguments will exist on fundamental issues. Figure 2-1 presents the observed temperature rise in the last 160 years.

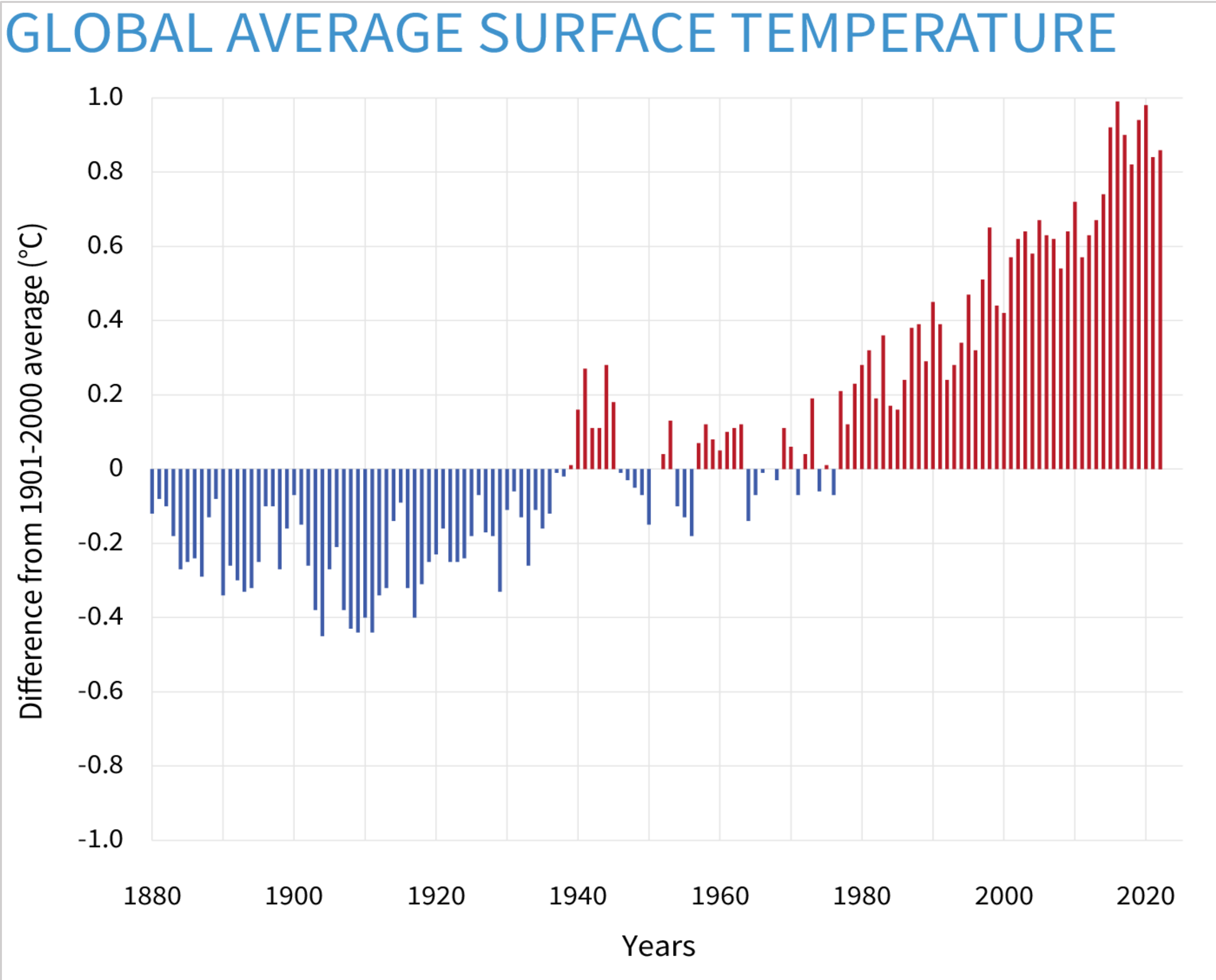


Figure 2-1 Evolution of global mean surface temperature (Climate Change: Global Temperature, 2023)

Global warming has resulted in the most significant ice reduction in the Arctic and has contributed to greenhouse effects caused by CO_2 (Islam and Khan, 2019).

Furthermore, environmental impacts are being associated with climate change, such as heat waves, droughts, floods, blizzards, and hurricanes (Zheng et al., 2020), and that confirms that global warming is the biggest challenge for protecting the environment (Balasbaneh and bin Marsono, 2018). It is observed that this warming is associated with the industrial revolution over the last two centuries, which included many industries and productions that rely on fossil fuels and burning processes, such as iron factories, trains, electricity production, lighting, and concrete production.

Those were the significant environmental impacts caused by humanity on a large scale, and they exploited its ramifications on a small scale. The following section will present the direct impacts related to the construction industry.

2.3 Construction Environmental Impacts

As mentioned earlier, construction exerts a significant environmental footprint, particularly regarding energy consumption practices. The construction industry is essential to many economies but also significantly contributes to environmental degradation, accounting for 36% of global final energy use (Hao et al., 2020).

As vital as food and water for sustaining life, energy is equally essential for providing critical services to humanity (Caiado Couto et al., 2020). Given China's immense population and the escalating demands for energy resources, this necessity has prompted the country to pursue alternative and renewable energy sources (Hu and Cheng, 2017). China serves as a noteworthy example in this context.

(Röck et al., 2020) claim that the building sector is responsible for 40% of energy usage and contributes up to 30% of GHG emissions, and (Liu et al., 2020) argue that they can reach up to 50 % of energy use and 42% of GHG emissions. However, there is an agreement on the high contribution of construction to energy and emissions (Abey and Anand, 2019; Cabeza et al., 2021; Giiyasov, 2018; Harputlugil and de Wilde, 2021; Marzouk and Elshaboury, 2022), because there is a global concern about greenhouse gases caused by the construction industry combined activities (Liu et al., 2020), where buildings contribute significantly to carbon emissions globally (Teng and Pan, 2019).

According to (Voskresenskaya et al., 2018), construction has 50% consumption of energy and 60% of materials resources, and the buildings sector produces around 50% of CO_2 emissions (Balasbaneh and bin Marsono, 2018). "Construction" refers to the entire spectrum of associated sectors, including manufacturing facilities, transportation, machinery, materials, and activities at the construction site.

The words “building” and “construction” overlap, but it seems that construction is a broader concept and includes all relevant activities rather than using the term building sector, and this is guided by the higher percentages of energy consumption and GHG emissions compared to the usage of the building sector phrase.

Although operation-stage emissions of buildings are higher than those of other stages, such as the design and construction of projects, the density of construction-stage emissions is higher than that of the operational stage (Liu et al., 2020).

Density here refers to the concentrated emissions produced during a specific shorter period. The GHG emissions in the construction stage are becoming more significant over time (Mao et al., 2013), probably because the construction phase has intensive impacts on the environment, for example, in a short period in a specific location (Feng et al., 2018).

Monitoring GHG during the construction stage still needs to improve due to the complexity of construction sites and the need for more reliable models. However, using LCA methods can solve the problem of measuring GHG emissions of building systems (Liu et al., 2020) or life cycle sustainability assessment (LCSA) (Ullah et al., 2023).

Mitigating carbon strategies does not affect other stages of construction projects, and this is the main reason this research is trying to avoid words of decarbonisation or zero carbons, as introduced previously.

Figure 2-2 presents the general stages associated usually with embodied carbon emissions in construction projects.

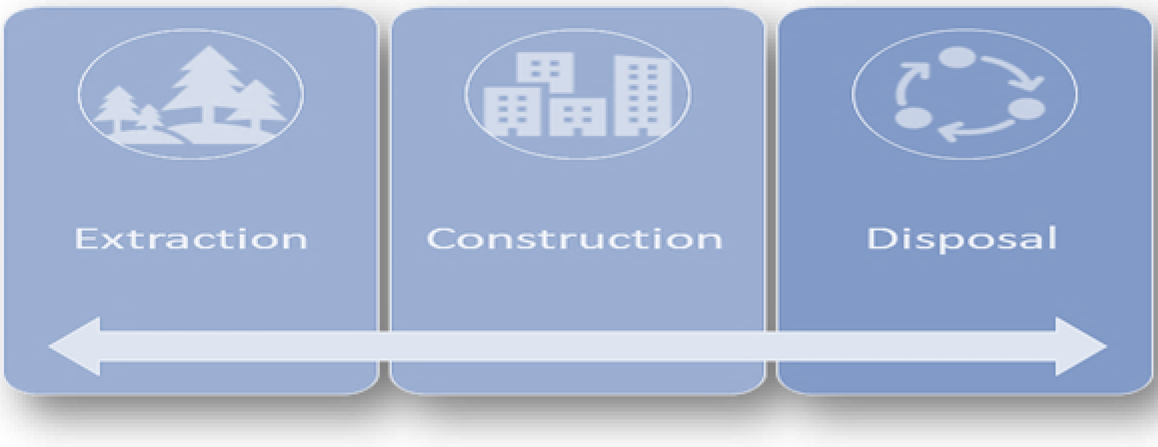


Figure 2-2 Construction project's main phases

The building sector is responsible for 40-50% of energy usage and 30-60% of GHG emissions, and buildings contribute significantly to carbon emissions globally (Hu and Cheng, 2017; Zhu et al., 2022).

The construction phase intensively impacts the environment, and more attention should be given to embodied carbons. Life cycle assessment methods can be used to measure building system GHG emissions, but monitoring during the construction stage still needs to be more robust due to the need for more reliable models.

2.4 Sustainable Construction

The existing literature needs to be more consistent in identifying the environmental aspects of construction activities. Bibliometric studies are more prevalent than comprehensive analyses (Araújo et al., 2020).

Sustainability is defined as a reference that connects environmental, economic, and social issues as a long-term strategy on a global scale, besides climate change, energy systems, food systems, transformation, and reflexivity (Pfister et al., 2016). Sometimes, sustainability is interrelated with sustainable development, mainly concentrating on social, economic, and environmental aspects (el Mekaoui et al., 2020).

Again, energy, represented in the adequate transformations of energy systems, is the key to greater sustainability, as stated by (Pfister et al., 2016). Moreover, the word sustainability is becoming, by default, referring to the environment, which shall be proven by the data collected in the research.

Traditionally, the emphasis has been on reducing energy consumption and minimising environmental impacts during the operational phase of building. However, there has been a recent shift in focus towards addressing these concerns during the construction phase of buildings (Feng et al., 2018).

Sustainable construction and environmental sustainability overlap and are highly related concepts, especially if we add the other dimensions of sustainability: economic and social.

Sustainability in construction encompasses more than just managerial decisions; it extends to the processes within factories and the production of materials. This holistic approach to sustainability involves strategies like energy recovery and the utilisation of mineral fractions like glass, ceramics, and stones to achieve environmentally friendly outcomes (Lee et al., 2020).

However, sustainable construction could also be achieved in the design stage, which could be achieved in diagrid construction, considering the angle, height, and shape to optimise sustainability, especially for high-rise buildings. The compromise of sustainable methods in different construction stages is delivered in the life cycle assessment of projects.

According to (Wu et al., 2017), few studies discuss the impacts and provide sustainable solutions for sustainable construction projects. Moreover, integrating sustainability in both academic and practice levels in construction project management was crucial for achieving balanced environmental, social, and economic targets (Yu et al., 2018).

Before exploring the status of sustainability in construction projects in aspects of practices and results, this research examines the main impacts related to the environment of the construction projects, and these impacts are classified into four main stages (Leśniak and Zima, 2018):

- Extraction of raw materials
- Production of materials used
- Construction of the building
- Operation and demolition of the building

(Zavadskas et al., 2017) explained that sustainable construction is considered the most critical issue in recent years besides construction technology and building structures and systems, which include the following aspects:

- Building structures and systems
- Construction technology
- Retrofitting
- Sustainable construction
- Construction management
- Building management
- Location selection

2.5 Optimisation in Construction

Optimisation is the process of designing and applying the minimum possible amount of materials when constructing a building. This research explores optimising materials and design in construction projects because many scholars suggest it is an alternative or part of sustainable construction techniques. There are several types of optimisations in construction, such as the optimisation of materials, the optimisation of structure, and optimisation of design (Stoiber and Kromoser, 2021), and even in job site layout planning (Muhammad et al., 2020).

Since the early 1960s, numerous outstanding research studies have emerged in optimisation-based structural engineering. This research has led to successful applications of structural optimisation in addressing various problems (Lagaros, 2018).

The optimisation approach can be considered part of the sustainable process, where, according to (Zhang et al., 2022), structural design optimisation can significantly reduce embodied carbons through the cradle-to-end of the construction stage. Nevertheless, the issue is that this method has other (Pongiglione and Calderini, 2016) design and safety problems, such as it should be applied very precisely to maintain the structure of the building and the quality of components.

(Pongiglione and Calderini, 2016) urged for the application of optimisation in the design and construction of tall buildings to enhance environmental sustainability, given their extensive material usage.

(Koronaki, 2020) in their thesis, they considered optimisation and sustainability as the same approach for reducing embodied carbon emissions but needed to explore the negative impacts of optimisation. Moreover, the optimisation process does not include architectural elements such as insulations, services, paintings, and decoration (Zhang et al., 2022).

In construction, the optimisation process should be clearly understood to include two key components: firstly, the optimisation of materials and structural elements, and secondly, the optimisation of construction processes and project durations (Kandil et al., 2010). Both aspects are crucial for improving efficiency, reducing costs, and minimizing environmental impacts.

Optimisation problems are that using LCA methodology, the approach often falls short of fully complying with LCA principles. This is because it typically focuses only on the environmental impact of operational energy use, while neglecting the significant impacts of embodied energy used in construction (Kiss and Szalay, 2020). By overlooking the embodied energy and associated emissions of materials, the assessment does not capture the complete environmental footprint of the building.

In the subsequent sections, the research will dig into the detailed application of optimisation methodologies within construction projects, focusing on their implications for environmental sustainability. This exploration will be complemented by an in-depth examination of the extensive dataset gathered through rigorous data collection methodologies in this research. Furthermore, the study will establish the critical link between optimisation strategies and sustainable construction practices, emphasising their pivotal role in mitigating embodied carbon emissions, especially in large-scale projects.

2.6 Carbon Emissions

A deeper understanding of the importance and the impacts of CO_2 on climate change was only introduced in recent decades (Planet, 2020). The carbon increase has contributed highly to the environment and climate change, making the Paris Agreement limit climate change and make more commitments in the UK and around the globe to imply carbon mitigation strategies, reaching over 195 countries (Kuzemko et al., 2018).

The 2022 Global Status Report for Buildings and Construction highlights that the building and construction sector needs to be on track to achieve decarbonisation by 2050 (Global Status Report for Buildings and Construction, 2022). The report renews the call to decarbonise the built environment and emphasises the need for policies, codes, and standards to support the transition to a low-carbon-built climate. The report also finds that the building sector must still catch up to achieve decarbonisation by 2050 (Hamilton, 2023).

The report argues that decarbonisation of the building stock must prioritise energy efficiency, renewable energy, and low-carbon materials. The World Green Building Council (WGBC) is working with green building councils across the network to develop tools and strategies to reach the goal of total built environment decarbonisation by 2050.

The greenhouse effect, a significant impact resulting from the increase of CO_2 emissions, is defined by (Zheng et al., 2020) as "*a natural process that warms Earth's surface*". Moreover, as the CO_2 definition indicates, all the terms presented so far are combined towards the exact causes and impacts regarding the environment. Concrete, for example, is causing 5 % of CO_2 emissions (Grado, 2017), which is a significant contributor to climate change and shall be discussed intensively.

The Kyoto Protocol recommends including six types of GHG in embodied carbon results, namely CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6 (Gan et al., 2017). However, since HFCs, PFCs, and SF_6 are insignificant in the building sector, this research focuses only on CO_2, CH_4, and N_2O minor. To convert the emissions of these gases to CO2 equivalent, the global warming potential (GWP) is multiplied by 1, 25, and 298 for CO_2, CH_4, and N_2O, respectively. The outcomes are presented in kilograms of CO_2 -e per meter squared gross floor area.

Two types of CO_2 emissions are associated with construction: embodied and operational. In comparison, embodied carbon emissions are divided into two types (Teng and Pan, 2019).

1. Initial: produced by materials extraction until the end of construction
2. And recurring produced by maintenance, repair, restoration, and refurbishment

(Hu and Esram, 2021) defined a third type associated with demolition and the end of a building's life.

The consumption of energy is classified accordingly. In this context, there are embodied and operational energy, again:

- Embodied energy is the amount of energy consumed, while EC is the amount of GHG emitted to produce material, product, or building (De Wolf et al., 2017)

- Operational energy, which is the energy consumed during the usage stage of buildings

While energy cost and GHG emissions are related, they are not directly equivalent, and this research will concentrate on the latter, using the term 'CO_2 e' as Figures 2-3 show the energy through the life cycle of construction and building operations.

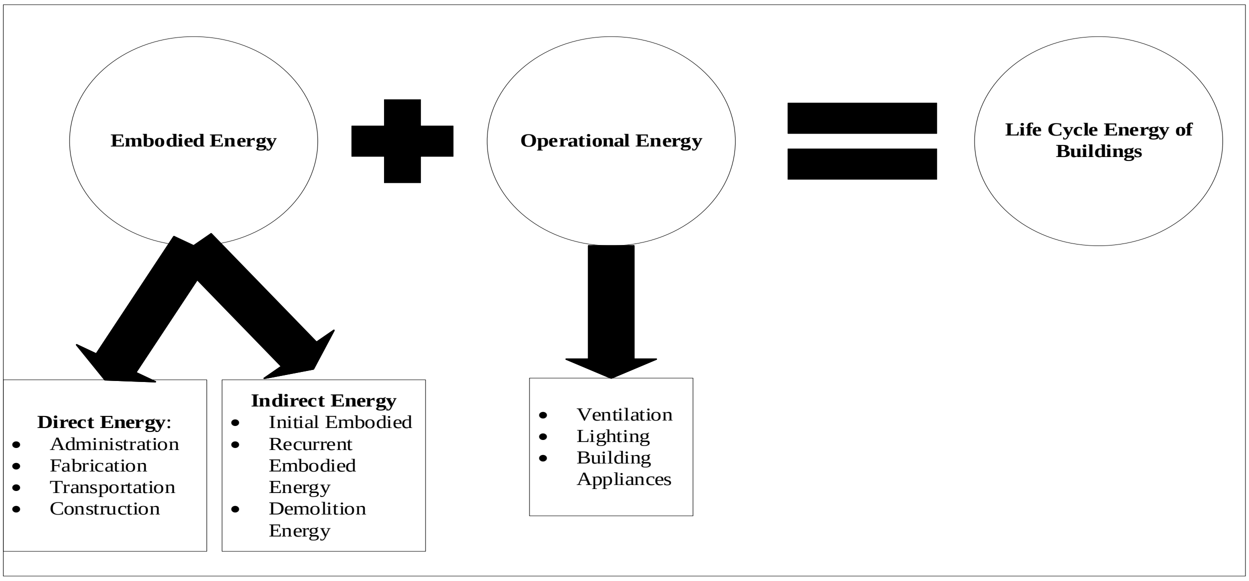


Figure 2-3 The energy life cycle consumption (Marzouk and Elshaboury 2022)

Energy consumption results in CO_2 emissions. However, embodied energy and emissions are unrelated (Marzouk and Elshaboury, 2022).

The embodied carbons (EC) "*represents the emissions produced by construction materials during manufacturing, construction, replacement, and end-of-life stages*" (Marzouk and Elshaboury, 2022) and resource extraction (López-Guerrero et al., 2022). See Figure 2-4.

Figure 2-4 Types of carbon emissions emitted by buildings (CarbonCure, 2020)

Embodied carbon calculation can depend on the project stage and life cycle and should be determined in the design stage. The margin of calculated EC is significant and will be covered in the data collection chapter.

After exploring the difference between EC and OC in terms of stages, Table 2-1 presents the conducted bibliometric study for the most critical aspects and differences between EC and OC. The utilized resources were consolidated to present the findings.

Table 2-1 Bibliometric study for EC and OC

Category	EC	OC	References
Definition	Emissions are produced in the extraction of materials, production, construction, and demolition	Emissions produced in the use and operation of buildings	(Pan 2014; de Wolf et al. 2017; Jeong et al. 2017; Schwartz 2018; Teng et al. 2018; Futas et al. 2019; Teng and Pan 2019; Arashpour et al. 2020; Habert et al. 2020; Röck et al. 2020; Teng and Pan 2020; AzariJafari et al. 2021; Han et al. 2022; Marzouk and Elshaboury 2022; Marzouk and Elshaboury 2022; Zhu et al. 2022;Jeong et al., 2017; Marzouk & Elshaboury, 2022) (World Green Building Council, 2022)
Stage	Cradle to produce, cradle to site, cradle to construction, cradle to use, cradle to grave, cradle to cradle, cradle to demolition, use stage (maintenance and repair)	Design, use	
Frequency	Initial, fixed, and recurrent	Recurrent	
Involved people	Architects, engineers, contractors	Engineers, stakeholders, residents	
Environmental impacts	Climate change, global warming	Climate change, global warming	
Quantity	1:10 rate for now, but can reach to **1: 1** after a specific time, 11% out of 39%	60 %, 28% out of 39%	
$KgCO_2eq/m^2$	253 - 900	15- 26 (reoccurring)	
Mitigation strategies	OSC, BIM, LCA, Lean management, Additive Manufacturing (AM), 3D printing	Solar panels, wind turbines, water energy, renewable electricity resources	

RPS Group has summarised the differences between embodied and operational carbons in the simple way presented in Figure 2-5.

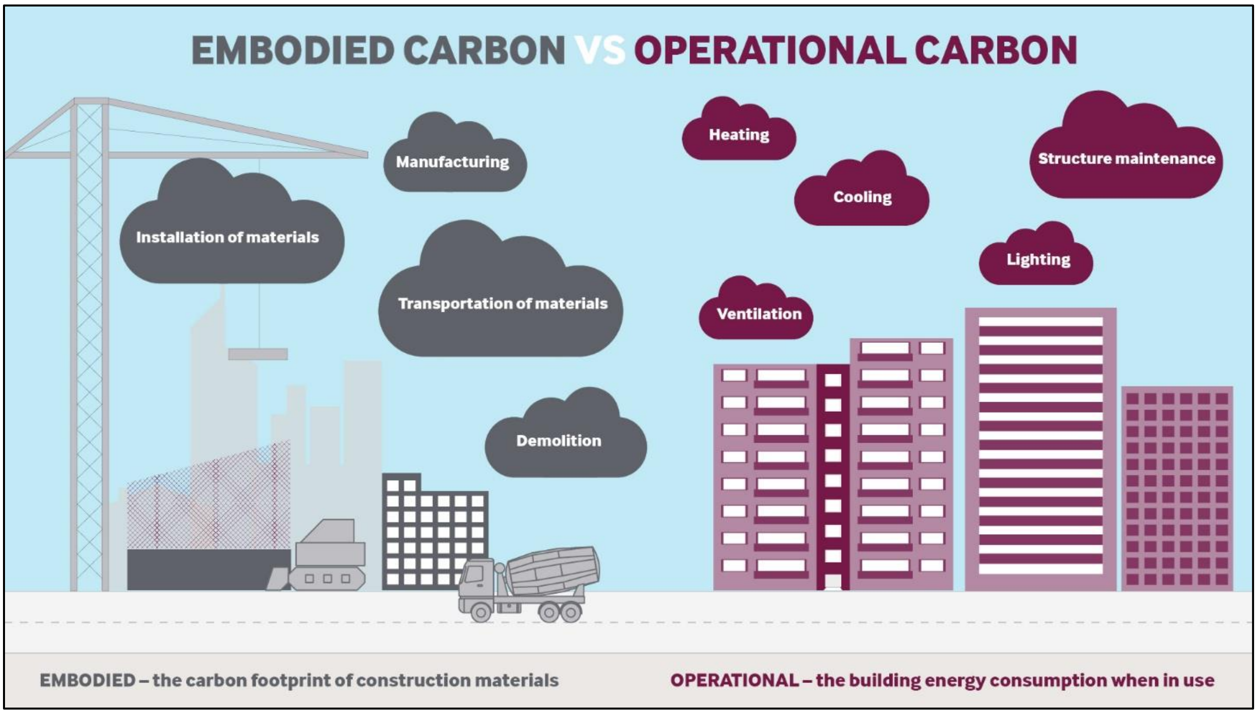


Figure 2-5 Embodied carbons vs operational carbons (rpsgroup, 2023)

Figure 2-6 introduces the life cycle stages of carbon-emitting stages.

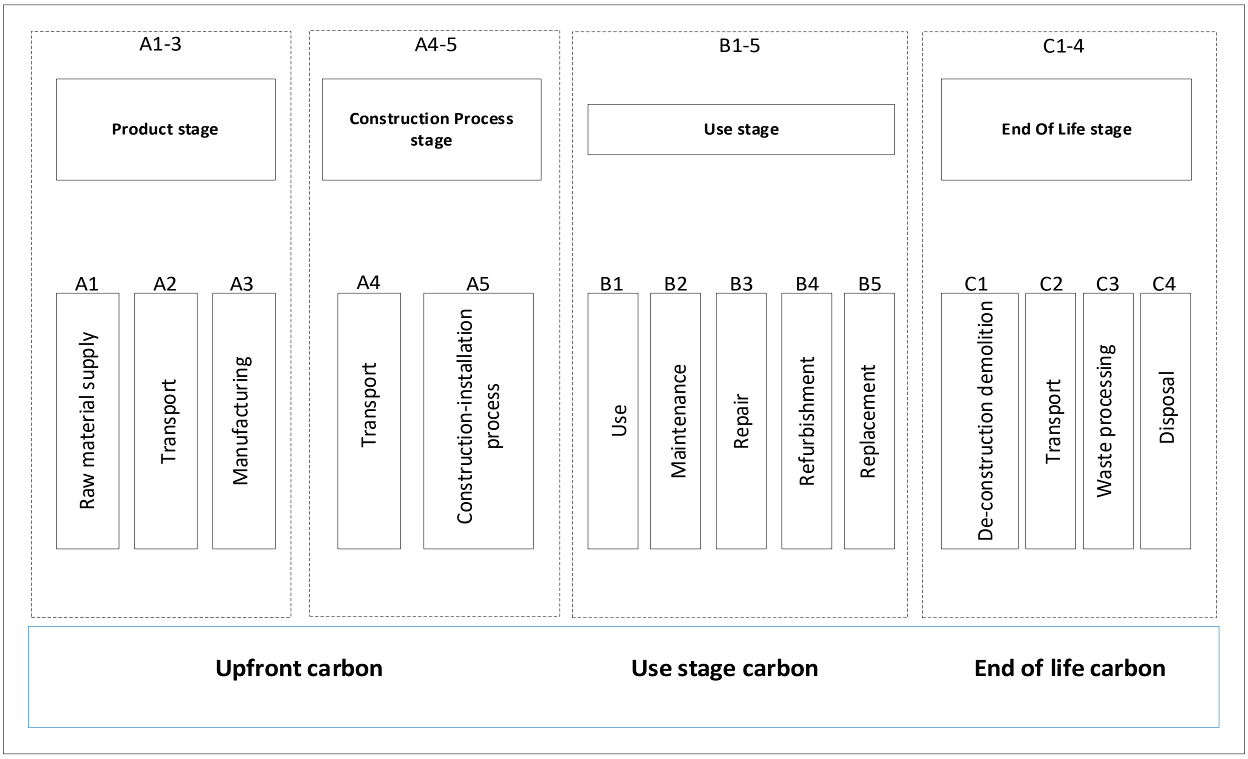


Figure 2-6 Carbon emissions lifecycle (RIBA, 2024)

Moreover, similar stages were conducted by (Hu and Esram, 2021), but different ways are presented in Figure 2-7.

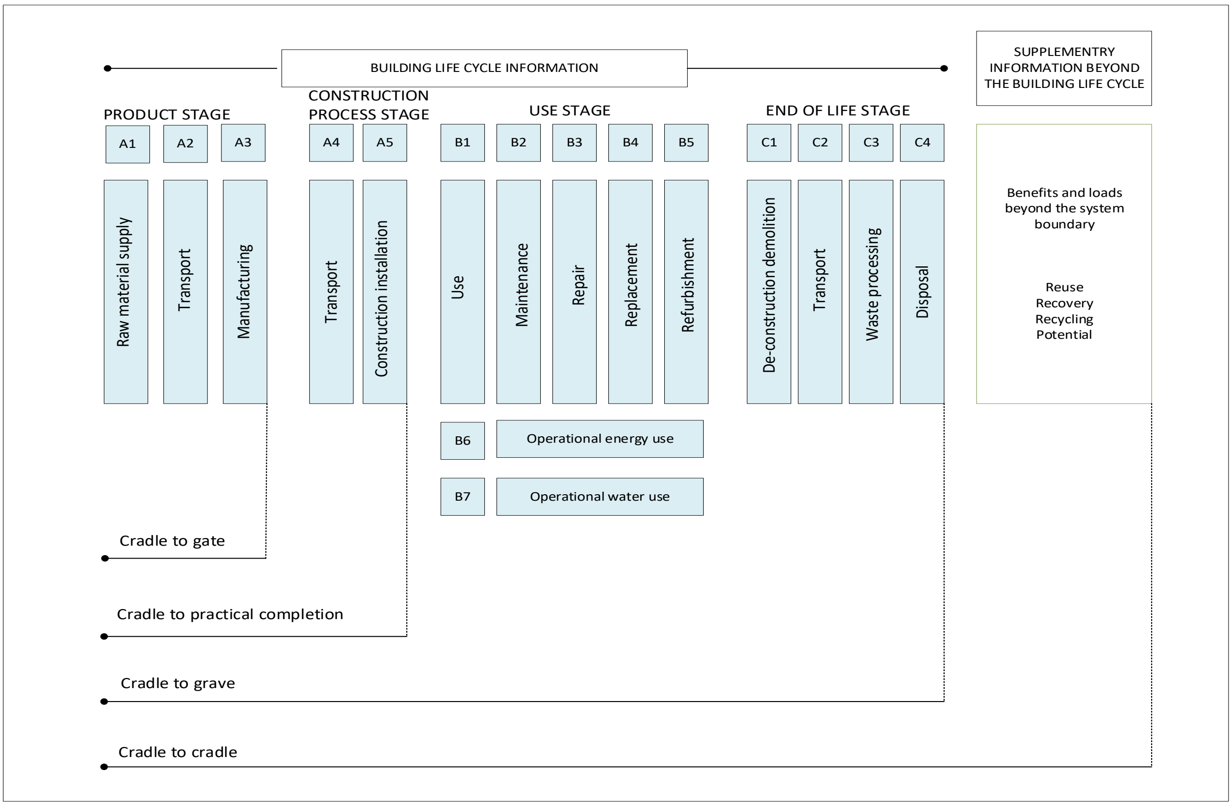


Figure 2-7 Building's life cycle stages (Hu and Esram, 2021)

The embodied carbons calculation process is explained in equation 1, demonstrated by (Chau et al., 2015) through Life Cycle Carbon Emission Assessment, which considers all the carbon-equivalent emission output from a building over different phases of its life cycle. The amount of life cycle carbon emission can be computed by:

$$CO_2 = CO_2Extraction + CO_2Manufacture + CO_2Onsite + CO_2Operation$$

$$+ CO_2Demolition + CO_2Recycling + CO_2Disposal$$

Equation 1

Where CO_2 represents the CO_2 emission of the whole life cycle of a building.

Moreover, according to the same author, embodied carbon emissions are calculated through equation 2:

$$CO_2\ embodied = CO2;\ Extraction;\ I + CO_2;\ Manufacture;i\ + CO_2;Transportation;i$$

Equation 2

Surprisingly, the author omitted the construction process and on-site activity from Equation 2, even though they were incorporated in Equation 1. According to (Gan et al., 2017), embodied carbon calculations include First Cradle-to-Gate, which provides for resource extraction, material processing, manufacturing, and finishing treatment. Second is the Cradle-to-Site stage, which consists of transporting construction materials. The GHG emissions are highly related to GWP and can be extracted in the following equation 3, GHG emissions factor (Mao et al., 2013) **:**

$$\sum_{c=1}^{c} Fc \times GWPVc$$

Equation 3

Where Fc is a given gas factor c emissions factor per unit, and GWPVc is the GWP of the mentioned gases.

The focus of this research is on embodied carbons, as introduced earlier. Moreover, the total energy needed to produce construction materials (embodied energy) can represent 400% of operational energy in the future (Sicignano et al., 2019).

A case study conducted by (Tumminia et al., 2018), examined five different types of buildings: traditional, low energy, net zero energy, prefabricated, and container housing buildings. It was shown that through the whole life cycle of the building (including operational energy), the material production phase (embodied carbons) alone accounted for 70-90% of the total environmental impacts through the cases examined. This study supports this research by focusing more on embodied carbons, especially after eliminating the operational energy factors, using different design methods such as net zero buildings, passive houses, renewable resources, and others.

The process of measuring and estimating embodied carbon emissions through construction projects is clarified by (Alotaibi et al., 2022), presented in Table 2-2.

Table 2-2 Assessment process of embodied carbons modified after (Alotaibi et al., 2022)

Steps	Goals	Requirements	Output
Modelling	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 foods	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 ggbs-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	Annual energy and water bills Selected equipment details	Emissions caused by energy and water consumption Emissions caused by renovation changes
Estimate the embodied carbon	To identify the embodied carbon in the operation 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	Type of material used and the original design of building components 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

Carbon emissions from construction activities significantly contribute to climate change. To address this, it is imperative to establish supportive policies, codes, and standards for adopting a low-carbon built environment. Within the construction industry, there are two key types of carbon emissions, EC and OC, each with unique characteristics in terms of sources, stages, frequency, personnel involvement, and environmental impacts. Understanding these distinctions is pivotal for informed decision-making in sustainable construction practices.

EC represents emissions produced by construction materials during manufacturing, construction, replacement, and end-of-life stages, while OC represents emissions produced in the use and operation of buildings. Considering both types of carbon emissions in building design is crucial to achieving total decarbonisation of the built environment by 2050.

2.7 Construction Practices, Methods, and Tools

This section will discuss the most assumed essential techniques and practices in project management that promote sustainability in construction. The focus will be on systems designed to support environmental sustainability and energy efficiency, while offsite and on-site construction practices will be explored separately.

The concept of Construction 4.0 emerges from a convergence of trends and technologies poised to revolutionise the design, construction, and operation of built environment assets. The industry stands at the brink of a significant shift, propelled by the extensive embrace of Building Information Modelling (BIM), lean methodologies, digital advancements, and offsite construction (Sawhney et al., 2020).

It is essential to verify that the introduced sections mentioned below are relevant to this research and have been under exploration. These sections have been included in establishing a robust database through questionnaires, interviews, and case studies.

2.7.1 Lean Construction Management

The lean concept was considered popular after the publication of the book "The *Machine That Changed the World* "by Womack in 1990 (Abdallah et al., 2019). However, it is hard to define Lean in a few words. In brief, Lean Management is an approach that aims to eliminate and reduce waste (Chiarini et al., 2018).

The Lean concept was derived from the Toyota Production Principles, including techniques and methods such as Just-In-Time, Kanban, and Value Stream Mapping used to apply the lean concept in factories and manufacturing processes (Mayr et al., 2018).

Introducing the Lean concept to the construction industry was aimed at getting over several project management limitations such as time, cost, and waste (Di Domenico, 2020) and is considered a solid tool to make improvements in environmental quality and waste elimination throughout the following core drivers (Ogunbiyi et al., 2014):

1. Waste elimination
2. Process control
3. Flexibility
4. Optimisation
5. People utilisation

6. Continuous and efficient improvements

(Sebastian, 2019) stated that waste issues in the construction process could be eliminated by managing the time spent on checking information or materials to meet the requirements of the project and through the time spent on transfer, perhaps more than focusing on materials waste such as steel and concrete, which does not exceed 3 % for the concrete and 1 % for the steel. Moreover, (Gao S and Low S, 2014) explain the benefits of lean construction by improving cost structure, increasing productivity, better delivery times, improving quality, and meeting job satisfaction.

As outlined by Parfenova et al. (2020), lean construction techniques encompass various strategies to enhance the efficiency and effectiveness of project execution. These techniques include (Parfenova et al., 2020):

1. Lean operation, focuses on optimising individual processes and enhancing the responsibilities of engineers at the construction site to streamline operations

2. Strategic techniques that aim to optimise the flow and management of the construction process, ensuring smoother project progression and better resource utilisation

This research will cope with the environmental and energy aspects, in which (Francis and Thomas, 2020) agree that the construction sector contains complexity, uniqueness, and on-site production but claim that the construction sector produces a hard impact on the environment and increases emissions and raw materials loss.

This research emphasises the significance of sustainable construction in reducing environmental and energy footprints. (Carvajal-Arango et al., 2019) further affirms that the interconnection between lean construction and sustainable construction, a trend gaining traction since 2009, yields parallel enhancements in project management while concurrently minimising energy consumption and utilising energy-intensive materials.

(Francis and Thomas, 2020) showed that the positive relationship between lean construction and environmental sustainability could be summarised in the following outcomes:

1. Minimising resource depletion
2. Reducing the pollution caused by eliminating waste
3. Less environmental impact

Criticisms and challenges of lean construction could be illustrated according to (Gao S and Low S, 2014), that lean systems lack credibility and complexity and that each project has its specifications and low levels of automation.

Moreover, Lean management serves objective 2 of this research related to OSC, as lean management can produce environmentally clean precast concrete alongside OSC (Hu and Chong, 2021).

2.7.2 Building Information Modelling (BIM)

BIM is a framework centred around 3D modelling, intended to integrate and digitise comprehensive building information, enabling the representation of all building components and their interconnections (Hu and Zhang, 2011). The BIM method has benefited the construction industry in managing the reuse of materials and efficiently recycling the components and materials of buildings (Jayasinghe and Waldmann, 2020). Moreover, BIM can improve social performance in construction management (Zoghi et al., 2021).

According to (Chen et al., 2019), the combination of lean management and BIM can increase the construction industry's flexibility, visuals, and standard management because of the numerous advantages they offer to project stakeholders, including improved design visualisation, enhanced data exchanges, decreased construction waste, heightened productivity, and elevated product quality. Moreover, the combination of BIM and LCA software can validate the extracted bill of quantities data in any construction project (J. Xu et al., 2022).

This research explores project management practices and tools, such as BIM and Lean construction, and their consequences on the built environment's impacts. BIM and lean methods are applied in the construction industry to enhance and create more efficiency and better environmental impacts (Fernández-Rodríguez et al., 2018). According to (Pan and Zhang, 2021), BIM is leading in digitalising construction projects.

Zhou and co-workers (Zhou and Huang, 2018) argue that BIM is still not widely understood, maybe because it contains several obstacles illustrated by technical issues with the application level (Chen et al., 2019), and has a lack of safety analysis information (Hu and Zhang, 2011).

However, (Jayasinghe and Waldmann, 2020) stated that BIM motivates sustainable resource management, and (Zhong et al., 2018) agreed that BIM supports applications in the field of environment such as energy performance and CO_2 emissions.

However, BIM and lean methods applications have resulted in more efficient production and better environmental, social, and economic impacts detailed in the following areas (Fernández-Rodríguez et al., 2018):

- Climate change
- Indoor air quality
- Energy systems
- Green spaces
- Infrastructure ecology
- Sustainable management

(Abioye et al., 2021) explained that construction and demolition waste (C&DW) production is increasing annually due to rapid and continuous development. These construction activities negatively impact the environment, natural resources, and human well-being.

Abioye (2021) developed Table 2-3 to cover most boundaries of AI and BIM in construction projects.

Table 2-3 AI and BIM in construction projects modified after (Abioye et al., 2021)

Sub-domain	**State-of-the-art**	**Potential opportunities**
Resource and Waste Optimisation	Data analytics for waste management and collection	BIM-based 3D model for construction waste quantification BIM-based construction waste minimisation framework BIM for waste minimisation design AI-driven holistic waste analytics tool
Estimation and Scheduling	BIM for cost and time estimation	Deep learning for cost and time estimation
Construction Site Analytics	Project control on construction sites	Construction performance analytics , Site layout planning, AI-driven BIM-based construction site analytics, AI chatbot for site information
Job creation	BIM jobs and competences	Green jobs, Effects of robot automation on jobs, Construction automation tools developer, Systems trainers, System testers
AI and BIM with industry 4.0 tools	Intelligent building energy monitoring	IoT-enabled BIM platform for prefabrication construction, IoT for safety warning on construction sites, AI-driven IoT platform, AI-enabled BIM for IoT
AI with Smart Cities(SC)	Smart homes energy consumption management	Smart city development and urban planning using sensors, Metadata schema for smart building infrastructure, Urban energy performance using BIM and CIS, AI-driven built environment analytics, Interoperable building management systems (BMS)
AI with Augmented Reality(AR)	Application areas of AR in construction	Defect management using BIM, AR and ontology-based data collection, Mobile-based virtual reality and augmented reality, health and safety education, RFID combined with blockchain for materials logistics, Integrating IoT

In conclusion, BIM and lean management are two practices that have been applied in the construction industry to increase efficiency and productivity, reduce waste, and digitalise construction. Both methods have positively impacted the built environment, including reducing resource depletion and pollution, improving energy performance, and promoting sustainable management.

Although BIM has primarily emphasised the design phase of construction projects, its potential to facilitate sustainable resource management is evident. Nonetheless, technical and research hurdles must be overcome to fully harness the benefits of these approaches within the construction industry.

2.7.3 Green Buildings

"*Green buildings are known as sustainable or high-performance buildings, have been intertwined within the manifold milestones of global sustainability and passive systems comprising 'roof ventilators and underground air-cooling chambers' were used to improve the indoor air quality"*(Wuni et al., 2019).

The green concept in construction is crucial for project management and the construction phase.

Environment Protection Agency (EPA) has stated that green buildings enhance and support environmentally friendly buildings, such as design, action, and operation (Zhang and Mohandes, 2020).

(Sim and Putuhena, 2015) discuss that the purpose of turning to green technology and construction is related to climate change and the future of construction. Moreover, it could be developed in project management practices to achieve sustainable development, leading to clean and efficient resources. This was agreed by (Zhang et al., 2019).

Green construction management is advancing sustainable development by using responsible management of projects aiming to achieve environmentally friendly buildings (X. Wu et al., 2019). This includes several aspects such as land, water, materials, and the application of project initiation, planning, design, construction, and operation and is aimed to (Zhang and Mohandes, 2020):

1. Balanced relationship with nature
2. Environment protection
3. Low consumption
4. High-efficiency construction

The challenges and limitations of using the green buildings concept are that projects have a higher cost due to consuming more sustainable materials (Lu et al., 2019), and going green has been creating challenges and obstacles related to health and safety (Zhang and Mohandes, 2020). That is why there have been several studies in recent years that have shown the importance and need for green management (Sim and Putuhena, 2015).

Green construction management encompasses responsible project management practices to achieve environmentally friendly buildings. This responsibility includes considering land, water, materials, and applying green principles throughout the project life cycle. The goals of green construction management include maintaining a balanced relationship with nature, protecting the environment, minimising consumption, and promoting high-efficiency construction practices.

2.7.4 Artificial Intelligence in Construction

Artificial Intelligence (AI) has emerged as a transformative technology with the potential to revolutionise various sectors, and the construction industry is no exception. With its ability to process vast amounts of data, analyse complex patterns, and automate tasks, AI could reshape traditional construction practices, enhancing efficiency, productivity, and sustainability (Ekici et al., 2021).

(Pan and Zhang, 2021) have emphasised the role of AI within the construction engineering and management (CEM) approach, where CEM involves collecting large amounts of diverse data, especially with technologies like BIM and wireless sensor networks (WSN). This data-intensive nature makes it suitable for employing various AI techniques to effectively address the unique aspects of CEM throughout a project's life cycle.

AI is transforming the design and planning phases of construction projects. AI can create and refine design models through machine learning algorithms and computer vision, substantially cutting time and expenses. This technology empowers architects and engineers to craft groundbreaking structures, employing sophisticated algorithms to scrutinise structural robustness, energy efficacy, and material enhancement. AI-driven software fosters immediate collaboration and data-guided decision-making, culminating in more knowledgeable design selections (Ekici et al., 2021).

AI-driven automation streamlines construction processes, improves productivity, and reduces human error. Robotic systems with AI capabilities can perform repetitive tasks with precision and speed, such as bricklaying, concrete pouring, and material handling. Drones and autonomous vehicles assist in site inspections, surveying, and monitoring progress, ensuring safety and efficiency (Al Rashid et al., 2020; Chea et al., 2020; Kontovourkis and Tryfonos, 2020). More exploration of this is included in on-site construction technologies will follow.

According to (Choi et al., 2021), AI's data analysis capabilities enable predictive analytics and risk management in construction projects by analysing historical data, weather patterns, and project-specific factors.

AI enables the creation of innovative building systems, promoting intelligent and sustainable structures. By integrating IoT technology and AI algorithms, buildings can optimise energy usage, monitor performance, and enhance occupant comfort. Through data analysis on temperature, occupancy, and energy consumption (Aguilar et al., 2021; Farzaneh et al., 2021).

The relationship between AI and sustainable construction should be mutually beneficial. AI enables sustainable construction practices by optimising resource allocation, improving energy efficiency, and reducing waste. Through data analysis and predictive modelling, AI helps identify opportunities for energy savings, optimise building designs, and enhance overall environmental performance.

This distinct limitation sets the construction industry apart from other sectors where AI is more extensively employed (Abdirad and Mathur, 2021; Abioye et al., 2021; Aziz et al., 2014; Gazulla et al., 2014; Hu and Zhang, 2011; Lalmi et al., 2021; Pan and Zhang, 2021).

For instance, AI's current capabilities do not encompass tasks like designing complex architectural structures such as buildings or bridges. However, it can generate original content like poetry or stories from scratch, produce the best coffee combination through a machine, and even formulate detailed plans for school activities spanning a specific academic year.

On the other hand, engineering software programs such as AutoCAD and Revit can create or develop structural designs but with human directions and inserting inputs. This comparison exemplifies AI's current limitations in direct applications that require intricate human creativity and contextual understanding while showcasing its potential in more rule-based and data-driven tasks.

2.8 Modular and Off-Site Construction

2.8.1 Introduction

OSC manufactures and preassembles specific building components, modules, and elements before their movement and installation on the construction site (Hosseini et al., 2018). It is a tool that transforms the construction sector from a labour-intensive to a modernised green industry (Gan et al. 2018).

"*Some scholars define modular construction as a well-developed off-site manufacturing approach*" (Wang et al., 2020).

Modular construction has been extensively utilised for low-rise buildings across the globe, especially in countries like the UK, North America, China, Singapore, and Australia. Despite facing significant technical challenges in high-rise applications, recent advancements in manufacturing and material technologies have made it possible to construct several modular high-rise buildings. However, the adoption of modular construction for high-rise buildings remains relatively rare, with these buildings accounting for less than 1% of all high-rise structures worldwide (Thai et al., 2020). This is why this research will focus more on the off-site and prefabrication systems.

Moreover, off-site prefabrication is a construction system that contains a process where components of buildings are manufactured and assembled in an off-site factory and then transported and installed on-site, also called modular construction, off-site construction, prefabrication (Hammad et al., 2019), panelised construction or tilt-up construction (Jin et al., 2018), industrialised construction (Hu et al., 2019), and prefabricated, prefinished volumetric construction (PPVC) (Wang et al., 2020).

OSC is a relatively new construction method because it moves the construction process from the job site to a controlled factory environment (Jin et al., 2018). Especially in the last 20 years (Wang et al., 2020). Therefore, OSC interest has been increasing in the previous decade, and any related research and publishing publications make it challenging to evaluate and extract the required knowledge (Hosseini et al., 2018).

According to (Jin et al., 2018), OSC research and application area includes the same definitions such as prefabricated construction, industrialised building, modular construction, panelised construction, tilt-up construction, or off-site manufacturing. Furthermore, the construction industry and research area could combine the multiple definitions into one terminology to facilitate research and application.

The benefits of adopting OSC are (Hosseini et al., 2018):

- Enhancing structural reliability
- Increasing productivity
- Decreasing construction time
- Labor reduction
- Material waste reduction

The previous benefits serve and enhance the aims and objectives of this research, especially in aspects of productivity, time, and material waste. However, the most crucial outcome of OSC is that it claims to provide environmental and social sustainability and improve health and safety (Hossain and Poon, 2018). Furthermore, prefabrication construction is a technology that is gaining popularity because it can reduce construction waste (Hao et al., 2020).

However, OSC has barriers and challenges to consider. Those barriers and challenges are summarised by (X. Gan et al., 2018):

- High cost
- Ineffective logistics such as storage and transportation issues
- Manufacturing capacity is associated with the design of manufactures
- Quality problems are where the quality adopted by OSC is challenging and challenging to achieve
- Complicated management because OSC requires a high management level involving multi-parties
- Lack of knowledge and experience

Also, (Hu and Chong, 2021) emphasised the environmental limitations, such as energy consumption and pollution during the transportation stage, but (Jin et al., 2020) stated that OSC is considered a time-efficient and cost-saving method that can deliver sustainable construction and greener industry.

2.8.2 OSC and Environmental Sustainability

Table 2-4 explores the environmental sustainability concerning OSC, based on the study by (Brissi et al., 2021). The table illustrates the boundaries related to OSC in most environmental sustainability.

Table 2-4 Environmental sustainability for OSC modified after (Brissi et al., 2021)

Factors	Subfactors	References	Frequency
Environmental sustainability	General concepts such as environmental performance; environmental sustainability; sustainability requirements, environmental impact; environmental awareness; ecological construction; ecology preservation	28	62%
Waste and pollution	Waste management including recycling and reuse strategies; waste and pollution reduction; waste disposal; on-site noise and air pollution	25	56%
Materials and practices	materials consumption and savings; recycled, reusable and renewable materials; material waste in construction; environmentally preferable materials; embodied energy-intensive materials (reduction of greenhouse gases emissions); carbon footprint; use of regional materials (reduction of negative impacts of transportation); material durability	22	49%
Building performance	Energy efficiency (energy consumption during the building life cycle); energy consumption associated to thermal performance; carbon and greenhouse gases emissions; renewable energy; water and wastewater efficiency; water reuse and recycling systems; water harvesting systems; environmental certifications	21	47%
Site disruption	Project site and surrounding local communities' disturbance; impacts on environmentally sensitive sites; traffic congestion; noise during construction; imposition of specific hours to on-site work; planning for stormwater management; post construction environmental recovery	17	38%
Climate, weather and resilience	Severe local area condition, harsh weather and climate; wind speed; humidity and other weather conditions that degrade labour performance; climate independence; climate responsive housing; housing for resilience; building safety and security	13	29%
Building comfort and IEQ	Indoor air quality; indoor comfort; thermal and acoustic quality; health of occupants	9	20%

The percentages shown in Table 2-4 represent the number of published studies since 2001, with a total of 135 references.

2.8.3 Comparing OSC with Traditional Construction Methods

Industrialised building systems (IBS) are compared with traditional building systems (TBS), mainly based on operational and embodied carbon emissions, besides waste reduction (López-Guerrero et al., 2022). Such comparisons can provide several environmental and social advantages (Hosseini et al., 2018), called wet and dry construction systems (Di Ruocco and Melella, 2018).

According to (Teng et al., 2018), OSC can reduce carbon footprint, especially embodied carbon emissions, depending on the materials used. For example, wood has higher reduction rates than concrete. According to (Hao et al., 2020), prefabrication can lead to a 10% reduction in carbon emissions per cubic meter of concrete. Nevertheless, (Bei et al., 2021) were more specific in their study, clarifying that the transition from “cast-in-situ” to “prefabrication” reduces embodied carbon emissions noticeably, especially in high-rise residential buildings.

Moreover, (Tumminia et al., 2018) stated that GHG emissions can be reduced by 3.2% at least when using prefabricated construction methods. However, their study was on tiny, prefabricated buildings, such as a 45 m^2 building in Messina /Italy.

Some of the challenges give some advantages to TBS, such as cost (Hong et al., 2018). Table 2-5 was conducted as a systematic review approach, which, according to (Goel et al., 2019), is characterised by a well-defined procedure to search and shortlist relevant articles. Moreover, to make a deep comparison between IBS, specifically OSC, and TBS, in terms of environment, sustainability, and other aspects.

According to (Tumminia et al., 2018), prefabrication cannot replace conventional construction. However, this research seeks the best usage of it and collaboration that can create a resilient and sustainable construction project.

A bibliometric study by (Tavares et al., 2019) presents clearly that prefabricated buildings, especially those made from concrete and timber, have lower embodied carbon emissions in the cradle-to-site stage. The bibliometric study is illustrated in Table 2-6.

Table 2-5 Systematic reviews for OSC and material selection and technologies

No.	Category	Material technologies	OSC practices
1	Time	Consumes more time especially in the production stage	Reduces time in the construction stage
2	Cost	Requires higher expenses especially when having additive materials	Should reduce the expenses when reducing time, labour, and waste
3	Resilience	Depends on the availability of materials, knowing the how-technology and professionals.	More resilient in the construction site
4	Applicability	Yes	Yes
5	Environmentally Sustainable	Yes	Yes
6	Carbon emissions	Reduces EC and OC	Reduces EC and OC
Abey & Anand, 2019; de Wolf et al., 2017; Futas et al., 2019; Habert et al., 2020; Hammad et al., 2019; Han et al., 2022; Jin et al., 2020, ; Limphitakphong et al., 2020; Marzouk & Elshaboury, 2022,; Pan, 2014; Pervez et al., 2021; Röck et al., 2020; Salari et al., 2022; Tao et al., 2018; Teng et al., 2018; Wang et al., 2019)			

Table 2-6 illustrates the EC of various buildings constructed with different materials and methods. The resulting emissions varied, yet consistently, steel demonstrated higher levels of embodied carbon and operational irrespective of the construction method employed.

Table 2-6 Bibliometric study for comparing between types of buildings according to embodied energy and embodied GHG modified after (Tavares et al. 2019)

Reference	Construction type	Location	Distance plant to Building site (km)	Type	Structural material/Alternatives	Embodied energy/ Embodied m² (GJ/m²)	Embodied GHG ($kgCO_2eq/kg$)
Adalberth, 1997	Prefabricated	Sweden	-	Residential	Timber house 1 (1-Floor 130m²)	3.7	-
Achenbach et al. (2017)	Prefabricated	Germany	350	Residential	Timber average single and double Family house (143m²)	-	213
Pons and Wadel (2011)	Prefab and conventional	Catalonia, Spain	100-300	Educational	Non-prefabricated Concrete Timber Steel	- - - -	752 692 526 852
Monahan and Powell (2011)	Panelised Modular and conventional	Norfolk, United Kingdom	213	Residential	Timber frame larch cladding Timber frame brick cladding Conventional masonry	5.7 7.7 8.2	405 535 612
Quale et al. (2012)	Modular and conventional	USA	483	Residential	Timber modular Timber conventional	-	73
Aye et al. (2012)	Prefab and conventional	Australia	-	Residential	Concrete (conventional) Steel(prefab) Timber (prefab)	9.6 14.4 10.5	578 864 630
Mao et al. (2013)	Partially prefab and conventional	Shenzhen, China	45-95	Residential	Concrete semi-prefabrication Concrete conventional	-	336 368
Bonamente et al. (2014)	Prefab	Perugia, Italy	-	Industrial	Steel 1000m² Steel 2500m² Steel 5000m² Steel 10000m² Steel 20000m²	14 12.8 12.2 11.8 11.5	895 821 783 757 738
Cao et al. (2014)	Partially prefab and conventional	Beijing, China	-	Residential	Concrete precast Concrete traditional	-	-
Hong et al. (2016)	Partially prefab and conventional	China	100	Residential	Concrete and steel precast façade Concrete and steel precast form	-	-
Atmaca and Atmaca, 2016	Prefabricated and container	Turkey	100	Residential	Concrete and aluminium sheet prefabricated Concrete and steel sheet container	4.1 3.2	-
Islam et al. (2016)	Container	Melbourne, Australia	100	Residential	Steel container base case	3.24	-
Heravi et al. (2016)	Prefabricated	Tehran, Iran	100	Residential	Concrete frame Steel frame	1.75-3.01 2.36-4.16	-
Vitale et al. (2018)	Prefab and conventional	Campania, Italy	15-900	Residential	Prefab LSF Traditional concrete	9.9 8.5	923

Table 2-6 explored the embodied energy (EE in MJ/kg) and GHG emissions (in kg CO_2 eq/kg) of the Moby prefabricated house, ECs were calculated using the Inventory of Carbon and Energy (ICE) Version 2.0. The ICE is a cradle-to-gate database for construction materials, with EE and CO_2 eq values for most conventional building materials. Garcia et al. (2014) created data for electricity production in Portugal and fuels for transportation from GHG emissions based on the

Intergovernmental Panel on Climate Change (IPCC) method v1.02 which uses a 100-year time horizon (IPCC, 2007).

Table 2-7 presents a more detailed comparison between OSC and traditional construction methods than previous tables, through systematic and bibliometric reviews.

Table 2-7 Bibliometric comparison between OSC and TBS

No	Category	OSC	TBS	Sources
1	**Time**	Less operation and construction time	Consumes more time	(Hong et al. 2018), (Lu et al., 2021), (Hwang et al., 2018)
2	**Cost**	Higher initial and installation costs	Relatively low for short-term	(Hong et al., 2018), (Hu et al. 2019), (Brissi et al., 2021)
3	**Waste**	Waste is reduced throughout the whole life cycle of the project	More waste produced	(Lu et al., 2021), (Hwang et al., 2018), (Jin et al. 2020)
4	**Labour**	Less labour used covers labour shortage	More labor intensive	(Abey and Anand 2019), (Hong et al. 2018),(Brissi et al., 2021)
5	**Inventory**	Requires more space	Fewer storage demands	(Hu et al. 2019; Brissi et al. 2021)
6	**GHG emissions**	Lower	Higher	(Mao et al. 2013), (Pervez et al., 2021)
7	**Operational CO_2 emissions**	Can reduce to 30 Kg/m^2	It depends on many variables, but mostly more than 8.4 %, can reach up to 60%	(Feng et al. 2018), (Teng and Pan, 2019), (Teng et al. 2018), (Han et al. 2022)
8	**Embodied CO_2 emissions**	Can reach over 650Kg/ CO_2/M^2, but usually lower than TBS	Uncontrolled, higher CO_2 emissions	(Hammad et al. 2019), (Teng and Pan 2019), (de Wolf et al. 2017)
9	**Transportation**	Intensive and more demand	Dependable and demanded but less intensive	(Wang et al., 2019), (de Wolf et al. 2017; Teng and Pan 2019)
10	**Sustainability performance**	More sustainable	Less sustainable	(Brissi et al., 2021), (Hu et al. 2019)
11	**Quality**	Better product quality but harder to control	Easier to control	(Hu et al. 2019), (Gan et al. 2018), (Hong et al. 2018), (Brissi et al., 2021), (Teng et al. 2018)
12	**Productivity**	More productive	Relatively less productive	(Hosseini et al., 2018), (Blismas et al., 2010),(Brissi et al., 2021)
13	**Efficiency**	More efficient	Less efficient	(Jin et al. 2020)

Most of the data gathered in Table 2-7 showed a logical advance of OSC over TBS, except in some categories such as cost (category No. 2), which is due to the high reliance on transportation means to deliver the final products from the factory to the construction site, which also affect the embodied carbon emissions and the GHG emissions sometimes. Nevertheless, these results can vary depending on many factors, such as the distance between the factory and the site, the type of OSC, and the type of the project.

Time category No. 1 was put in first deliberately because it is highly related to most categories, especially numbers 3,6,8,10, and 12, which gives a clear lead for OSC and can affect the other categories relatively.

Labour category No. 4 clearly has an advantage for OSC because of the increasing manufacturing process, and it could be even higher when using 3D printing technologies.

In category No 5, there was another advantage of TBS is the inventory process, in which OSC, most of the time, requires more warehouses either on the site or off the site, but to overcome such issues (N. Wang et al., 2019) suggest three supply chain management rules to be applied, which are:

- Adopting buffer evaluation to allow for demand uncertainty
- Adjusting the due date to shift the production closer to the assembly date
- Scheduling production to optimise inventory planning

Inventory problems have apparent reasons to be more complex when adopting OSC due to mass production and prepared components to be assembled and installed, but this can be solved, according to (Salari et al., 2022), by creating a supplier warehouse based on regional conditions to meet the needs of the construction sites and adopting just in time (JIT) technique (N. Wang et al., 2019).

Categories 6,7, and 8 highly interact together; however, as introduced earlier, these categories should be taken separately as they can have different causes and mitigation procedures in the construction project's life cycle.

In Category 7 specifically, (Teng et al., 2018) stated that there is evidence that OSC can even reduce operational carbon emissions by up to 3.2%, which supports the contribution to the knowledge part mentioned in this research.

In category No. 10, sustainability and carbon footprint in terms of the impact of construction on the environment have been extensively studied and are highly linked to CO_2 and GHG emissions caused by the construction industry (Marzouk and Elshaboury, 2022).

Quality category No. 11 is a broad concept. However, recently, there has been more focus on specific quality aspects such as the quality of the product, quality of life and health, quality of the building, and most importantly, the quality of the environment (Brissi et al., 2021). Moreover, prefabrication can improve the quality and efficiency of construction facilities (Teng et al., 2018).

The last two categories, 12 and 13, show that OSC increases the productivity and efficiency of any given construction project, also supported by (Hong et al., 2018d; Hu et al., 2019a; Jeong et al., 2017b; Tao et al., 2018).

2.8.4 On-Site Construction Technologies

This section aims to provide an in-depth introduction and exploration of contemporary construction technologies that have recently been adopted in construction projects generally. Establishing a solid foundation in this area sets the stage for further data collection and analysis in this research endeavours. Where according to (Melenbrink et al., 2020). on-site traditional construction can enhance environmental sustainability and mitigate barriers by adopting autonomous construction robots.

Carbon capturing technologies, additive manufacturing, 3D printing, and machine usage are vital mitigation strategies for all carbon emissions through the project's life cycle assessment.

a. Carbon Capturing

Carbon capturing is a modern technology in which we can use the carbon emissions produced by different stages of construction from different equipment for two purposes: capture and store and capture and use (LETI, 2020). This concept is named carbon capture and storage (CCS). According to several authors, this technology can significantly mitigate the carbon emissions caused by human activities, resulting in maintaining and reducing global warming and climate change (Osman et al., 2021; Rubin et al., 2012; Wei et al., 2022).

(Rubin et al., 2012) describes CCS as capturing CO_2 produced in fossil fuel sources and compressing it to a dense fluid to facilitate transportation and storage. Moreover, (Wilberforce et al., 2021) explain it by separating carbon dioxide CO_2, produced in industrial and transportation sectors and then passing it to a regulated location, which is ideal for storage.

According to (Rubin et al., 2012), this technology has a high price, cost, and energy. However, a recent study by (Wei et al., 2022) states that costs could be reduced significantly when using proper pipelines for transportation.

Cement is an extensively manufactured product that utilises fossil fuels for energy generation (Osman et al., 2021). However, CCS must still be explored and become famous in the construction industry, especially in high-rise projects. However, the expectations are high soon. See Figure 2-8.

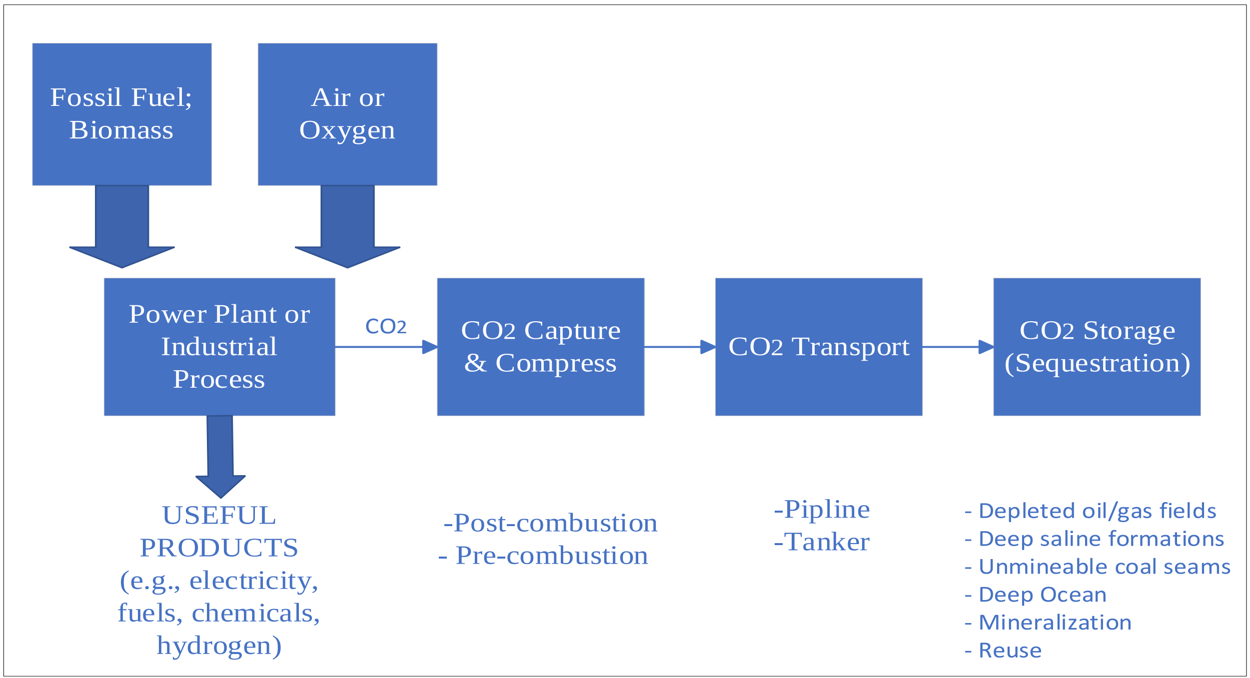


Figure 2-8 CCS Process (Rubin et al., 2012)

Figure 2-8 presented the simple Schematic of a CCS system, which consists of CO_2 capture, transport, and storage. Carbon inputs may include fossil fuels and biomass.

b. Additive Manufacturing and 3D Printing

3D is part of the construction automation process, and many academic efforts are concentrating on on-site additive manufacturing, which, alongside prefabrication, can reduce construction waste and provide a more environmentally friendly construction project (Melenbrink et al., 2020).

Although 3D printing is more suitable for small or medium-sized projects, it improves environmental conditions by reducing carbon emissions (Alhumayani et al., 2020).

3D printing technology can play a role in building high-rise projects to reduce carbon emissions. Nevertheless, it is only feasible to rely partially on it when building large projects, especially high-rise buildings, due to its limited size of machines and equipment. To address this issue, (Al Rashid et al., 2020) explained in their study that integrating additive manufacturing (AM) into large-scale construction presents apparent challenges and risks. As a result, the commercialisation of this technology is advancing slowly, as the literature indicates only a limited number of 3D printing trials for large-scale construction.

c. Site Machinery

On-site equipment and machines can help mitigate embodied carbons, such as the usage of HVO (hydrotreated (or hydrogenated vegetable oil) and hybrid machines; however, their contribution is minimal, which will be investigated through the data collection process. (Figure 2-9).

Figure 2-9 HVO machine (Speedy, 2021)

The author visited the UK Construction Week held in Excel London in May 2023. HP company demonstrated a robotic surveying machine that can improve and enhance surveying work during the construction of projects. This method can support sustainable construction goals by reducing the time and equipment used in conventional surveying methods.

2.9 Summary and Research Gaps

Many impacts are associated with construction projects, some of which are direct, such as greenhouse gases GHG, land depletion, waste, and water pollution. At the same time, indirect impacts are climate change, global warming, ice melting, and others. In comparison, GHG and climate change are the most tangible and noticeable impacts.

Applying the concept of “sustainable construction” is vast and just like pieces of one puzzle, which needs to be broken down as much as possible, and this research so far has explored most of the components involved.

GHG and specific carbon emissions are the most direct impacts of construction projects. Moreover, embodied carbons are now given priority according to energy status. Renewable and energy replacements have already minimised the burden of operational carbons, especially in buildings' use stages.

All proposed practices or methods can reduce the embodied carbons. However, it is almost impossible to adopt them all together simultaneously, logically, because the product will eventually result in higher costs, more time duration, and eventually higher carbon emissions.

Choosing the best practice that reduces embodied carbons needs extensive search and collaboration through data collection and should be based on the following criteria:

- Construction project type
- Construction phase
- Construction location
- Materials availability and selection
- Existing knowledge and expertise

Differentiating between sustainability and optimisation methods can cause a research gap. Both can lead to mitigating environmental impacts. However, both have different methods and consequences, such as that optimisation can affect the design, structure, and quality of components. On the other hand, sustainability usually deals with practices that do not affect a building's safety. Moreover, it ensures quality and productivity.

To demonstrate this research gap, (Zhang et al., 2022) considered optimisation as part of sustainable solutions, especially for high-rise projects. However, the optimisation process should be done for structural elements, excluding finishing components. It shall be done delicately and professionally, which might affect the whole project's duration or produce more waste. More investigation is conducted through the data collection chapter.

Tables 2-5 and 2-7 provided a deep comparison and illustration of OSC with other construction methods, showing that prefabricated elements or off-site practice are more sustainable in terms of environmental impacts, especially embodied carbons, several variables, and uncertainties can be summarised by the following:

- The size and type of project are crucial in determining the applicability and feasibility of OSC
- Transportation has many boundaries, such as the location of the projects, the type of trucks used, the availability of materials, road conditions, and so on. However, most studies state that transportation accounts for less than 10 % of carbon footprints (EC)
- Logistics are crucial when adopting OSC practices, as inventory, for example, can cause severe problems in the project
- OSC adoption requires skilled labour and trained construction managers because accurate work is required on-site

This chapter provided a comprehensive review of OSC's state of the art, emphasising its advantages and benefits regarding environmental sustainability. The research focused on OSC's advantages over traditional construction methods, such as shorter construction time, less waste, and fewer labour requirements. The research also identified OSC's barriers, such as high cost and complicated management, and the current efforts to reduce these barriers, such as carbon capture and storage, additive manufacturing, and on-site machines.

Overall, the systematic review and bibliometric study concluded that OSC is more sustainable than traditional construction methods in terms of time, cost, waste, labour, and environmental sustainability. The research further concluded that OSC is a viable option for the construction industry in terms of reducing carbon emissions and that further research is needed to explore how to reduce the barriers of OSC and increase its sustainability performance. While on-site methods can be very supportive in applying clean energy concepts, they are primarily under development and must be appropriately implemented.

In the forthcoming stages of this research, the robust data collection process will be instrumental in unveiling and comprehensively examining these uncertainties. This will be achieved by posing targeted inquiries to experts in the field and conducting in-depth case studies that delve into the intricacies of the subject matter.

Chapter 3 Large Scale Projects: Modern High-Rise Buildings

3.1 Introduction

This research mainly considered modern high-rise buildings as large-scale projects that should hypothetically demonstrate environmentally sustainable construction, especially when adopting modular and sustainable construction methods.

High-rise building projects have the specifications of repetitive work and high-volume components, most are considered large-scale projects, and most importantly, they consume many resources (Zhu et al., 2022). Moreover, they have great ways to cope with rapid urban population growth (Al-Kodmany, 2022). Most importantly, they are practical solutions for meeting the high-density development within the land becoming more expensive and scarcer (V. J. L. Gan et al., 2018).

According to (Navaratnam, 2022), multi-story buildings can effectively achieve affordable living space and dense settlements. Such settlements can promote efficient and active transport and productivity while limiting urban expansion. Considering these advantages, multi-story apartment blocks are expected to become more relevant as an architectural archetype. This is likely due to the growing need for affordable and sustainable housing solutions in densely populated areas, where space is limited, and the population is increasing. Multi-storey buildings can help to meet these needs while minimising urban sprawl and supporting a more sustainable way of living.

Interestingly, the rates of high-rise tower buildings declined throughout the century, which might have caused many economic, social, political, or environmental setbacks. Figure 3-1 was produced by (R. Sacks and Partouche, 2010) to present the construction rates for the world’s 100 tallest high-rise buildings built between 1929 and 2008, and the trend for tall building projects was toward slower rates. Nevertheless, a recent study by BBC showed increased demand for high-rise towers, especially skyscrapers over 200 meters tall. The study graphic is shown in Figure 3-1.

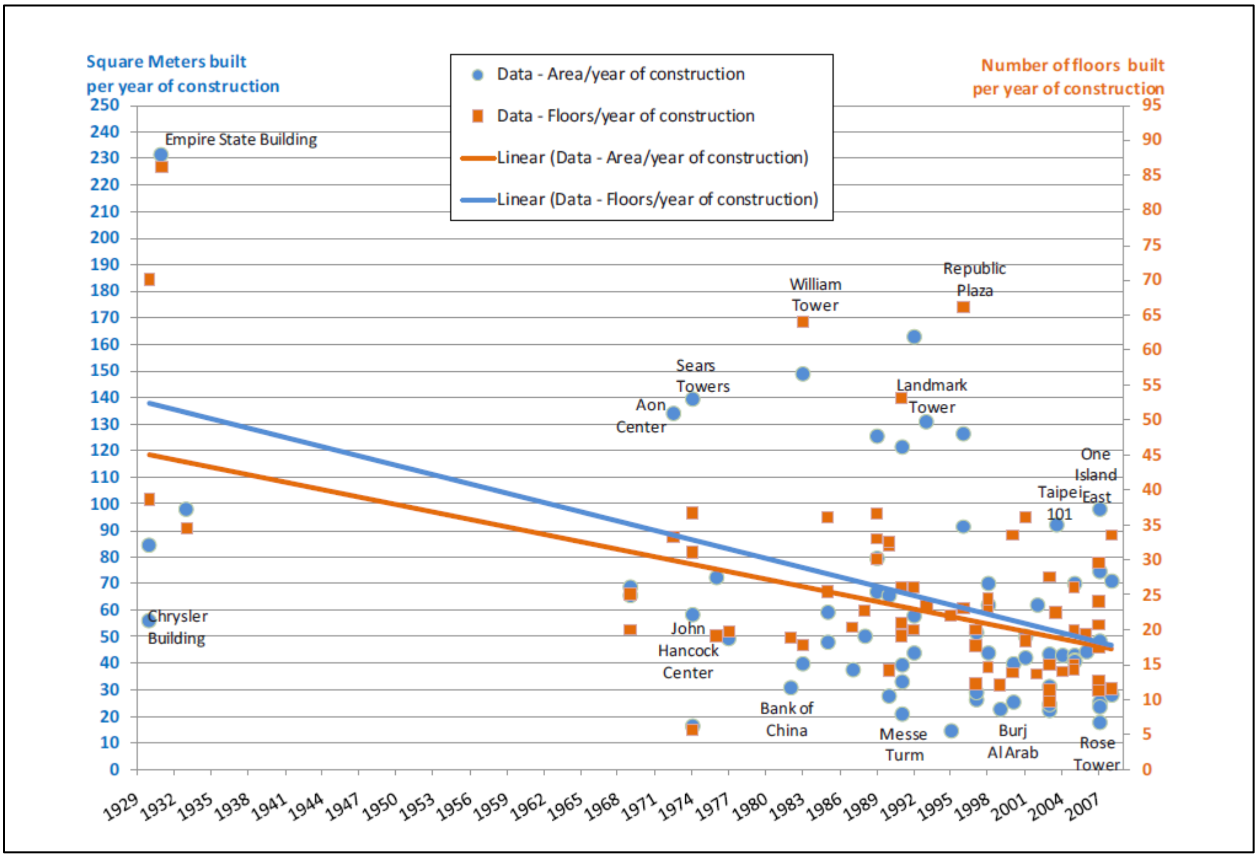


Figure 3-1 Construction rates for the world's 100 tallest buildings built between 1929 and 2008 (R Sacks and Partouche, 2010)

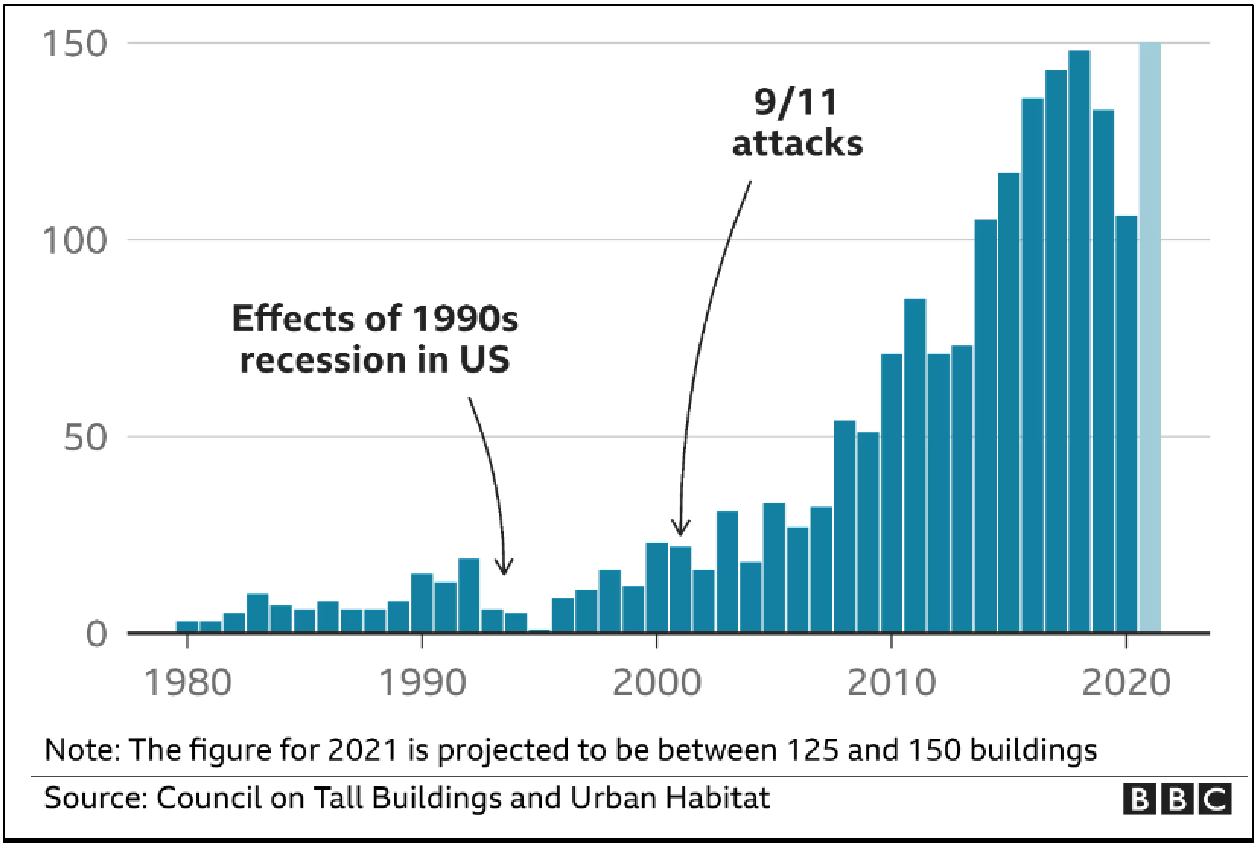


Figure 3-2 Tall buildings progress (BBC, 2021)

Figure 3-2 presents the status of high-rise buildings, especially skyscrapers, showing two main incidents. The first was the ’90s recession in the US, which slowed the pace of the number of projects. Second, the 9/11 attacks did not seem to have affected the pace of skyscraper projects.

Depending on the final findings, this research can examine the status of the construction of high-rise buildings, especially by producing them as an urgent environmentally sustainable solution for the construction industry and urbanisation.

Despite that, most consider a building as a high-rise when it is over 27 stories (Gan et al., 2017), and argue that the high-rise building threshold can be determined by a 12 to 40-story (35-100m) type of building.

3.2 Materials Contribution and Role

In this section, the research explores and examines the most bulky and fundamental materials used in construction projects, especially in high-rise buildings. These materials are concrete, steel, and wood, which will be the primary reference for carbon emissions scaling and evaluation research.

(Gan et al., 2017) claim that structural steel, steel rebar, and ready-mixed concrete contribute over 90 % of embodied carbon emissions in buildings. Moreover, (Bei et al., 2021) stated that material production (cradle-to-site) generates 92-93% of the total embodied carbon emissions, but the author excluded transportation and construction works. Even the embodied carbon emissions of prefabricated and cast-in-place concrete are similar during the prefabrication and cast-in-place stages (Hao et al., 2020).

To explore the distinguished impacts among those materials and others, such as brick, glass, ceramic, and cementitious blocks (Zhang et al., 2023) developed a comparison study presented in Figure 3-3.

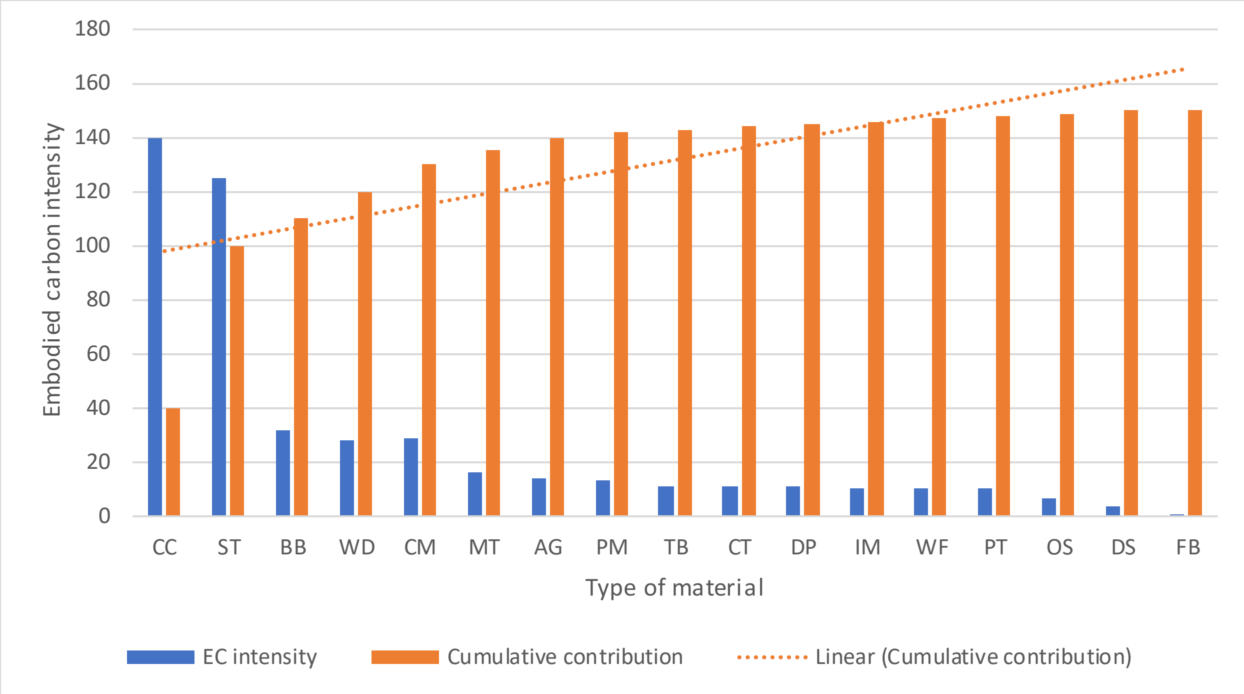


Figure 3-3 Materials contribution in embodied carbons (Zhang et al., 2023)

Figure 3-3 uses a 1 m^2 floor area as the functional unit. Where the symbols stand for CC: concrete; ST: steel; BB: brick and block; WD: window and door; CM: cement; MT: mortar; AG: aggregate; PM: prefabricated member; TB: timber; CT: ceramic tile; DP: decorative plate; IM: insulation material; WF: waterproof material; PT: painting; DS: decorative stone; FB: floorboard; OS: others. This study table explains the most preferable selected materials that will be evaluated in the data collection part of this research.

On a global scale, the building sector consumes 60% of raw materials by weight. This sector accounts for 6% of worldwide energy consumption and contributes to 11% of associated carbon dioxide emissions. Throughout construction, operation, and demolition, materials like concrete, steel, and timber are generated and discarded, exacerbating material depletion, and adding strain to landfills (Minunno et al., 2021).

Construction materials are dominant contributors to embodied carbon emissions. Reducing their use of low-carbon or non-carbonate materials, such as wooden structures, is possible, especially considering availability factors, transportation distances, construction time, and structural design (Teng and Pan, 2019). (Kumar et al., 2021) claim that sustainable materials are the most effective way to achieve environmental sustainability. However, this compromises the materials selection approach and the practice methods, illustrated in section 2.8.3 Chapter 2.

According to (Tumminia et al., 2018), the main contributor to GHG emissions reduction is the ECs of building materials, with a percentage that reaches 86.5%. The following sections will consider the primary bulk materials used in the construction industry. Moreover, sustainable building materials and construction methods have recently been highlighted to reduce environmental and human health impacts (Jeong et al., 2019).

However, certain materials such as fibre and polymers were deliberately excluded from the scope of this research. The rationale behind this decision is that these materials are not typically utilised as structural components nor classified as bulk materials in the construction of large-scale projects. This study focuses primarily on materials that significantly impact the structural integrity and overall performance of construction projects in environmental terms.

Furthermore, it is essential to note that any evaluation or calculation conducted in this research aims to gain a comprehensive understanding of the environmental implications associated with construction projects. The intention is not to provide precise numerical values but to offer an environmental assessment encompassing various factors and considerations.

By adopting this approach, the research aims to contribute to a broader understanding of the environmental aspects of construction, providing valuable insights and guidance for sustainable practices without solely relying on exact measurements or specific numerical data.

3.3 Cement and Concrete

Concrete is one of the most popular and used construction materials (Nazari and Sanjayan, 2017), which is the primary material used in main building components such as the structural frames, retaining walls, , foundations, staircases etc. Furthermore, it is considered a vital player in achieving environmental sustainability and a critical element for the 2050 net zero map (GCCA, 2021).

The concrete industry should adopt innovation systems for long-term sustainability (Blismas et al., 2010). Such systems are OSC and 3D printing technologies. Construction companies were developing OSC to improve construction quality and productivity and transfer conventional on-site pollution to a controlled off-site factory to improve the environmental sustainability of projects (Hu et al., 2019). Moreover, cement production is "energy intensive" and accounts for a significant impact of CO_2 (Bos et al., 2016). Furthermore, this research aims to evaluate and link these technologies to environmental sustainability.

Reinforced concrete was developed in the 19th Century upon the need for economic and fireproof building materials (Khajavi et al., 2021). On the other hand, the advantages of contemporary prefabricated concrete are, as clarified by (Abdulhameed and Said, 2019):

- Reduction in construction costs
- Improving quality
- Saving resources
- Waste eliminations

Achieving sustainability in concrete materials still needs to be clarified. A case study for a factory project in China showed increased CO_2 emissions when using OSC in precast concrete column production (Jeong et al., 2017). Another residential apartment project study showed a decreased concrete carbon footprint when using the LCA method (Jia Wen et al., 2015).

Nevertheless, only some construction industry sectors are willing to adopt prefabricated, off-site concrete buildings, such as the housing sector. Also, it is limited to specific regions like the USA, the UK, and some parts of Europe (Blismas et al., 2010). Furthermore, another justification for focusing on concrete materials is that other elements such as doors, windows, wood jobs, and kitchens cost the same in off- and on-site construction (Khajavi et al., 2021), requiring much less consumption than concrete.

The OSC of concrete elements such as walls, slabs, and floors are presented by the new digital construction of 3D printing, which can eliminate formwork, for example, by using additive manufacturing technique by creating the parts of the structure using a layer-by-layer process to add materials (Khajavi et al., 2021). According to (Albus and Hollmann-Schröter, 2023), prefabrication of concrete components within a factory setting holds significant promise for enhanced cost-effectiveness; precast building systems encounter limitations in design flexibility due to their constrained variability. However, any elimination of materials or resources will eventually serve environmental sustainability.

In conclusion, concrete is the most widely used construction material, often paired with steel in building construction. Developing reinforced concrete and modern prefabricated concrete has brought about cost reduction, quality improvement, resource-saving, and waste elimination benefits. However, achieving environmentally sustainable concrete remains a challenge, and using OSC and 3D printing technologies is recommended to improve the concrete industry's sustainability.

3.4 Steel

Steel is a cornerstone material within the construction sector, playing a pivotal role in fuelling the exponential growth of modern construction endeavours over the past century. While steel holds undeniable significance and influence, concrete has historically boasted superior efficiency and environmental benefits compared to steel (Xing et al., 2008).

Despite being widely used in construction, steel exhibits significant variation in embodied energy and carbon, spanning from 6.36 to 85.5 MJ/kg (with the latter value often viewed as an outlier). The carbon emissions range from 0.34 to 4.55 kg CO_2 eq/kg. This variability may be attributed to the geographical context of the studies. Notably, studies in Australia and Europe recorded the highest environmental impact for structural steel (Institution of Structural Engineers (Great Britain), 2020; Minunno et al., 2021).

Steel can be produced nowadays through blast furnaces- basic oxygen furnaces (BF-BOF) and electric arc furnaces (EAF). According to (Gan et al., 2017), steel should be produced using electric arc furnaces, which reduced the EC of high-rise building projects by over 60 %. This steel production method was supported by (Vitale et al., 2018).

Steel materials overlap with concrete in the production of reinforced concrete, as produced in the previous section. Nevertheless, steel shall be considered separately in the carbon accounting process due to its different manufacturing and transportation processes.

In the cradle-to-gate stage, steel rebars are entirely separated from concrete. In contrast, in the cradle-to-site stage (construction works), steel is combined with concrete steel in the final structural product. So, it is essential to differentiate stages when calculating carbon emissions, especially embodied ones.

3.5 Wood

Despite being a tremendous environmental material, wooded buildings are not favourable to high-rise projects due to load-bearing problems as they could not be designed as the main structure on high-rise buildings or even multi-floor buildings; however, (Li et al., 2019) believe that timber high-rise buildings could be constructed up to 43 floors.

The ambitions to build taller timber projects have increased, such as the buildings of the (73m) HAUT in Amsterdam and (84m) HoHo in Vienna (RIBA, 2012). However, according to their total size, they still need to be considered large-scale projects.

According to (Li et al., 2019), timber buildings help reduce embodied carbon emissions. The latest (Ciria, 2021) – (Construction Industry Research and Information Association) report shows that prefabricated timber soffit units are 27 times more carbon efficient than steel comparators.

(Tumminia et al., 2018) argue that timber buildings significantly contribute to the environment, emphasised by (Dudley, 2023) and (Minunno et al., 2021), who insist that wood is the best sustainable material among steel and concrete. This research could agree, but it can also define and give a reasonable claim that wood is not the best material for constructing high-rise buildings, especially when compared to steel frames or bulky structural materials. Moreover, fire and safety issues are the primary concerns when using general buildings, especially residential ones, because they include longer occupation durations.

A study conducted by (Achenbach et al., 2018) specifically used timber in prefabricated houses; the paper provided practical recommendations for reducing the environmental impact of prefabricated timber houses in the construction industry. It suggests choosing a nearby house manufacturer to minimise transportation impacts and incorporating prefabrication processes within the product stage of EN 15804. These suggestions aim to help reduce the environmental footprint of prefabricated timber houses. Nevertheless, this approach is generable and applicable to all materials, making no exceptions for timber buildings.

3.6 Transportation

Transportation is crucial in sustainable construction projects, as it can significantly impact the project's carbon footprint. One way to reduce the carbon footprint of transportation in sustainable construction projects is to use low-carbon materials, such as through the following practices:

1. Local Sourcing: Choosing materials sourced locally can significantly reduce transportation distances, thereby minimising the carbon emissions associated with transportation
2. Lightweight Materials: Opting for lightweight materials reduces the energy required for transportation. These materials are often less dense and require less fuel to transport, consequently lowering carbon emissions

Transportation is an integral part of making high-rise projects as they consume large amounts of materials requiring higher transporting requirements.

Several studies have looked at the environmental impact of transporting low-carbon materials. For example, a recent study published in the International Journal of Sustainable Transportation examined the carbon footprint of transporting low-carbon concrete in the United States. The study found that transporting low-carbon concrete over long distances can increase the carbon footprint, but local low-carbon concrete can significantly reduce it (Sustainable Transportation,2024).

Another study by (X. Xu et al., 2022) examined the carbon footprint of transporting bamboo as a low-carbon alternative to conventional construction materials in China. The study found that using bamboo as a building material can reduce the carbon footprint, but transporting the bamboo over long distances can increase it.

Interestingly, some studies, such as Elshaboury and Marzouk (2021), have emphasised waste transportation in the construction sector by proposing a model for identifying the optimum fleet required for waste transportation. Waste management is a critical aspect of sustainable construction, and transportation plays a crucial role. The proposed model could optimise waste transportation and reduce the environmental impact of construction waste.

A more holistic study by (Tavares et al., 2019) explored the distance from the plant to the construction site, which plays a crucial role in determining the transport-related impacts. Most studies, such as, (Aye et al., 2012; Bonamente et al., 2014; Cao et al., 2015) reported relatively short distances ranging from a few kilometres to a few hundred kilometres.

However, there are exceptions to this trend. (Monahan and Powell, 2011) reported distances of around 200 km, while (Quale et al., 2012) reported distances of almost 500 km. (Vitale et al., 2018) Reported distances ranging from 15 km to 900 km (Achenbach et al., 2018) reported 350 km, and (Pons and Wadel, 2011) reported distances between 100 km to 300 km.

(Pons and Wadel, 2011)specifically discussed the impact of modular construction on transportation. Due to the high volume of components being transported, they highlighted that modular buildings could have significant transport-related impacts. They also mentioned two exceptional cases: 900 km for a modular steel structure and 1600 km for a timber structure. Pons and Wadel concluded that steel had the highest transport-related impacts due to the plant's remote location and the components' modularity.

It is important to note that transportation impacts cannot be neglected, as they can contribute up to 20% of the total embodied impacts (Achenbach et al., 2018), (Elkind, 2022). The type of modular, particularly for prefabrication construction, further influences transport-related impacts. Factors such as module size and weight, transport distance, mode of transportation, and chosen routes all contribute to the overall impact of transportation in construction projects (Kamali and Hewage, 2016).

Overall, these studies highlight the importance of transportation in sustainable construction practices. Especially when considering large-scale projects. Waste transportation and low-carbon materials are critical factors in reducing the environmental impact of construction activities, and careful consideration of transportation logistics can help optimise these processes.

Using more electric vehicles can help reduce carbon emissions in the transportation sector within the construction industry. According to the US EPA (EPA, 2023), electric vehicles typically have a smaller carbon footprint than gasoline cars, even when accounting for the electricity used for charging. A study by the Natural Resources Defence Council (NRDC) also found that electric vehicles can dramatically reduce carbon pollution from transportation and improve air quality. Although producing electricity to power electric vehicles can generate emissions, those emissions are far lower than the pollution emitted by conventional vehicles. They could be even lower as the electric power sector cleans up over the next few decades (Luke Tonachel, 2015).

However, it is essential to note that the production process for EVs can be more taxing on the environment than that of internal combustion engine (ICE) vehicles (Samsara, 2023). The production of EV batteries creates upstream emissions, and the electricity used to charge EVs may create carbon pollution, depending on how local power is generated. Therefore, while using more electric vehicles can help reduce carbon emissions in the transportation sector within the construction industry, it is crucial to consider sustainable electricity generation options, such as renewable resources like wind or solar power, to reduce carbon emissions further.

3.7 Embodied Carbon Factors

In their study, (Gauch et al., 2023) explored the sensitivity of a wide range of design and operation parameters regarding embodied carbon, construction cost, and heating and cooling loads for multi-story buildings.

The study found that increasing building compactness, using steel or timber instead of concrete frames, lowering the window-to-wall ratio, choosing the most suitable glazing, and employing mechanical ventilation with heat recovery are the most important measures to decrease embodied emissions and operational energy. The study estimated that 28-44% of yearly heating and cooling energy and 6 Gt cumulative embodied CO_2 e until 2050 could be saved in multi-story buildings without employing new design approaches.

However, (Zhang et al., 2022) revealed a significant potential for EC reduction in concrete modules through structural design optimisation, providing a new direction for achieving low-carbon modular buildings. However, this research explores the most realistic and efficient approach to reducing embodied carbons, especially for high-rise buildings, whether OSC, materials, optimisation, design, or anything else.

While it is hard to obtain accurate measurements for carbon emissions, especially within large-scale projects, it can still be measured approximately and compared to determine each project's (carbon status).

The Embodied Carbon (EC) can be calculated by using the equation:

$$EC = EC\ quantity \times Carbon\ factor.$$

Equation 4

Table 3-1 provides carbon factors for each main element used in construction projects, whereas Table 3-2 adds the transport distance factor. Both tables are introduction indicators to the bibliometric study, which will take place in Chapter 5.

A detailed and sophisticated table produced by the (BSRIA) Building Service Research and Information Association has studied 1800 records of EC and EE for 34 classes of materials used in construction (Hammond et al., 2011), which is added in **Appendix 5.**

Table 3-1 Carbon factors for primary materials in the construction stage modified after (Orr John 2020)

Material	Type	Specification/details	A1-A3 ECF ($kgCO_2/kg$)	Data source
Concrete	in situ; piling, substructure, superstructure	Unreinforced, C30/37, UK average ready-mixed concrete EPD(1) (35% cement replacement)	0.103	MPA, 2018(2)
		Unreinforced, C32/40, 25% GGBS cement replacement(3]	0.120	ICE V3(4)
		Unreinforced, C32/40, 50% GGBS cement replacement	0.069	ICEVS
		Unreinforced, C32/40, 75% GGBS cement replacement	0.063	ICEVS
		Unreinforced, C40/50, 25% GGBS cement replacement	0.138	ICEVS
		Unreinforced, C40/50, 50% GGBS cement replacement	0.102	ICEVS
		Unreinforced, C40/50,75% GGBS cement replacement	0.072	ICE V3
	Precast	Reinforced 150 mm prestressed hollow core slab: British Precast Concrete Federation average EPD	0.178	ICE V3
Steel	Reinforcement bars	Federation average EPD	502kgCO₂/m*	BPCE,20175)
		UK: BAC EPD	0.684	BRC, 2019(6)
		Worldwide: Worldstol LCI study data, 2018, world average	1.99	ICE V3
	PT strands	Assume the same as reinforcement bars		
		UK open sections: British Steel EPD	245	BS, 202017)
	Structural sections	Europe (excl. UK): Bauforumstah|[8] average EPD	1.13	BouformstaN, 2018
		Worldwide: Worldsteel LCI study data, 2018, workd average	1.55	ICE V3
	Galvanized profiled sheet (for decking)	UK: TATA Comflor EPD	2.74	TATA, 2018
Blockwork	Precast concrete blocks	Lightweight blocks	0.28	ICE V3
Brick	Single engineering clay brick	Generick, UK		

Table 3-2 Embodied carbon factors for construction materials modified after (Gan et al. 2018)

Material type		**Usage**	**Embodied carbon**	**Unit**	**Source location (transport mode)**	**Distance (km)**
Rebar C30 Concrete		Steel reinforcement Concrete for floor slab	2.25[a]	kg CO_2e/kg	Guangdong, Mainland China (Ship)	150
	100% OPC		295[a]	kg CO_2-e/m^2	Hong Kong (HGV)	50
	75% OPC + 25% FA		227 *	kg CO_2,-e/m	Hong Kong (HGV)	50
	65% OPC + 35% FA		200 *	kg CO_2 e/m^2	Hong Kong (HGV)	50
	65% OPC + 35% GGBS		208 *	kg CO_2-e/m°	Hong Kong (HCV)	50
	25% OPC + 75% GGBS		108 *	kg CO_2-e/m^2	Hong Kong (HGV)	50
C40 Concrete	100% OPC	Concrete for shear walls	335[a]	kg CO_2-e/m^2	Hong Kong (HGV)	50
	75% OPC + 25% FA		258 *	kg CO_2-e/m^2	Hong Kong (HCV)	50
	65% OPC + 35% FA		227[a]	kg CO_2-e/m^2	Hong Kong (HCV)	50
	65% OPC + 35% GGBS		235 *	kg CO_2,-e/m^2	Hong Kong (HGV)	50
	25% OPC + 75% GGBS		120*	kg CO_2e/kg	Hong Kong (HCV)	50
Concrete block		Partition walls	0,25 °	kg CO_2-e/kg	Guangdong, Mainland China (Ship)	150
Clear glass		Windows	1.15 €	kg CO_2-e/kg	Guangdong, Mainland China (HGV)	200
		Clear glass + tinted/reflective coating	1.24 °	kg CO_2-e/kg	Guangdong, Mainland China (HCV)	200
Mineral wool		Thermal insulation materials	1.02 °	kg CO_2-e/kg	Guangdong, Mainland China (HCV)	200
Polystyrene			3.78	kg CO_2-e/kg	Guangdong, Mainland China (HGV)	200
Wood		Doors	0,02	kg CO_2-e/kg	Guangdong, Mainland China (Ship)	15

Embodied carbon emissions can also be calculated simply by combining direct and indirect embodied carbon emissions in the following (Zhu et al., 2022):

$$DC = DEC \text{ (direct embodied carbon)} + IEC \text{ (Indirect embodied carbon)}$$

Equation 5

More detailed equations are in **Appendix 6**.

3.8 Summary and Research Gaps

It still needs to be made clear how much high-rise projects can rely entirely on prefabrication components due to the complexity of the designed buildings. Knowing that steel structure frames and steel floor slabs can be wholly delivered using OSC to the construction site, it is undetermined how much concrete buildings can depend on OSC when constructing a high number of floors, especially when considering the logistics of the project, especially transportation, and other quality problems associated with it such as the quality of joints and columns. Alternatively, wood-based projects are excluded, as introduced before.

Materials' contribution and role are vital in determining and achieving sustainability; therefore, there was a consensus on each material contribution to carbon emissions, precisely embodied ones. Moreover, the materials amount of ECs, according to (Tumminia et al., 2018), indicated that steel structures are responsible for the highest CO_2 emissions in the material production stage (about 700 kg CO_2 eq/m^2), while timber structures cause the lowest emissions (about 300 kg CO_2 eq/m^2). For the use stage, the steel technology and the non-prefabricated building had the highest emissions values (about 600 kg CO_2 eq/m^2) (Alotaibi et al., 2022).

According to (Alotaibi et al., 2022), electricity should be included as part of achieving sustainable high-rise buildings, as electricity is responsible for the highest rates of carbon emissions. The role of electricity in the embodied carbon emissions of high-rise buildings is significant. However, we can significantly reduce the carbon emissions associated with high-rise building operations by sourcing electricity from renewable sources, purchasing renewable energy credits, and designing energy-efficient buildings.

It has been found that the steel structure frames, and steel floor slabs designed can be delivered entirely to the construction site using OSC. However, the project's logistics, especially transportation, and other associated quality problems can make relying entirely on prefabrication components difficult. Furthermore, it is suggested that materials selection and practice methods are vital for achieving environmental sustainability, as well as data collection methods that will be used to clarify and answer issues.

The data collection process shall be more capable of investigating and clarifying such issues in the multi-data collection method adopted in this research.

Chapter 4 Research Methodology

4.1 Introduction

"*Research methods are the instruments and/or tools that researchers employ whilst they administer any form of inquiry or investigation*" (Almalki, 2016).

This research adopted mixed methods of data collection, in which combined quantitative and qualitative methodologies are utilised.

The quantitative method depends on testing an existing theory and being more objectivist and oriented to social sciences in epistemological orientation (Bryman, 2016); on the other hand, (Davies, 2014) stated that the qualitative method is more directed to activities with direct observations.

The research can use a mixed method with the following strategies:

1. Quantitative methods can help the researcher examine and analyse existing and previous analyses to make a solid foundation for relevant literature review, which can lead to achieving the objectives and aims and even a new finding for the research

Quantitative data can answer the (What) and (How many) questions of the research.

2. The qualitative method can build upon the data obtained by quantitative methods, examine it, and create new data and findings. However, this time, it was based on direct observations and case studies through qualitative tools, specifically interviews with professionals and case studies for direct construction projects

The qualitative data can answer the (Why and How) questions of the research.

3. A convergent strategy will be used to analyse collected data after analysing all possible data. In this strategy, qualitative data will be collected simultaneously with the quantitative data and provide a how and why answer for the quantitative questions

Figure 4-1 shows the sequence of the selected research approaches in this thesis.

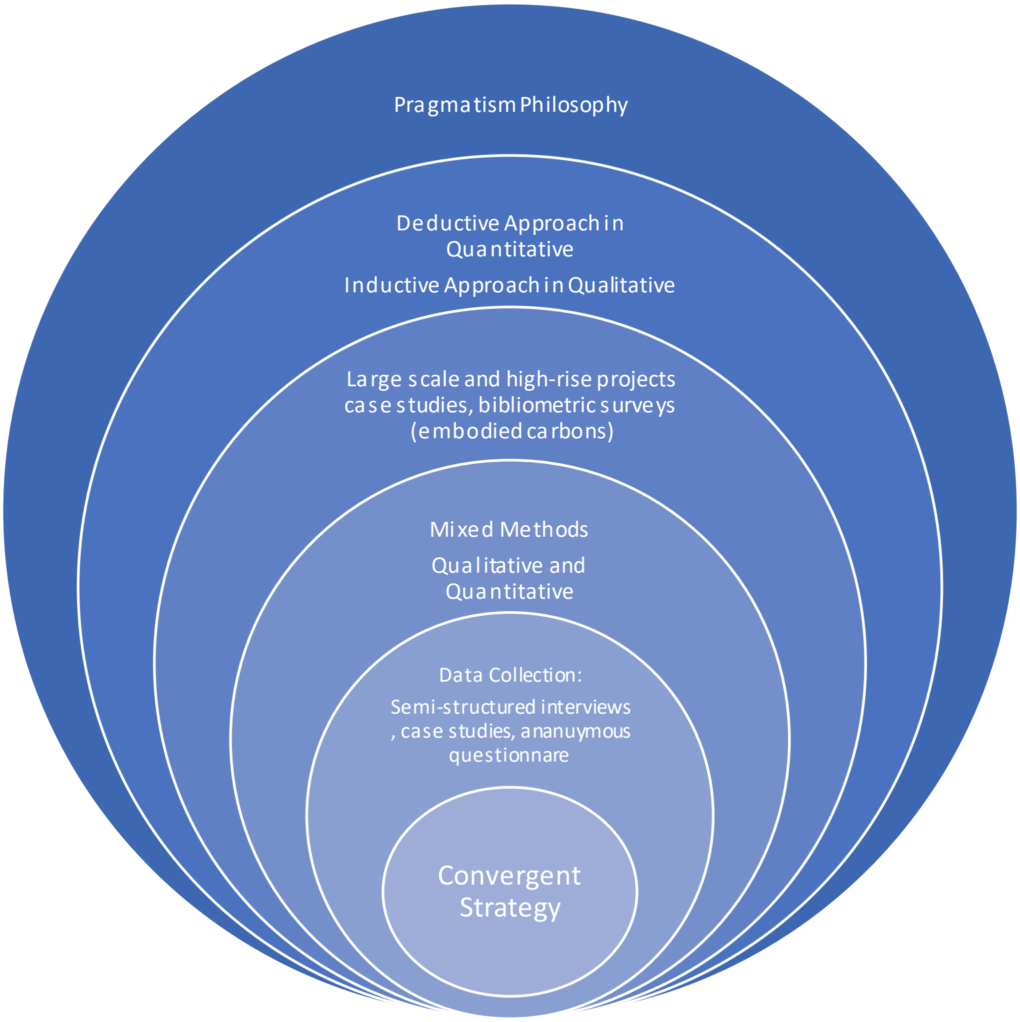


Figure 4-1 Research map using Saunders shape

4.2 Research Design

Figure 4-2 introduces the research design, in which a convergent approach was selected to interpret and analyse the collected data.

Other research approaches, such as exploratory sequential design, rely first on qualitative data and build on it. The quantitative data is designed and based on qualitative data. The other approach is explanatory sequential design, which is the opposite of the exploratory sequential approach. It relies on producing quantitative data and then building a qualitative method to explain the quantitative data obtained (Creswell and Clark, 2018).

The convergent approach was chosen because this research believes that quantitative and qualitative data are essential separately; moreover, it is assumed that convergent research approaches will have less bias. See Figure 4-2.

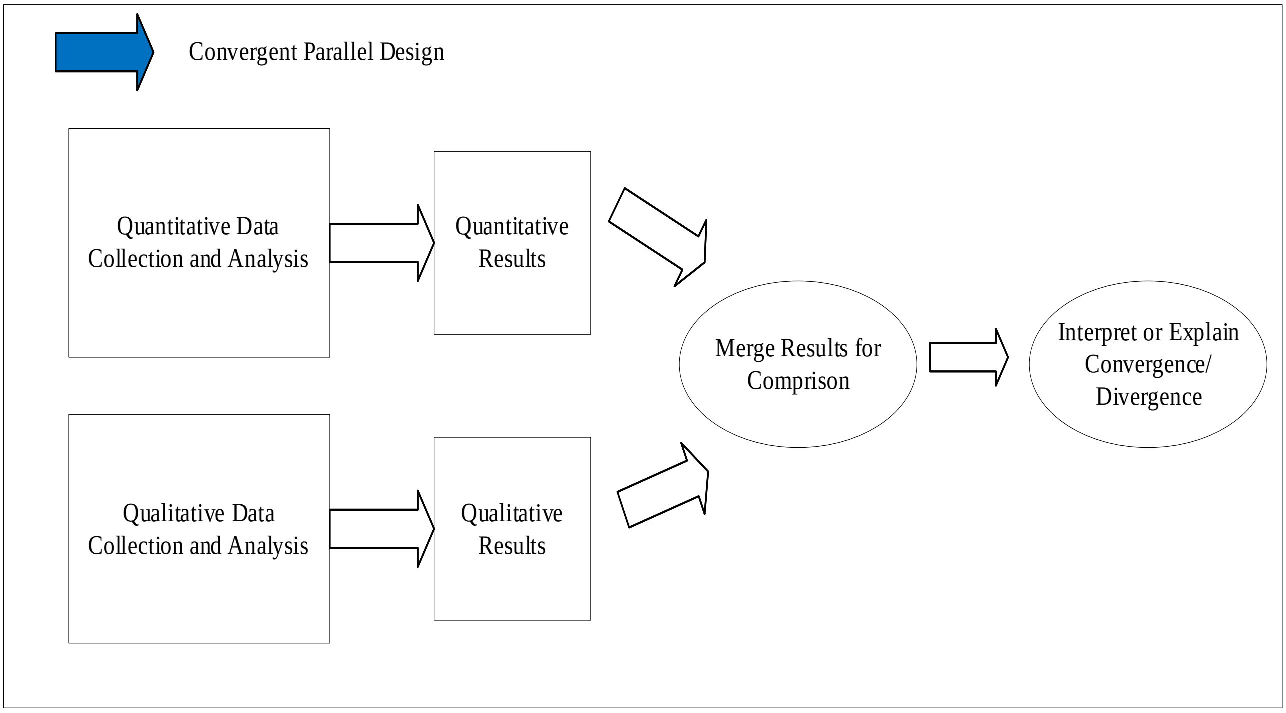


Figure 4-2 Research design methods (Creswell, 2013)

4.3 Pragmatic approach

As introduced in the thesis strategy section, the pragmatic approach is believed to deliver the best data obtained and analysis. Where according to (Taguchi, 2018), using pragmatic approach, mixed methods research is a promising approach that integrates quantitative and qualitative data analyses within a single study. This combination allows for the identification of patterns of change over time while simultaneously uncovering individual and contextual factors.

“Qualitative *research should be aligned with quantitative research standards and moved the arbitrary division between theory and research*” (Coşkun, 2020).

In this research, the quantitative data collection was primarily conducted through anonymous questionnaires. Despite the use of a structured and systematic approach, there was clear evidence of subjectivity in the responses. This subjectivity is seen as beneficial because the closed-ended questions and diverse sample of respondents provided insightful feedback that addressed the research questions effectively. However, as discussed in the data collection chapter, such subjectivity can also introduce biases. For instance, the sequence of questions and the pre-defined answer options influenced how many respondents answered, potentially distorting the data.

To address these potential biases and gaps in the quantitative data, the research incorporated qualitative methods. Specifically, two qualitative tools were employed: case studies and interviews. These methods allowed for a deeper exploration of the subject matter, providing a more nuanced understanding that complemented the quantitative findings.

The semi-structured interviews significantly enhanced the data collection process, especially by clarifying and expanding on areas that were ambiguous or insufficiently addressed in the anonymous quantitative questionnaire. For example, questions 11 and 12, which dealt with the comparison between embodied and operational carbon emissions in construction, highlighted a gap in respondents' understanding. Despite providing definitions, many participants struggled to differentiate between these two types of carbon emissions. During the interviews, the researcher was able to address this gap directly. When it became apparent that an interviewee did not fully grasp the distinction between embodied and operational carbon, the researcher could explain these concepts in more detail, ensuring a clearer understanding and more accurate responses.

4.4 Deductive and Inductive Approaches

As represented through Saunders research map, the quantitative deductive and qualitative inductive approach were used in the process of data collection and analysis process.

According to (Soiferman, L.K., 2010), In a deductive approach, researchers start from a broad theory and then narrow it down to specific hypotheses and data collection, ultimately aiming to either support or refute the initial theory. This process is often described as working from the "top down." Conversely, inductive research works from the "bottom up." Researchers begin with detailed observations or participants' views, then identify patterns and build broader themes, eventually generating a theory that interconnects these themes.

To demonstrate the application of deductive reasoning in this research, the initial hypothesis was that large-scale projects, especially high-rise buildings, could be developed in an environmentally sustainable manner. If these projects were not inherently sustainable, the research aimed to identify strategies to enhance their sustainability. This hypothesis was tested through a comprehensive review of recent literature, followed by bibliometric and systematic analyses, and further validated using data collected from survey questionnaires. This multi-step approach allowed for a robust examination of the potential for high-rise buildings to achieve or improve upon sustainable construction practices.

The results showed some arguments especially wither to consider high-rise projects can be sustainable and gave priority to other types of projects such as pavement and infrastructure construction projects.

In this research, the qualitative inductive approach involved using case studies and semi-structured interviews to generate observations that led to new insights and assumptions. The case studies of selected projects not only provided quantitative data on environmental impacts and carbon emissions, but also uncovered new construction practices not previously addressed in the literature review.

The semi-structured interviews highlighted that all types of construction projects have the potential to be sustainable. However, this research specifically focused on high-rise buildings for several reasons, as detailed in the first chapter. High-rise projects are particularly suitable for measuring environmental impacts due to their distinct characteristics and the challenges they present in design, planning, and construction (Blackburne et al., 2022; Cho and Lee, 2011; Kumar et al., 2021). Additionally, they offer more concrete and observable data compared to infrastructure projects, making them more accessible for analysis and practical evaluation of sustainability practices. This focus allowed the research to delve deeply into the specifics of making high-rise buildings more sustainable and to explore innovative construction practices within this context.

To summarise the previous methodology, Table 4-1 was established.

Table 4-1 Deductive and inductive approaches

Approach	Deductive	Inductive
Definition	“Top-down”	“Bottom-up”
Description	Deductive research begins with a broad theoretical framework and then narrows down to testable hypotheses and specific data collection. This method often starts with a general theory or model and seeks to confirm or refute this theory through empirical observation and data analysis	Inductive research starts with specific observations and data to build broader generalisations and theories. It is often exploratory in nature, beginning with detailed observations that lead to the development of patterns, themes, and eventually a theoretical framework
Data Methodology	Primarily Quantitative	Primarily Qualitative
Description	Deductive research relies heavily on quantitative data methods such as statistical analyses, numerical data, and pre-defined metrics. This approach often uses structured tools like surveys or experiments to test hypotheses	Inductive research relies on qualitative data methods like open-ended interviews, participant observations, and detailed case studies. This approach values context, depth, and the perspectives of participants, focusing on understanding complex phenomena from the ground up
Data used	Anonymous questionnaire, bibliometric studies, systematic reviews	Case studies, semi-structured interviews
Description	Deductive research often employs structured and standardised instruments like anonymous questionnaires to collect data that can be easily quantified and analysed statistically. Bibliometric studies and systematic reviews are also used to evaluate and synthesize existing research based on specific criteria	Inductive research utilises in-depth data collection methods such as case studies and semi-structured interviews. These methods allow for a deeper exploration of participant experiences and views, providing rich qualitative data that help in building new theories
Location	Chapter 5, Section 2	Chapter 5, Section 3
Advantages	Enriches consistency and allows for achieving specific aims	Enhances exploration and adaptability in research
Details	The deductive approach's structured methodology ensures a consistent and replicable process, making it easier to test specific hypotheses and achieve targeted research goals. Its systematic nature can provide clear, definitive answers that align closely with the research objectives	he inductive approach's flexibility and openness make it particularly useful for exploring new phenomena and developing new theories. It allows researchers to adapt to emerging patterns and insights, which can lead to more innovative and nuanced understandings
Disadvantages	Constrained by predefined research objectives	Risk of losing focus on the research aim
Details	The deductive approach can be limiting because it is bound by the initial theory and hypotheses. Researchers might overlook unexpected findings that don't fit their framework, and their investigation may be less responsive to emerging insights	The inductive approach, while open and exploratory, can sometimes lack direction and focus. Researchers might become overwhelmed by the data's complexity, leading to challenges in forming a coherent and focused theory. This approach can also be more time-consuming and resource-intensive

4.5 Case Study Framework

Table 4-2 outlines the overarching and detailed framework utilised during the data collection process for the case studies, with detailed specifics provided in Chapter 5. The research aims to maintain consistency across the six selected case studies; however, variations in the framework may occur depending on factors such as project design, location, and data availability. The specific framework is illustrated in Figures 5-37 and 5-38 in Chapter 5.

Table 4-2 Case Study Framework

Section	Content
Introduction	Case studies offer deep, contextual analysis, ideal for exploring complex dynamics in large-scale construction projects. This research utilises a mixed-methods approach, combining both quantitative and qualitative data collection and analysis to comprehensively understand environmental sustainability in high-rise construction
Research Methodology	**Mixed Methods Approach**: Utilises both quantitative (objective, numerical analysis) and qualitative (contextual, observational analysis) methodologies. **Quantitative Methods**: Test existing theories and analyse numerical data, focusing on systematic measurement. **Qualitative Methods**: Emphasise direct observation and exploration of participants' experiences
Data Collection Strategies	**Quantitative Data**: Collected via anonymous questionnaires, bibliometric studies, and systematic reviews. These data answer "What" and "How many" questions, providing statistical and objective insights. **Qualitative Data**: Gathered through case studies and semi-structured interviews. These methods address "Why" and "How" questions, providing in-depth, contextual understanding
Convergent Strategy	Quantitative and qualitative data are collected and analysed simultaneously to provide a comprehensive understanding of the research subject, reduce potential biases, and integrate diverse perspectives
Case Study Selection	**Criteria for Selection**: Projects were chosen for their relevance to high-rise construction and potential for environmental sustainability. Focus on projects providing rich quantitative metrics (e.g., carbon emissions, material usage) and qualitative insights (e.g., innovative construction practices). **Data Collection Methods**: Quantitative data included measurements of environmental impacts and project efficiency. Qualitative data involved detailed case studies and semi-structured interviews with industry professionals
Case Study Analysis Framework	**Quantitative Analysis (Deductive Approach)**: **Theory Testing**: Hypothesis that high-rise buildings can be sustainably developed, examined through literature review, bibliometric and systematic studies, and survey questionnaires. **Data Interpretation**: Provided objective metrics on environmental impacts, such as carbon emissions and energy efficiency. **Qualitative Analysis (Inductive Approach)**: **Observational Insights**: Case studies and interviews revealed new assumptions and detailed observations about sustainable construction practices. **Contextual Understanding**: Highlighted challenges and innovative practices not covered in the literature review
Integration and Synthesis	**Combining Data Sets**: The convergent approach integrates quantitative and qualitative data, offering a holistic view and identifying patterns and connections. **Addressing Research Gaps**: Complemented subjectivity in quantitative data with qualitative insights from interviews and case studies, providing a comprehensive understanding of high-rise project sustainability
Conclusion	The framework effectively combines quantitative and qualitative methods, validating existing theories while generating new insights into sustainable high-rise construction practices. This mixed-methods approach provides robust analysis of environmental impacts and practical recommendations for enhancing sustainability in high-rise buildings

Chapter 5 Data Collection and Analysis

5.1 Introduction

This research explores the role of embodied carbon emissions in off-site construction projects, particularly in large-scale and high-rise building projects. Quantitative and qualitative data methods are used to gain an in-depth understanding of sustainable construction.

Quantitative methods include bibliometric analysis, a questionnaire survey, and a statistical summary of the results. Qualitative methods include case studies and interviews. The results from this research provide valuable insights into the most effective ways to reduce embodied carbon emissions in the construction industry.

5.2 Quantitative Data

Quantitative research is characterised as a deductive approach that views the world as an objective reality independent of observations by dividing this reality into manageable subdivisions, allowing for the testing and reproduction of hypotheses through observations and data analysis, employing a more mathematically based method (Almalki, 2016).

Adopting the science mapping technique does help in the decisions of chosen data, which involves the co-occurrence of journal sources, keywords, regions, citations, and co-citation analysis (Marzouk and Elshaboury, 2022). However, according to (Araújo et al., 2020), environmental impact assessments are often inaccurate because they highly depend on perspective-based questionnaires, so this research will evaluate the quantitative data to validate the database extracted by the questionnaire and will utilise the qualitative methodology further to verify the validity of such perspective data questionnaire.

So, selecting an appropriate sampling method is critical to quantitative research. The choice of sampling method directly influences the validity and generalizability of the study's findings.

Research Objectives 1 and 2, about quantifying environmental and carbon impacts and reviewing construction practices, will be approached by quantitative systematic reviews shown in Tables 5-1, where the questionnaire survey shall assist these findings.

There were two techniques used in the search:

1. The first was searching for the topic of the research, which was "Environmentally Sustainable Construction", in a more comprehensive form, and
2. The second looked directly at "Modular Construction or Off-site Construction"

Furthermore, the second part will be an online survey questionnaire with close-ended questions distributed to relevant, experienced people. The questionnaire is in **Appendix 3**.

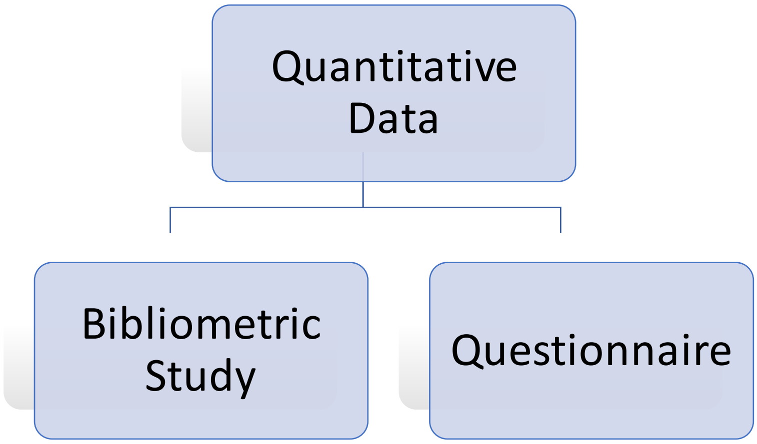


Figure 5-1 Quantitative data collection structure

First, Table 5-1 presents the conducted bibliometric study. Then, the selected keywords are illustrated in the same table. Then, the collected database from the questionnaire is presented.

Table 5-1 Bibliometric keyword selection

"Environmentally sustainable construction"	"Off-site and Modular construction"
Environmental and sustainable and construction and off-site construction or embodied and carbon and sustainability or environmental impact or construction industry	Off-site construction and engineering or energy or environment or construction industry or modular construction or project management construction, or prefabrication

When mentioning sustainable construction in the Scopus search, OSC comes up automatically. This research preferred Scopus over other database sources and online libraries such as IEEE (Institution of Electrical and Electronic Engineers). ICE (Institution of Civil Engineers), and Wiley, because it has holistic data with more functioning options such as exact discipline needed, described by (Abioye et al., 2021) as the most extensive citation database encompassing research literature and reputable web sources. It comprises data from prominent platforms like IEEE, ACM, and Science Direct.

In this section, specific project types, particularly high-rise or large-scale projects, have intentionally not been exclusively specified. This approach was done to demonstrate a broader approach to the research. The detailed categorisation of projects will be addressed in the subsequent database creation phase for a more rigorous and critical evaluation, where this approach should remove bias and provide a genuine link for sustainable construction with high-rise projects.

Consequently, SCOPUS was selected as the primary data source for several reasons, such as trustworthiness. In contrast, the rest of the data sources were employed to download complete articles and verify data. All types of articles, visualising the results, and so on. However, the results obtained from the other sources will be presented in Appendix 4. See Figure 5-2; the complete analysis is included in **Appendix 4**.

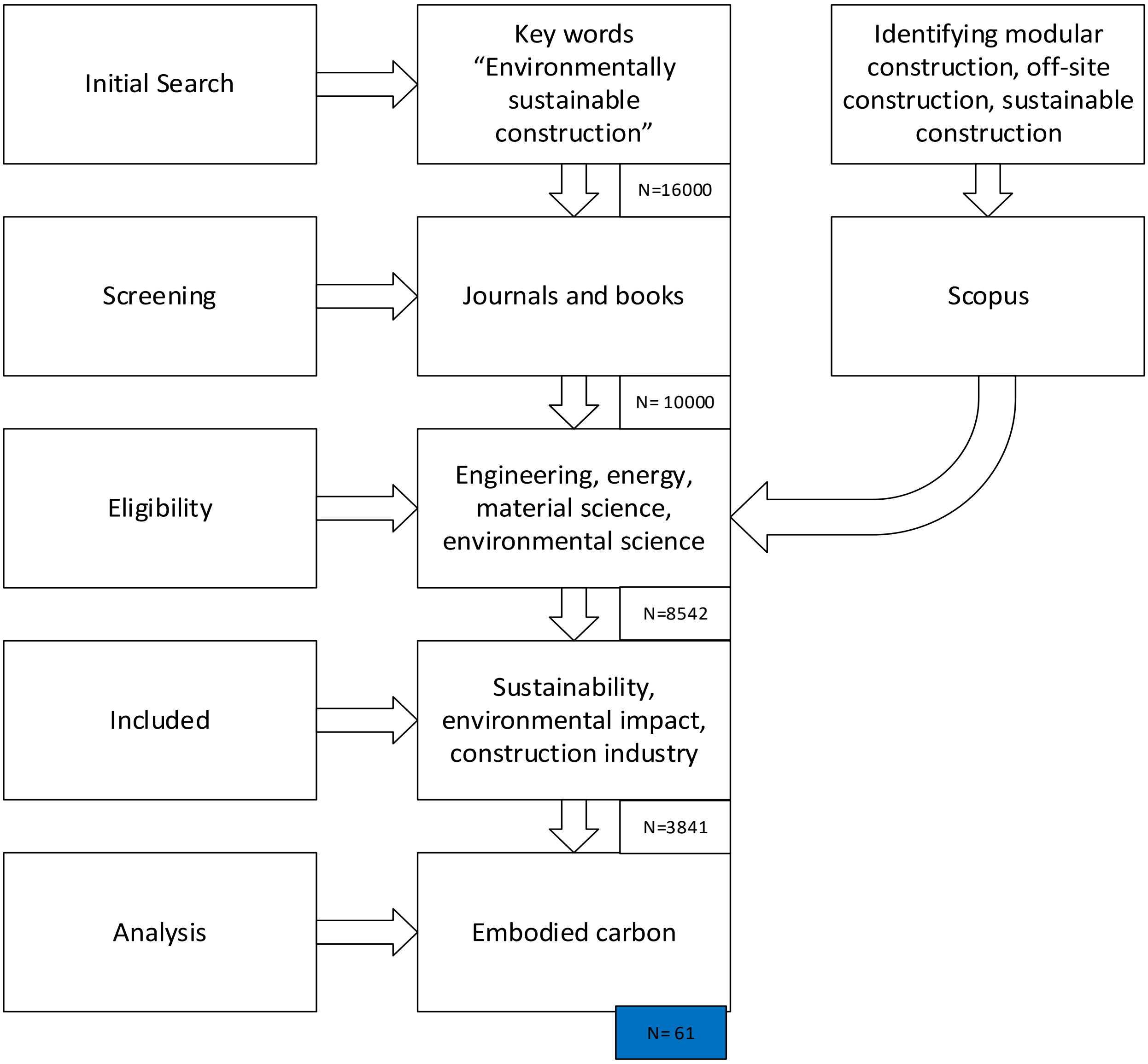


Figure 5-2 Resourcing map

5.2.1 Bibliometric Analysis Sample (embodied carbons)

This section involves a comprehensive analysis of existing quantitative data and newly acquired augmenting documents, employing visual and statistical methods. A unique mapping VOSViewer software was adopted to visualise the bibliometric study, a tool capable of visualising the impact of critical journals, publications, and countries.

According to (Wuni et al., 2019), science mapping, or visualising bibliometric networks, has become a popular tool for researchers to describe and analyse extensive collections of bibliometric data for various purposes. It also enables the analysis of the co-occurrence of research keywords, which are commonly found in literature review-based studies (Wang et al., 2020). The specific title "Environmentally Sustainable Construction" by Scopus was visualised, and the science map is presented in Figures 5-3 and 5-4.

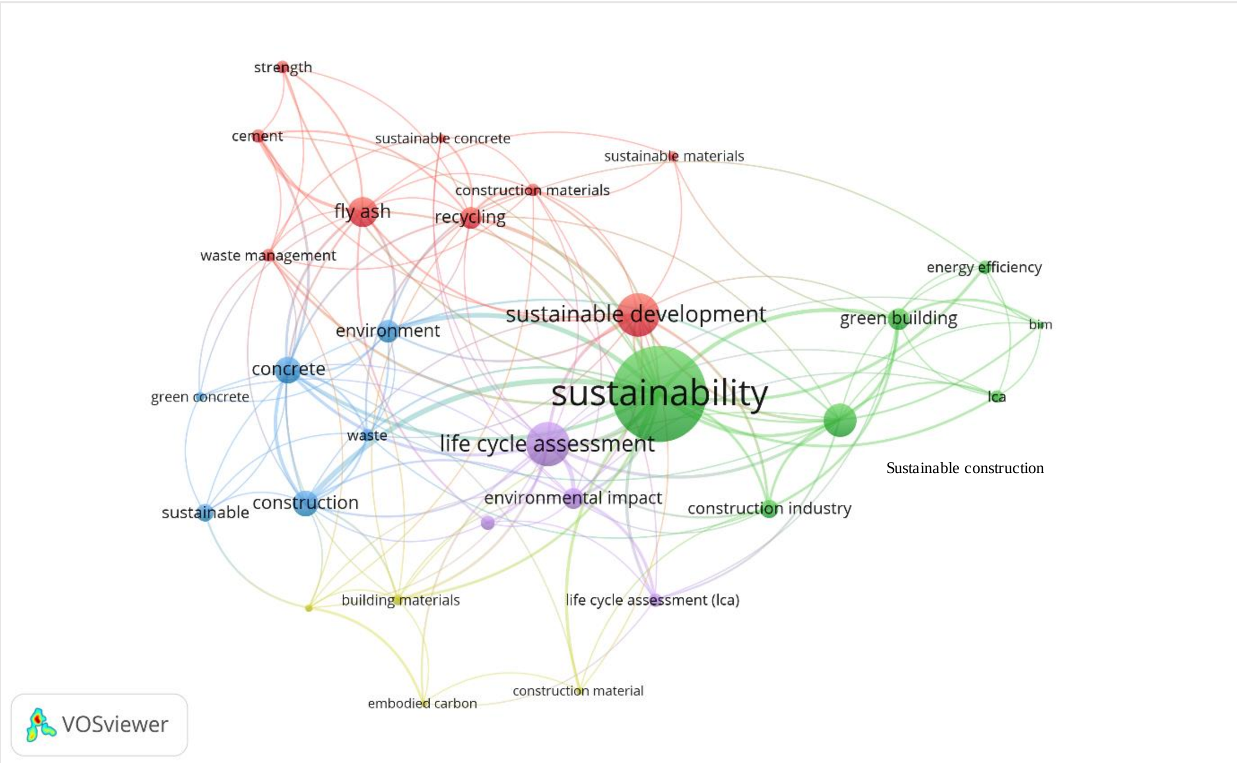


Figure 5-3 Bibliometric visualisation map of the research's main topic

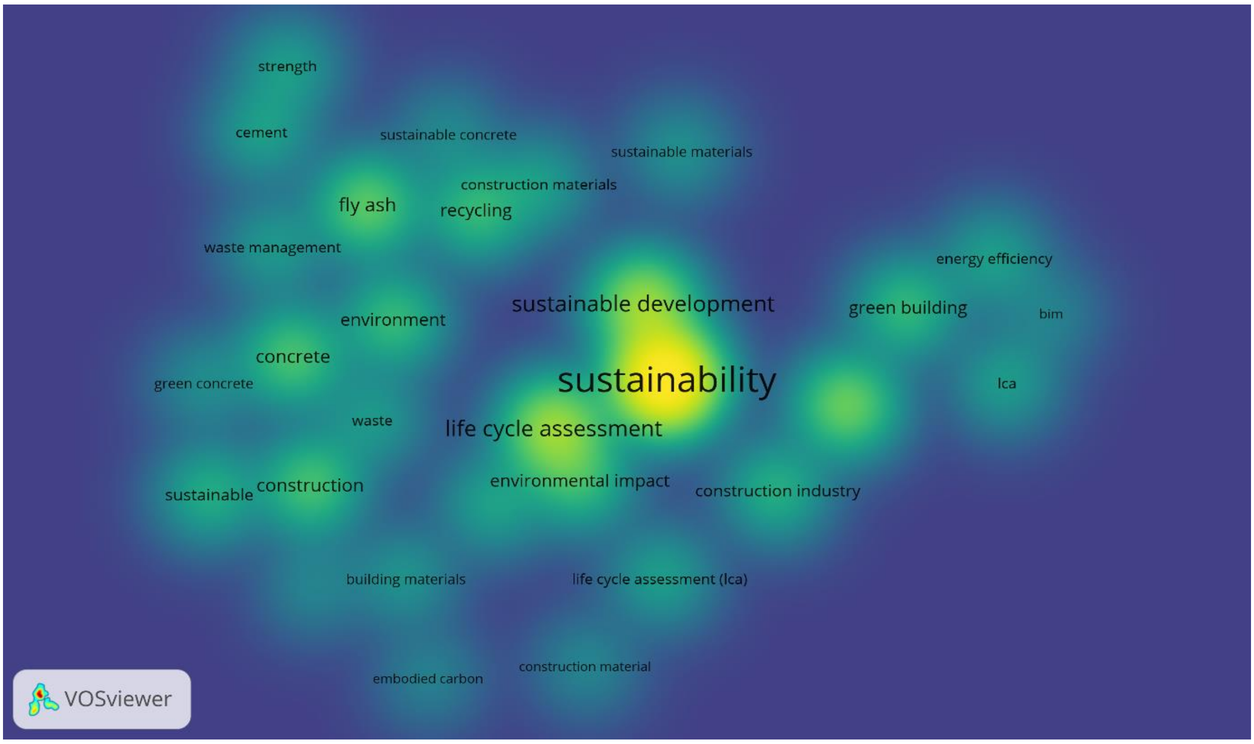


Figure 5-4 Density visualisation map of the research's main topic

The selected data presented in Figures 5-3 and 5-4 spans from 2018 to 2023, with 1629 articles obtained from Scopus. Using the visualising software, 50 keywords were filtered based on their occurrences. These keywords reveal a significant connection between the topic and critical areas such as embodied carbon, LCA, environmental impact, and sustainable development.

However, the word" steel" was absent, but it could be embedded in construction materials in the same figure map. Further investigation with quantitative and qualitative data can reveal the reasons for producing more links to subjects, which might be related to their sustainability and environmental performance.

The thickness between circles indicates the relationship between them. For example, the lines between sustainability, construction, and the environment are thicker than the relation between construction materials and sustainable development for the explanation was discussed by (Wang et al., 2020) in their study of digital technology adoption in off-site construction.

Figures 5-5 and 5-6 were extracted from the original map to understand the importance of visualising graphics in the research context. They present the topics associated with each sustainable construction and embodied carbons.

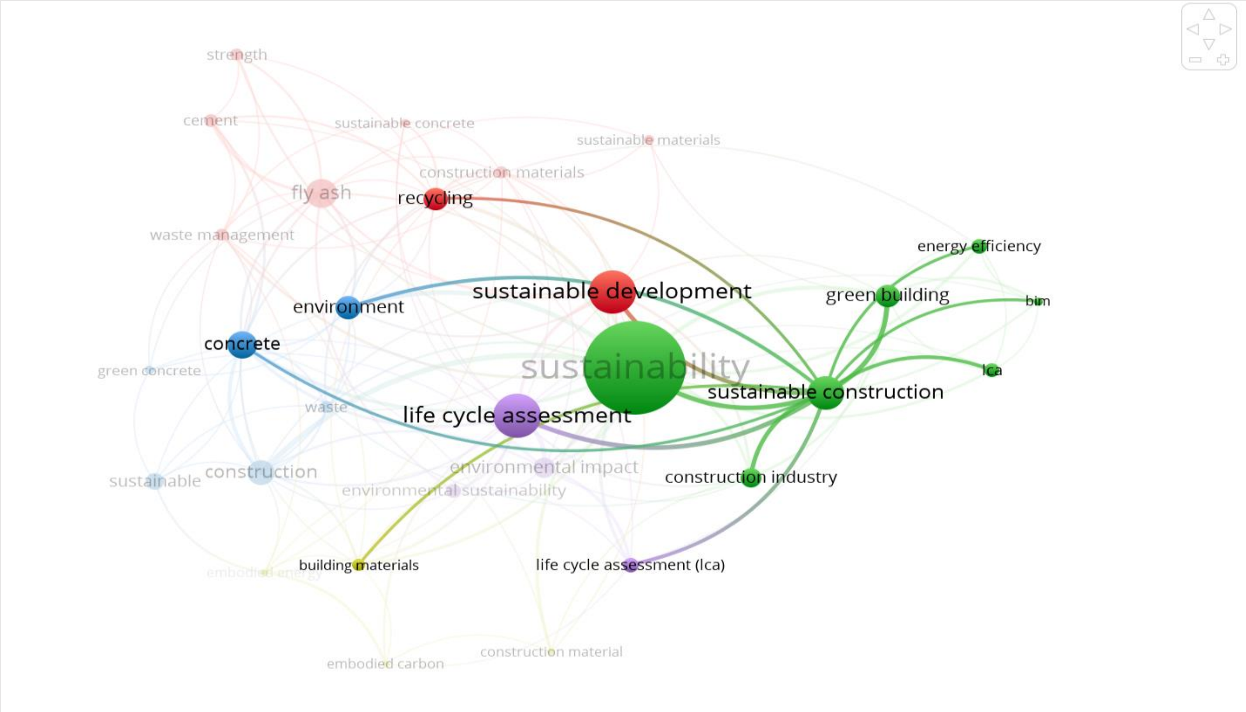


Figure 5-5 Sustainable construction visualisation

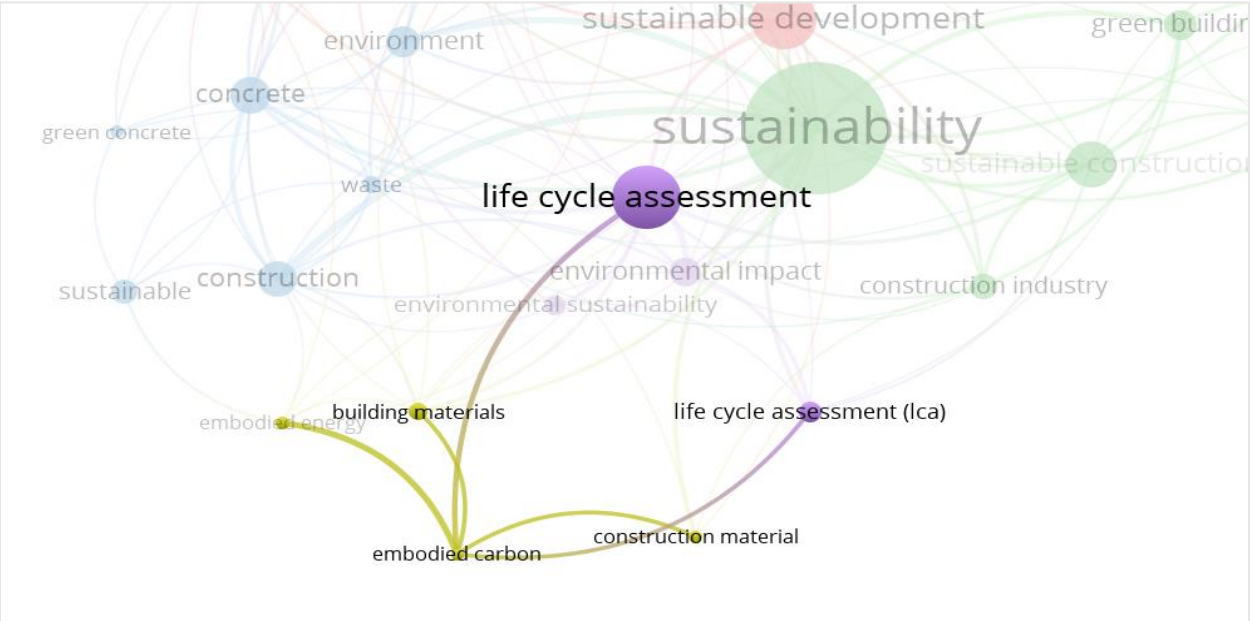


Figure 5-6 LCA visualisation

The interrelationship analysis of the topics is explained as the following:

Sustainable construction encompasses essential topics such as sustainable development, energy efficiency, LCA, green buildings, concrete, recycling, and BIM. These topics are closely connected to the overarching goal of sustainability.

Construction and building materials have a pronounced association between embodied carbon emissions and LCA. This connection highlights the growing recognition of the significant impact that life cycle assessment systems have on embodied carbon. It is a result of advancements in operational and usage energy and carbon considerations, which align with the focus of this research proposal.

Before exploring EC and LCA among large-scale projects, a bibliometric study was made on the type of building relation with EC in the last decade and extracted through Scopus after screening dozens of abstracts, which is presented in Table 5-2 and is considering the following criteria:

- Cradle to construction/ site/ prefabrication stage
- Modular, prefabricated, or semi-prefabricated construction projects only
- Embodied carbon emissions produced
- Projects within the same region and typical transportation distances

Table 5-2 Quantitative bibliometric study

No	Study	Project type	Number of case studies/ interviews	Mean EC ($Kg\ CO_2/m^2$)
1	Mao et al, 2013	Semi-prefabricated buildings	2	336
2	Jeong et al, 2017	RC columns in two factory projects	2	6001 $Kg.CO_2$/hour
3	Wolf et al, 2017	Office building	12	600
4	Teng et al, 2018	High-rise precast concrete residential building	27	342.83
5	Futas, 2019	Medium rise building	1	823
6	Teng and Pan 2019	Prefabricated high-rise building	1	561
7	Jin et al, 2020	Factory, office building, residential	8	72%
8	Kong et al. 2020	Prefabricated floor slabs	1	578.7
9	Teng and Pan, 2020	30-story concrete high-rise building	1	561
10	Han et al, 2022	Dormitory building	1	284.8

Considering the studies that have results in EC emissions per square meter, the mean value of the selected studies in Table 5-2 is 510.91 $KgCO_2/m^2$. Study number 2 was excluded because it is oriented only with column production and did not extract measured results, and number 7 was excluded because it is based on percentage. Many research studies overlook the inclusion of equivalent carbons as a crucial factor, similar to the findings presented by (Teng and Pan, 2019).

However, Futas et al. (2019) incorporated the importance of equivalent carbons in their results, indicating a value of 823 kg CO_2 eq/m^2. This is similar to (Deng and Lu, 2023) evaluation, which emphasised reducing the amount to 727 kg CO_2 eq/m^2 using more low-carbon materials. It is worth noting that this research focuses on climate change and global warming potential, as mentioned earlier. A more comprehensive and holistic approach can be achieved by integrating all equivalent carbon emissions into the assessment of embodied carbons. This approach allows for a broader understanding of the environmental impact and potential implications related to carbon emissions.

The mean was close to each of Teng and Pan (2020), (2019), Wolf et al (2017) and Kong et al, (2020). Teng et al (2018), compared with his studies with Pan in 2019 and 2020, had a lower value, which might be related to the type of building because all of them were prefabricated high-rise buildings. (Deng and Lu, 2023) had higher values between 727 and 837 kg CO_2 eq/m^2 when integrating sustainability in the project management in construction, focusing on only low carbon materials. This needs to be improved to reach a reasonable, sustainable number of embodied carbons.

The standard deviation of the selected studies, was obtained by the IBM SPSS software:

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Mean EC	8	510.91	179.25	63.38

The Median and Mode were 561. The same results were demonstrated by (J. Xu et al., 2022) and (Teng and Pan, 2020), which employed real-life prefabricated buildings in Hong Kong and compared them with the conventional LCA method. The assessment included the evaluation of the building's embodied carbon at various stages. Notably, the cradle-to-end-of-construction embodied carbon was calculated to be 561 kg CO_2 /m^2, demonstrating a slight 1% variation from the traditional LCA results. This disparity can be attributed to the inherent differences between the design and construction phases, which are inevitable. The calculation process is presented in Table 5-3.

Table 5-3 Summary

Mean EC

		Value
Standard Attributes	Position	5
	Label	Mean EC
	Type	Numeric
	Format	F9.2
	Measurement	Scale
	Role	Input
N	Valid	8
	Missing	1
Central Tendency and Dispersion	Mean	510.92
	Standard Deviation	179.25
	Percentile 25	339.42
	Percentile 50	561.00
	Percentile 75	589.35

Figures 5-7 and 5-8 present the selected bibliometric case studies' project type and carbon status.

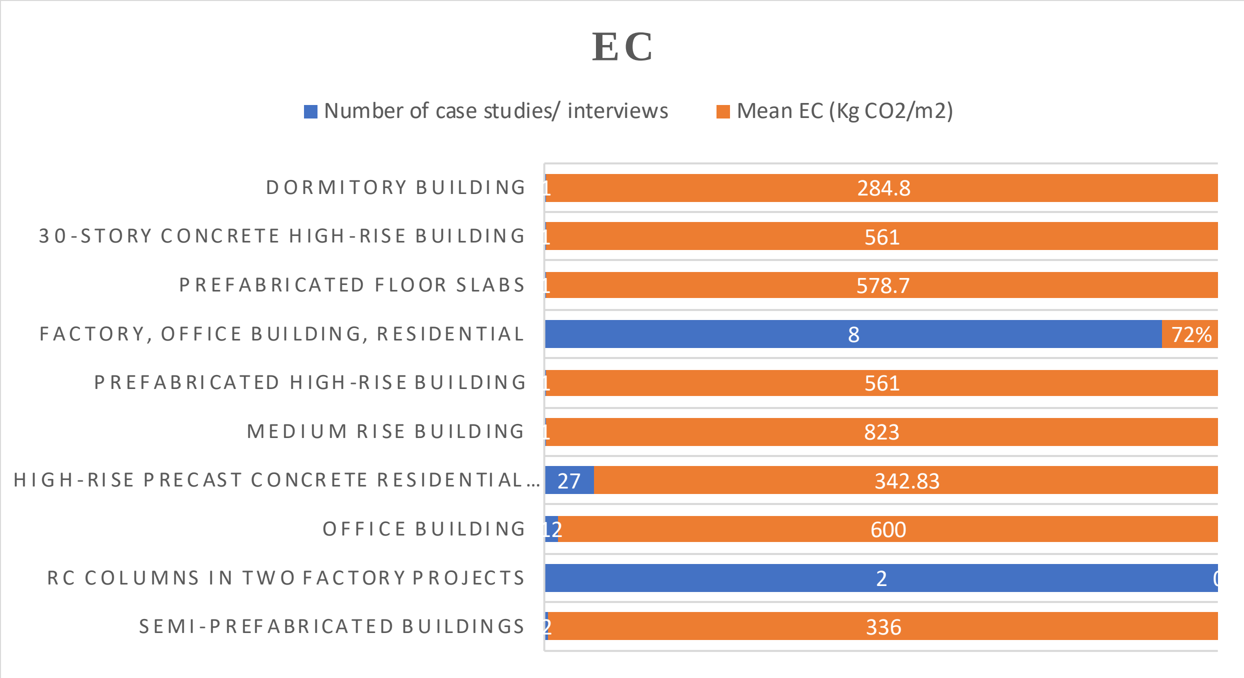


Figure 5-7 Embodied carbons from different types of construction projects

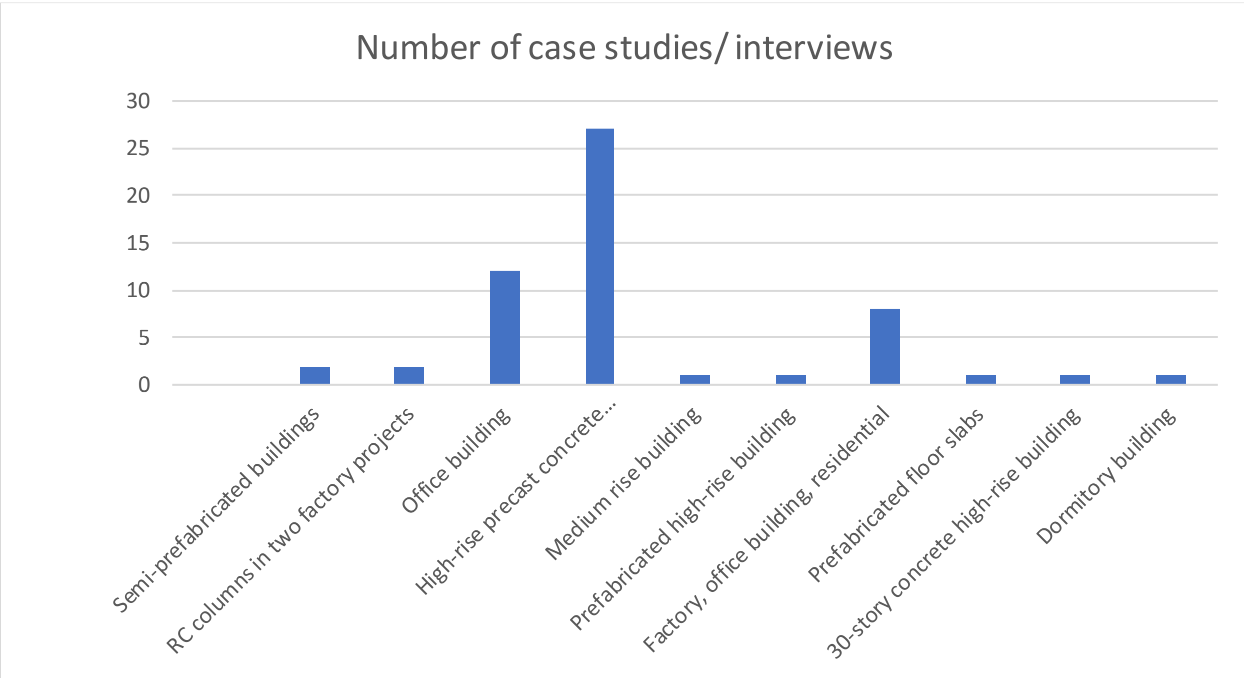


Figure 5-8 Types of construction projects used

Studies number 3 and 4 were included due to their importance, as precast columns have a paradox of higher EC when adopting OSC, and number 3 shows the approximate percentage usage of OSC in high-rise modern buildings.

Figures 5-7 and 5-8 presented inconsistency in results. Whether the building was prefabricated, semi-prefabricated, high-rise, or medium-rise does not fully control the outcome embodied carbons, which means some more reasons and boundaries should be studied.

5.2.2 Quantitative Data Questionnaire

The attached quantitative questionnaire, available in **Appendix 1**, was developed with careful consideration of the sampling method. This method was chosen to include a substantial number of individuals possessing extensive experience and professional expertise.

Essential criteria for participation included a background in engineering, with a preference for those specialising in civil and construction engineering. The corresponding Ethical Approval forms have also been included to maintain ethical standards in this research.

According to (Van Selm and Jankowski, 2006), internet-based surveys have the following privileges:

1. Anonymity for Sensitive Topics: Online surveys offer anonymity, encouraging respondents with deviant behaviours to openly share their experiences and opinions, especially for sensitive issues

2. Access to Younger Respondents: The Internet's appeal to younger age groups leads to higher response rates, particularly among young people, enhancing participation

3. Cost-Effectiveness: Online surveys are economically advantageous because they require fewer printing and distribution costs than traditional methods

4. Efficient Data Collection: Online surveys enable rapid data collection and processing, making the research process more efficient overall

According to (Siva et al., 2019), an inherent limitation of online surveys in questionnaire preparation is the researcher's inability to probe participants for answers or ask leading questions directly.

To understand and avoid the weaknesses of online-based survey questionnaires, Figure 5-9 was reproduced from (Evans and Mathur, 2005).

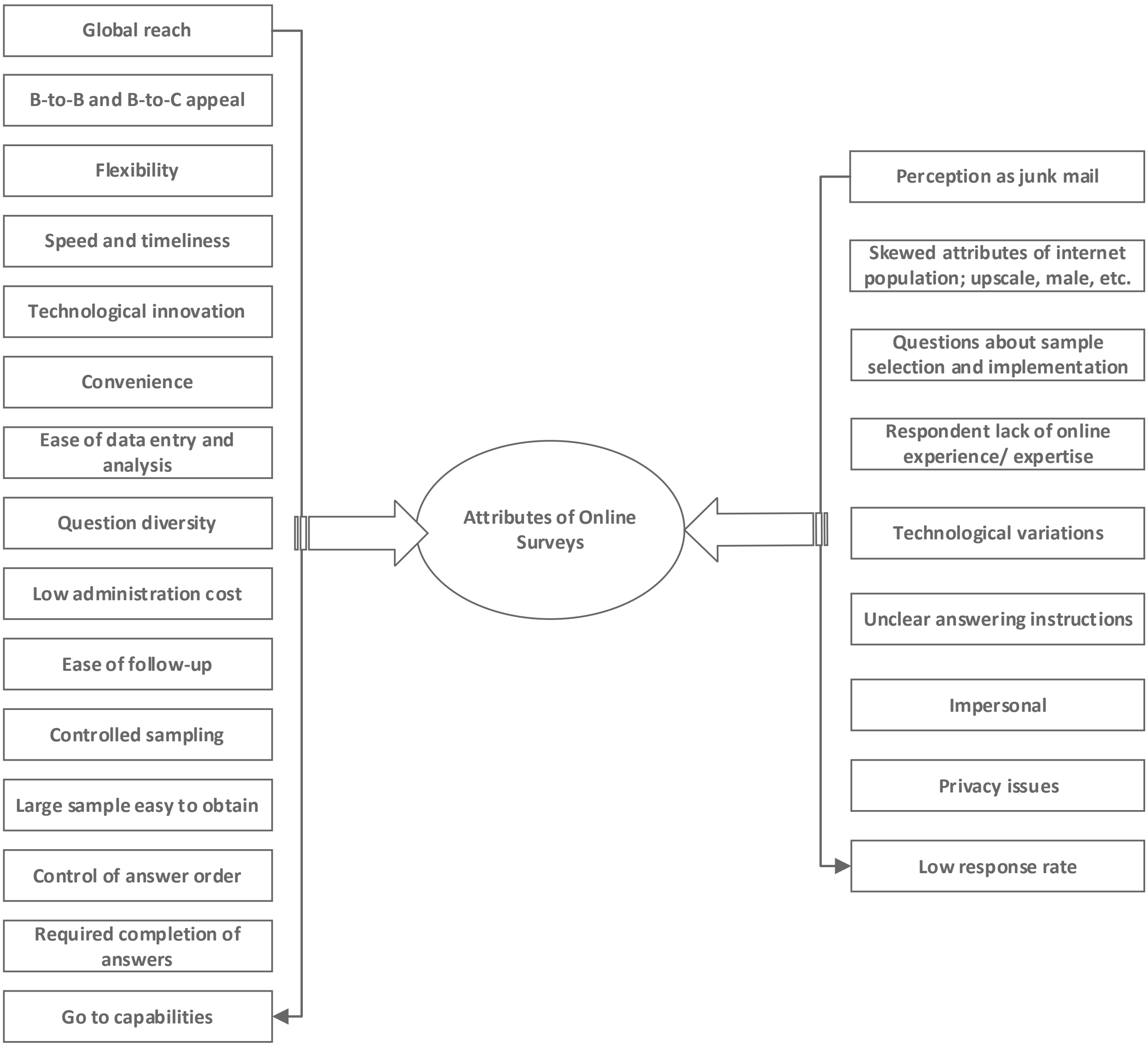


Figure 5-9 Online surveys (Evans and Mathur, 2005)

5.2.2.a Designing the Questionnaire

This study explores the versatility of online surveys, their relevance across engineering disciplines, and the methodology employed for data collection. It highlights the need for survey representation, outlines the online survey process, and previews the forthcoming methodology, data, and analysis sections.

The rationale behind encompassing various engineering backgrounds is recognising the multifaceted expertise and roles required in construction projects. This approach acknowledges the diverse skill sets and knowledge encompassed by broader engineering disciplines, contributing to a more comprehensive understanding of the research subject. Certain principles must be followed to be confident that those selected for the survey represent the population one is interested in describing (Dillman et al., 2014).

In this research, the selected questionnaire method employed an online survey approach. This approach was chosen to specifically target attributes of the target population, particularly when aiming to recruit potential respondents with unique interests. (Van Selm and Jankowski, 2006). This research mainly used formally designated emails, LinkedIn, Research Gate, phone calls, and SMS texting. The corresponding process was as follows:

1. Send advance notice and tailored emails to inform participants about the survey and encourage participation

2. Issuing individualised emails with the survey link to the questionnaire

3. Send follow-up emails as a reminder to complete the survey, including the survey link

4. Send a gratitude email after survey completion

The correspondence included a kind request to participate in the anonymous questionnaire, which will take only around 20 minutes, and noting that research objectives and ethical approval were attached.

According to (Siva et al., 2019), the success of a research project depends on the population sampled and how representative e it is of the target population; moreover, the ordering of questions and being salient and logical are essential to provide a successful survey (DONA A. DILLMAN, 2007).

There is a limited number of texts that specifically address quantitative research methods. Furthermore, only a few texts are explicitly dedicated to questionnaires and/or surveys (Rowley, 2014). However, converting a set of questions into a questionnaire entails more than just rearranging words; it involves making choices regarding paper size and binding. Additionally, it requires the thoughtful selection of questions that will not only prompt the recipient to begin responding but also motivate them to continue until they reach the end (DONA A. DILLMAN, 2007), which justifies selecting the number of questions used in this research questionnaire (25 questions).

The quantitative questionnaire primarily used close-ended questions to develop a consistent pattern of answers that avoid bias and could be generalised to the good of the research objectives. However, these questions can sometimes offer the most valuable insights to those conducting the survey (Dillman et al., 2014). Furthermore, most importantly, the questionnaire should align with the research objectives and the researcher's needs and be suitable for the respondents (Mirzakhanyan, 2005).

The number of respondents was selected carefully, anticipating that 100 plus would be convenient and sufficient for the objectives of this research, where the extent to which each survey mode is accessible is determined by both the availability of the mode and the existence of lists or databases that can be used to select members of the target population (Dillman et al., 2014).

The design of the questions mainly was formatted according to Dillman's principles of tailoring the survey situation, which (Dillman et al., 2009):

1. Phrasing questions to ensure clear comprehension without the need for rereading

2. Positioning instructions where they are contextually relevant, not solely at the questionnaire's start

3. Group questions with similar response categories carefully in a series

4. Asking one question in each instance

5. Reducing the use of matrices

6. Starting questions in the upper left quadrant, keeping unnecessary information in the lower left

7. Use prominent symbols to mark each page's starting point

8. Maintaining a consistent approach to marking the beginning of each new question

9. Number questions sequentially and simply, from start to finish

10. Employing a consistent figure/ground format, limiting reverse print usage to headings or question numbers

11. Inserting more blank space between questions than within question subcomponents

12. Using dark print for questions and lighter print for answer choices

13. If necessary, integrate special instructions within the question statement

14. Separate optional or occasional instructions from the question statement using different fonts or symbols

5.2.2.b Conducting the Survey

In this research, the choice of survey distribution method was significant. The integrity and reliability of the database relied heavily on the credibility of respondents, surpassing mere quantity. Consequently, official email addresses, reflective of the respondents' positions, were deliberately chosen over sending random emails. Emails were preferable, according to several studies that have shown that mail surveys can achieve reasonable response rates (Dillman et al., 2014).

According to (Rowley, 2014), several methodologies describe the samples for surveys, presented in Table 5-4.

Table 5-4 Samples description (Rowley, 2014)

Sample Type	Description
Probability sampling	
Random	Cases are selected at random - as in a lottery, a roulette wheel or using a table of random numbers
Stratified	Population is divided into groups by characteristics appropriate for the research questions (eg age, income, profit, location), and then a sample is selected from each group
Cluster	Population is divided into segments (eg. geographical, by street), then several segments (e.g. streets) are chosen at random
Non-probability sampling	
Systematic	Cases are selected by choosing every nth case - eg 5", 10 20" etc. Systematic sampling is often regarded as close to probability sampling, depending on the order of the list
Quota	Cases are selected on the basis of set criteria (eg gender, age, income group), to ensure that the sample has a spread of cases in different categories, even though some of those categories might be small
Purposive	The sample is "hand-picked" for the research. Used when the researcher already knows something about the specific cases and deliberately selects specific ones because they are likely to produce the most valuable data
Convenience	The sample is built from cases which are accessible, such as the organizations in a certain region, or the members of s social networking site
Snowball	A few key individuals are selected and asked to contact or recommend other relevant individuals. Could be viewed as a mix between purposive and convenience sampling

The sample types applied in this research data collection were the *non-probability* type illustrated in Table 5-4 and the *Snowball type*, which allows a few but significant individuals to be selected and then links the data questionnaire to relevant respondents.

The upcoming section will present and explore the collected data in a thorough discussion and analysis of the database, focusing exclusively on the database established through the quantitative questionnaires. This approach entails a deliberate separation from the qualitative data introduced earlier in our research strategy. The qualitative data will be integrated into the analysis after the comprehensive presentation of all the accumulated databases, allowing for a well-rounded comparison and a more holistic understanding of the research findings. Predictive and analytical research aims to explore potential connections or correlations between variables (Rowley, 2014).

5.2.2.c Questionnaire Results and Analysis

Q.1 Occupation and profession

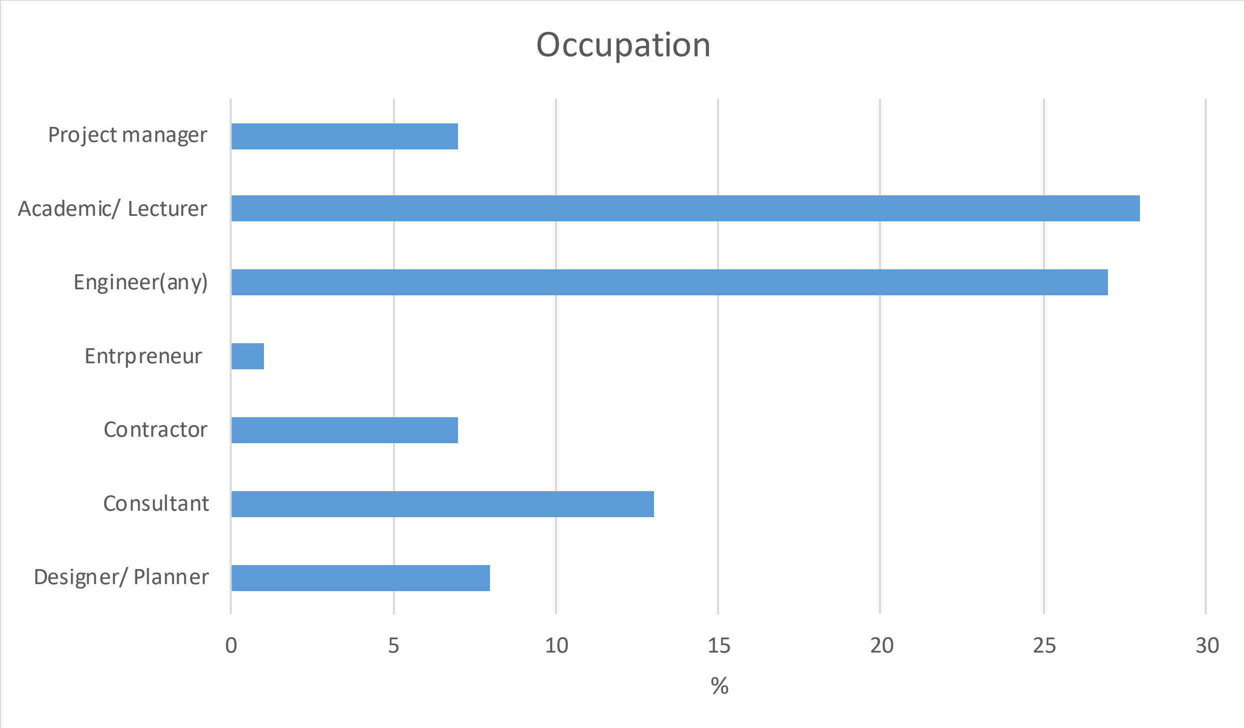


Figure 5-10 Occupation and professions of respondents

Academics and engineers were leading the response sample, yet because of the overlapping positions, Table 5-5 conceded by Question 2 shall be capable of breaking down the results more comprehensively.

Table 5-5 Occupation and area of expertise

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Academic/ Lecturer;	28	27.5	27.5	27.5
	Academic/ Lecturer;Engineer(any);Contractor;	1	1.0	1.0	28.4
	Academic/ Lecturer;Engineer(any);PhD Student;	1	1.0	1.0	29.4
	Consultant;	10	9.8	9.8	39.2
	Consultant;Designer / Planner;	1	1.0	1.0	40.2
	Consultant;Designer / Planner;Engineer(any);Academic/ Lecturer;Project Manager;	1	1.0	1.0	41.2
	Consultant;Engineer(any);	1	1.0	1.0	42.2
	Consultant;Engineer(any);Academic/ Lecturer;	1	1.0	1.0	43.1
	Consultant;management consultant;	1	1.0	1.0	44.1
	Contractor;	5	4.9	4.9	49.0
	Contractor;Academic/ Lecturer;Project Manager;Entrepreneur ;	1	1.0	1.0	50.0
	Contractor;Designer / Planner;Engineer(any);Academic/ Lecturer;	1	1.0	1.0	51.0
	Designer / Planner;	4	3.9	3.9	54.9
	Designer / Planner;Consultant;Contractor;Engineer(any);Academic/ Lecturer;	2	2.0	2.0	56.9
	Designer / Planner;Consultant;Engineer(any);	1	1.0	1.0	57.8
	Designer / Planner;Consultant;Project Manager;	1	1.0	1.0	58.8
	Engineer(any);	23	22.5	22.5	81.4
	Engineer(any);Academic/ Lecturer;	3	2.9	2.9	84.3
	Engineer(any);Academic/ Lecturer;Researcher ;	1	1.0	1.0	85.3
	Engineer(any);Designer / Planner;Academic/ Lecturer;Project Manager;	1	1.0	1.0	86.3
	Engineer(any);Project Manager;	2	2.0	2.0	88.2
	Engineer(any);Project Manager;Contractor;Product supplier;	1	1.0	1.0	89.2
	Engineering researcher;	1	1.0	1.0	90.2
	Entrepreneur ;	1	1.0	1.0	91.2
	Final year undergraduate engineering Student;	1	1.0	1.0	92.2
	Materials Director	1	1.0	1.0	93.1
	Project Manager;	4	3.9	3.9	97.1
	Research assistant;	1	1.0	1.0	98.0

	Student ;	1	1.0	1.0	99.0
	Supply Chain Manager;	1	1.0	1.0	100.0
	Total	102	100.0	100.0	

Q.2 Specify the type or branch of the profession

A good distribution of professions was collected. However, there is dominance in construction and civil engineering occupations, representing more than 30% in different forms related to the discipline; the tendency of construction industry professionals was intended to do so in the sampling system process. Table 5-6 provides the detailed database for the specified occupation of the respondents.

Table 5-6 Type or branch of occupation

	N	%
Academic Teaching and Researcher	1	1.0%
Aeronautics/Mechanical Engineer	1	1.0%
Aerospace Engineer	1	1.0%
Architect	5	4.9%
Associate Professor	1	1.0%
Associate Professor in construction engineering and management	1	1.0%
Associate Structural Engineer	1	1.0%
Automotive Engineer	1	1.0%
Banking	1	1.0%
Biomedical Engineer	1	1.0%
Building Engineering	1	1.0%
Building performance	1	1.0%
Building Services	1	1.0%
Carbon and sustainability	1	1.0%
CEO	1	1.0%
Certification	1	1.0%
Chemical Engineer	1	1.0%
Chief Engineer at a Contractor and Visiting Professor	1	1.0%
Civil Engineer	18	17.6%
Construction	2	2.0%
Construction - Text Analytics - Director - Cost / Time / Carbon	1	1.0%
Construction Engineer	1	1.0%
Construction Manager	1	1.0%
Construction Materials	1	1.0%
Contractor	1	1.0%
Currently Chief Engineer for Construction Engineering/Temporary Works at a London based contractor.	1	1.0%
Designer -Materials Engineer	1	1.0%
Education	1	1.0%
Electronic and Communications Engineering	1	1.0%
Engineer	2	2.0%
Engineering	2	2.0%
Engineering antimicrobial	1	1.0%
Environmental Engineer	1	1.0%
Environmental engineering	1	1.0%
Environmental Management	1	1.0%
Higher Education	1	1.0%
Innovation Manager	1	1.0%
Lecturer in Civil Engineering	1	1.0%
Major projects	1	1.0%
Management & Enterprise	1	1.0%
Manufacturing	1	1.0%
Materials Engineering	1	1.0%
Mechanical Engineer	3	2.9%
NGOs	1	1.0%
PhD candidate	3	2.9%
PhD student	1	1.0%
Planning Engineer and University Lecturer	1	1.0%
President of Jadara University	1	1.0%
Professor	3	2.9%
Project Manager	2	2.0%
Research	1	1.0%
Research scholar	1	1.0%
Researcher	1	1.0%
Residential construction	1	1.0%
Retired	1	1.0%
Senior Project Manager	1	1.0%
Software Development	1	1.0%
Structural Design	1	1.0%
Structural Engineer	3	2.9%
Structures / Infrastructure	1	1.0%
Surveyor	1	1.0%
Sustainability	1	1.0%

Telecommunications Engineer	2	2.0%
Temporary Works Designs	1	1.0%
Transport	1	1.0%
University graduate	1	1.0%
University Researcher	1	1.0%
Urban design	1	1.0%

Q.3 Level of education

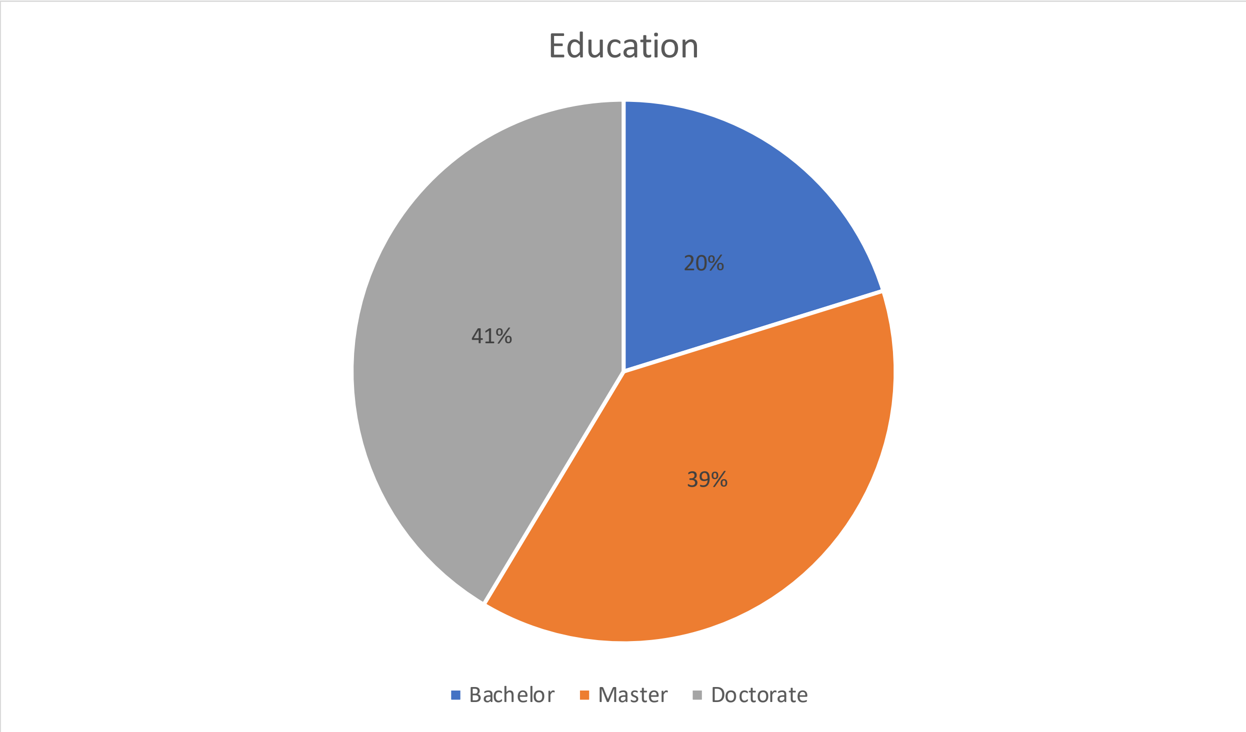


Figure 5-11 Level of education distribution

More than 79% of the respondents held higher education degrees, enhancing the credibility and reliability of provided feedback. As recommended by (Johnson et al., 2016), higher education improves innovation and progress in academia.

Q.4 Age group

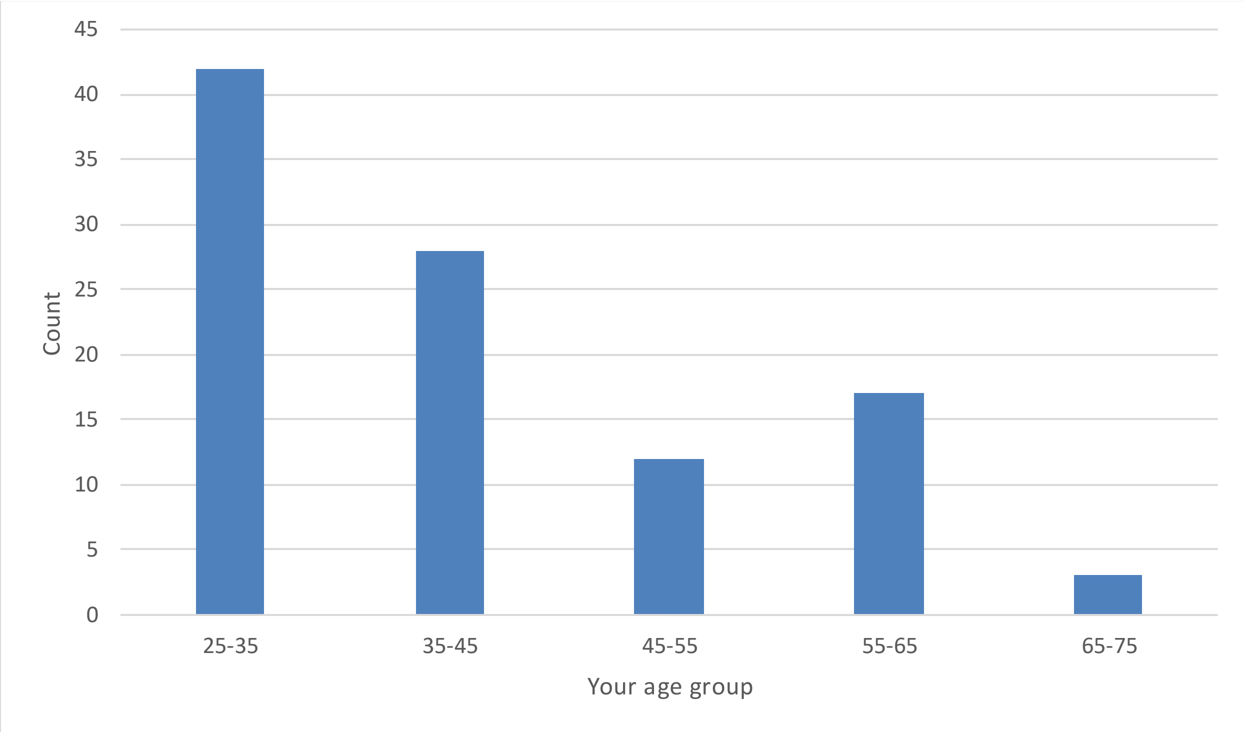


Figure 5-12 Age range among respondents

Table 5-7 Your age group

	N	%
25-35	41	41.4%
35-45	26	26.3%
45-55	12	12.1%
55-65	17	17.2%
65-75	3	3.0%

Table 5-7 represents the distribution of individuals across different age groups. Here's a breakdown of the information:

- 41 individuals are aged 25 to 35, making up 41.4%

- 26 individuals are aged 35 to 45, accounting for 26.3% of the total

- 12 individuals fall in the age range of 45 to 55, representing 12.1% of the total

- 17 individuals are aged 55 to 65, comprising 17.2%
- 3 individuals are in the age range of 65 to 75, making up 3.0% of the total

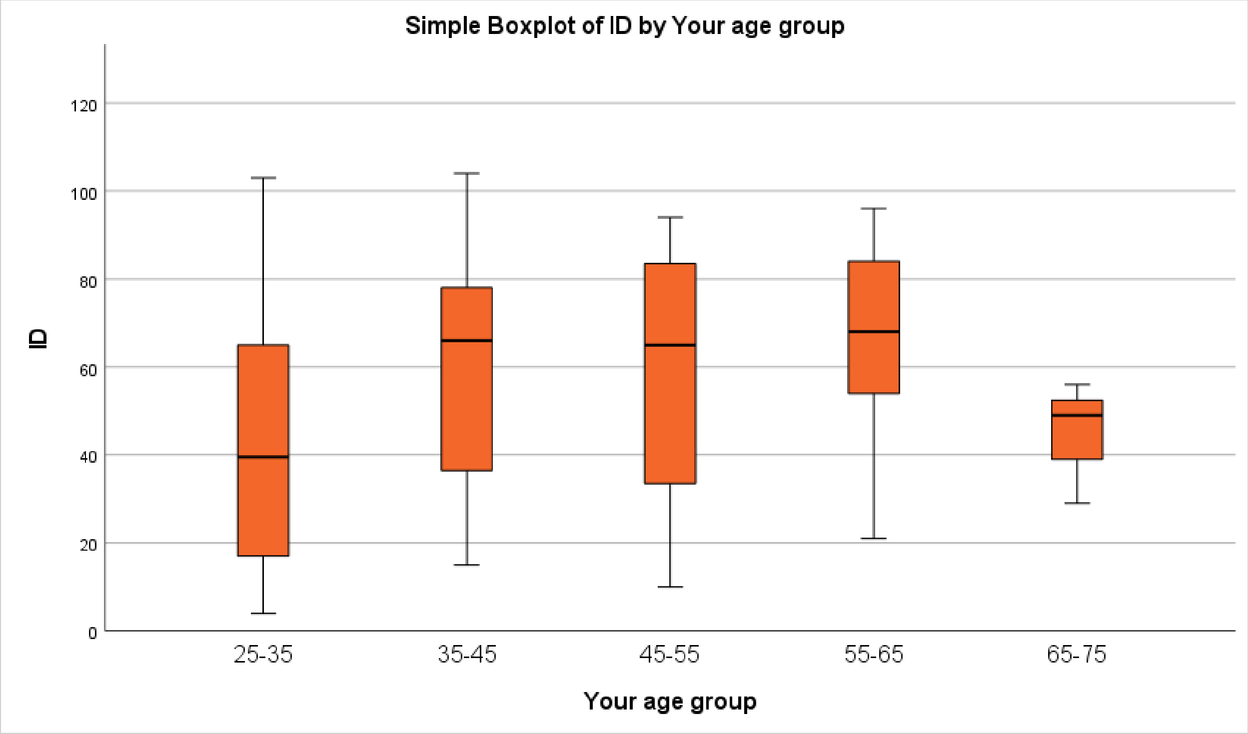


Figure 5-13 Age group range

This information provides a demographic snapshot of the surveyed population based on their age.

Q.5 Regions involved

There was a slight modification in some of the countries' names to keep consistency, such as the name (UK) representing other formats such as "England", "Great Britain", "South England", and so on. Figure 5-14 visualises the regions of respondents; moreover, Table 5-8 presents the detailed countries of regions.

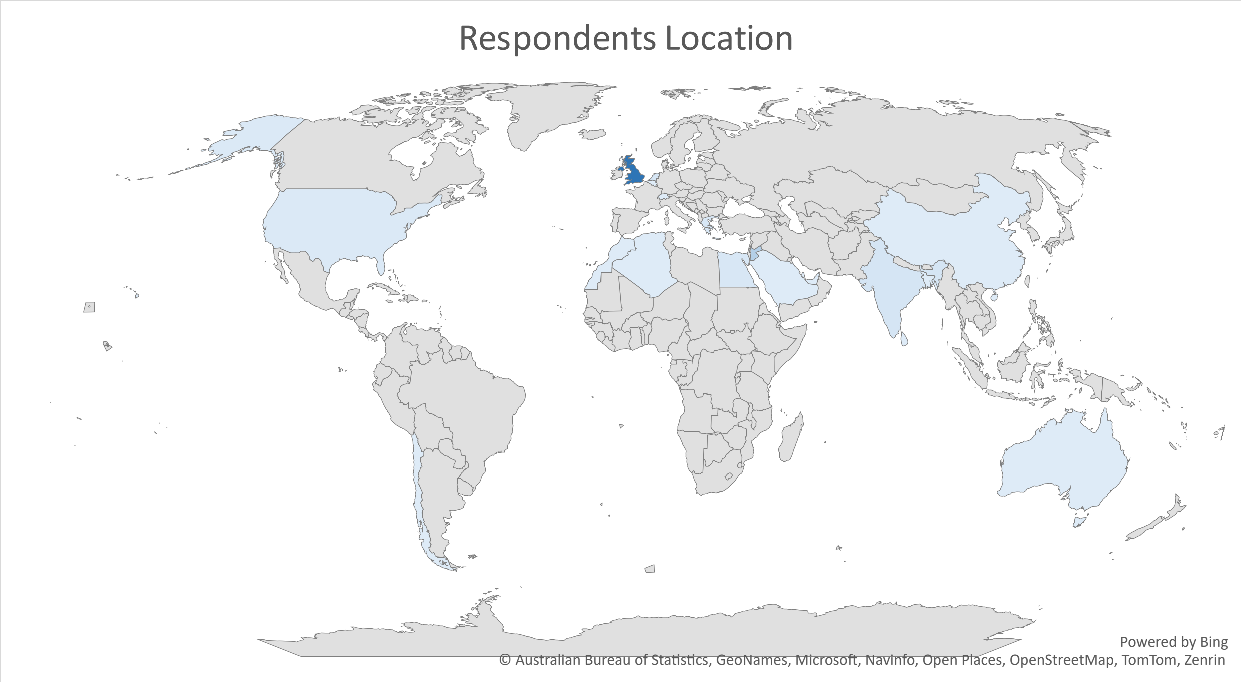


Figure 5-14 Responses world map

Table 5-8 Country or region of profession

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Algeria	1	1.0	1.0	1.0
	Australia	1	1.0	1.0	2.0
	Bangladesh	1	1.0	1.0	3.0
	Belgium	1	1.0	1.0	4.0
	Chile	1	1.0	1.0	5.0
	China Hong Kong	1	1.0	1.0	5.9
	Egypt	3	3.0	3.0	8.9
	Greece	3	3.0	3.0	11.9
	India	4	4.0	4.0	15.8
	Jordan	15	14.9	14.9	30.7
	Morocco	1	1.0	1.0	31.7
	Netherlands	4	3.0	3.0	34.7
	Qatar	1	1.0	1.0	35.6
	Saudi Arabia	1	1.0	1.0	36.6
	Sri Lanka	1	1.0	1.0	37.6
	Switzerland	1	1.0	1.0	38.6
	UAE	1	1.0	1.0	39.6
	United Kingdom	59	58.4	58.4	98.0
	United States	2	2.0	2.0	100.0
	Total	102	100.0	100.0	

The survey covered almost all the world's regions and explored all continents. This gives a non-biased and critical evaluation, especially since this research highlighted the region's importance in measuring and evaluating environmental sustainability for the designated construction projects.

The superiority of the UK (58.42%) is rational upon the research's headquarters, besides the UK being innovative and leading in environmentally sustainable actions, especially in the construction sector, as produced earlier. Then came Jordan (14.85%), where the author had several years of experience.

Q.6 Most crucial type of sustainability

Respondents were given three choices in this question: Economic, Environmental, or Social.

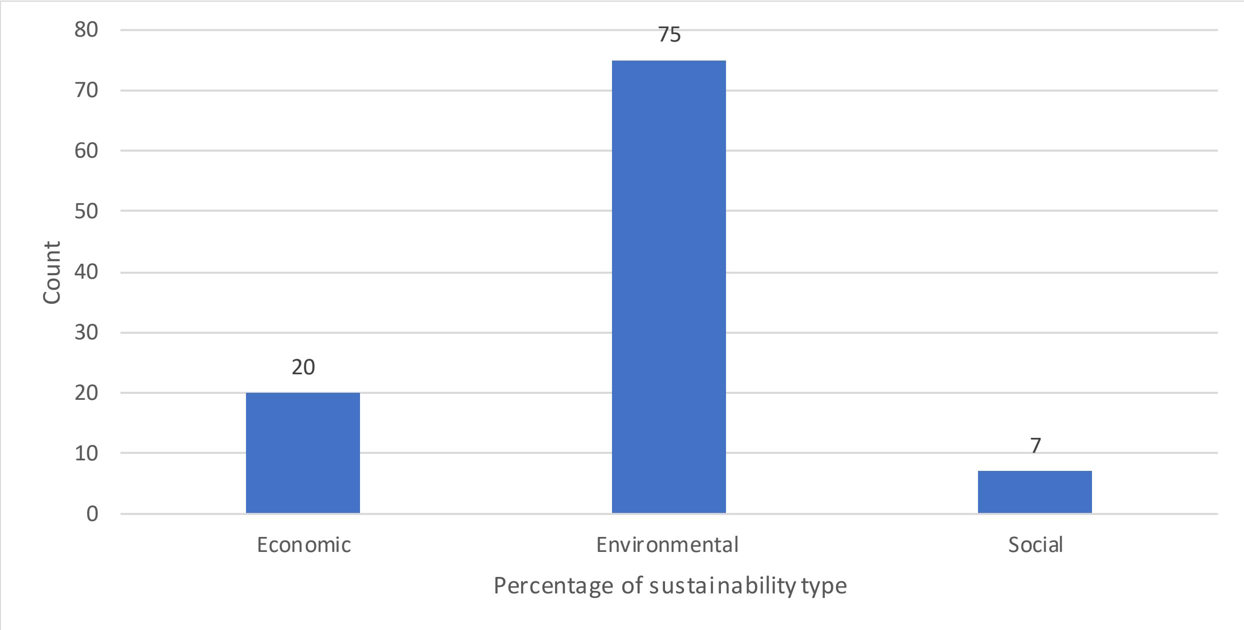


Figure 5-15 Construction sustainability

As expected, most respondents favoured and gave precedence to the environmental approach, aligning with the prior literature review in the research.

Q.7 What are the most influential environmental impacts of construction projects?

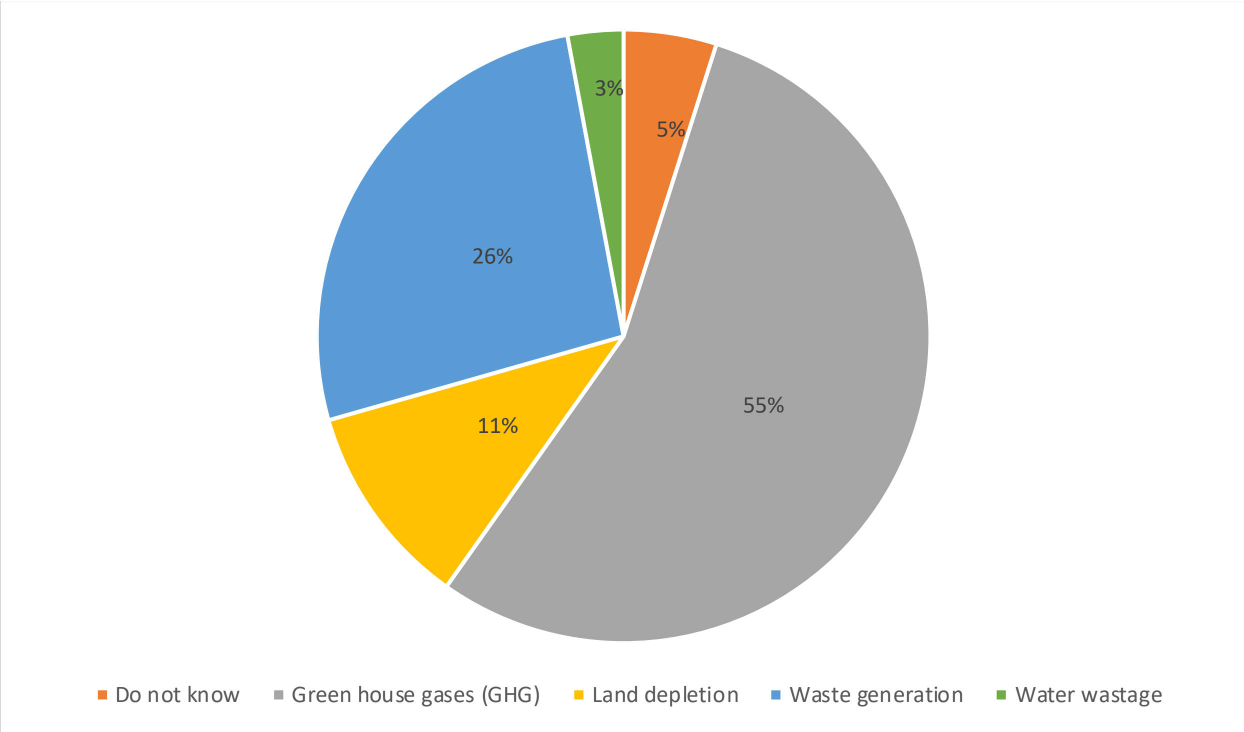


Figure 5-16 Construction environmental impacts

When respondents were asked to answer one specific environmental impact of construction projects, 55% chose GHG; however, this shows the importance of all other impacts discussed in this research. Few showed no acknowledgement of the answer (5%).

GHG preferences were by the literature and bibliometric studies explored previously in this research, presented in such studies made by (Elshaboury and Marzouk, 2021; Harputlugil and de Wilde, 2021; Liu et al., 2020; Röck et al., 2020), and others.

More details are included in Table 5-9.

Table 5-9 Percentages of chosen impacts

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Do not know	5	4.9	4.9	4.9
	Greenhouse gases (GHG)	56	54.9	54.9	59.8
	Land depletion	11	10.8	10.8	70.6
	Waste generation	27	26.5	26.5	97.1
	Water wastage	3	2.9	2.9	100.0
	Total	102	100.0	100.0	

Q.8 Which gases of GHG have the most environmental impact? (choose all that apply)

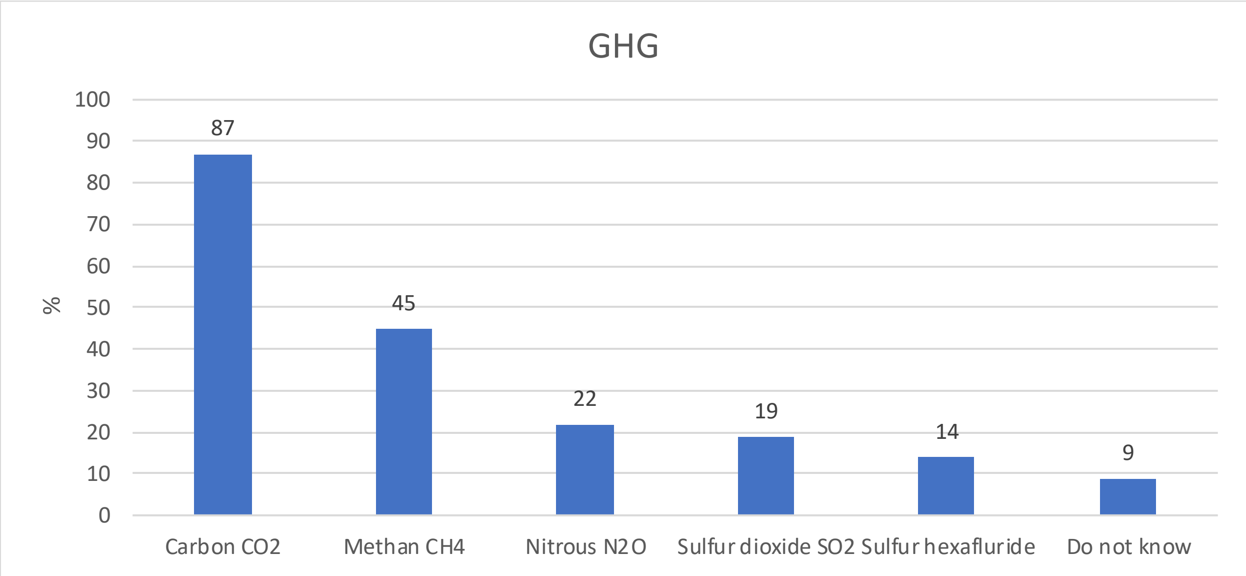


Figure 5-17 Greenhouse gases answers

Carbon dioxide had taken the lead as the solo answer of 39.4%. Moreover, it shared the answers with more than 87% of the sample. The second GHG gas was methane CH_4, more than 45% of the total sample.

A more detailed analysis is in Table 5-10.

Table 5-10 GHG have the most environmental impact

	N	%
Carbon dioxide CO2;	39	39.4%
Carbon dioxide CO2; Methan CH4;	13	13.1%
Carbon dioxide CO2; Methan CH4;Do not know;	1	1.0%
Carbon dioxide CO2; Methan CH4;Nitrous oxide N2O;	6	6.1%
Carbon dioxide CO2; Methan CH4;Nitrous oxide N2O;Sulfur dioxide SO2;Sulfur hexafluoride (SF6);	6	6.1%
Carbon dioxide CO2; Methan CH4;Nitrous oxide N2O;Sulfur hexafluoride (SF6);	1	1.0%
Carbon dioxide CO2; Methan CH4;Sulfur dioxide SO2;	1	1.0%
Carbon dioxide CO2; Methan CH4;Sulfur dioxide SO2;Nitrous oxide N2O;Sulfur hexafluoride (SF6);	1	1.0%
Carbon dioxide CO2; Methan CH4;Sulfur hexafluoride (SF6);	1	1.0%
Carbon dioxide CO2; Nitrous oxide N2O;Methan CH4;	1	1.0%
Carbon dioxide CO2; Nitrous oxide N2O;Sulfur dioxide SO2;	2	2.0%
Carbon dioxide CO2; Sulfur dioxide SO2;	1	1.0%
Carbon dioxide CO2; Sulfur dioxide SO2;Sulfur hexafluoride (SF6);	1	1.0%
Do not know;	8	8.1%
Methan CH4;	1	1.0%
Methan CH4; Carbon dioxide CO2;	4	4.0%
Methan CH4;Carbon dioxide CO2;Nitrous oxide N2O;Sulfur dioxide SO2;	1	1.0%
Methan CH4;Carbon dioxide CO2;Sulfur dioxide SO2;	1	1.0%
Methan CH4;Carbon dioxide CO2;Sulfur dioxide SO2;Sulfur hexafluoride (SF6);	1	1.0%
Methan CH4;Nitrous oxide N2O;Carbon dioxide CO2;	1	1.0%
Methan CH4;Sulfur dioxide SO2;	1	1.0%
Methan CH4; Sulfur dioxide SO2;Nitrous oxide N2O;Carbon dioxide CO2;	1	1.0%
Nitrous oxide N2O; Carbon dioxide CO2;Methan CH4;	1	1.0%
Sulfur dioxide SO2; Carbon dioxide CO2;	1	1.0%
Sulfur dioxide SO2; Carbon dioxide CO2;Methan CH4;	1	1.0%
Sulfur hexafluoride (SF6);	2	2.0%
Sulfur hexafluoride (SF6);Nitrous oxide N2O;Methan CH4;Carbon dioxide CO2;	1	1.0%

Q.9 What are the most severe consequences of environmental impacts? ***(choose all that apply)***

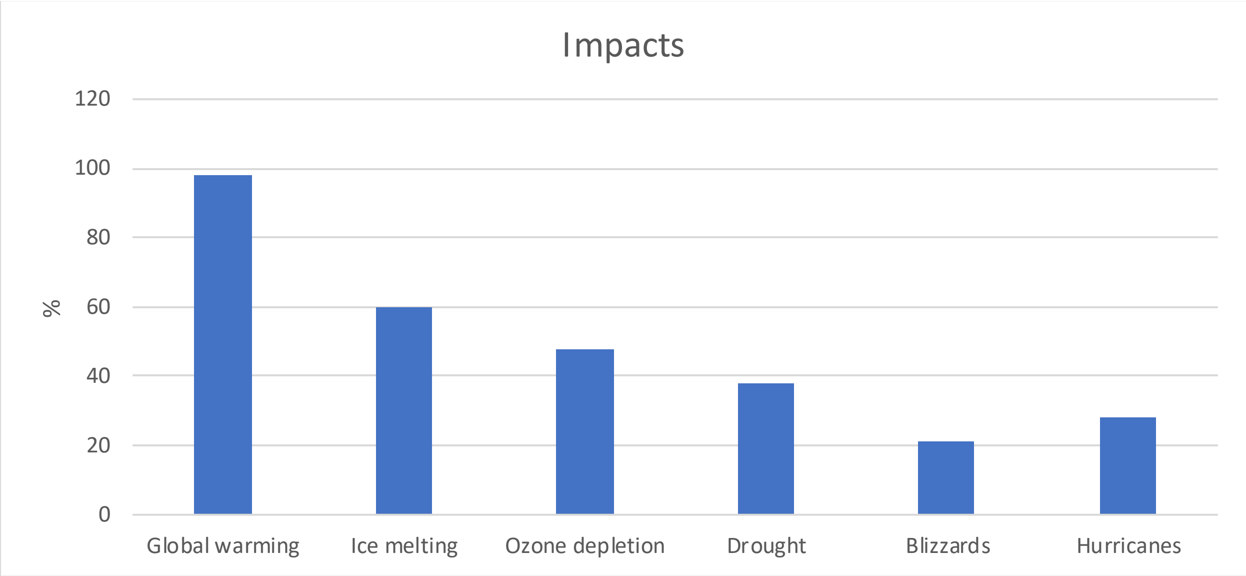


Figure 5-18 Consequences of environmental impacts answers

Global warming took the lead by solo answering 27.3% and sharing with more than 93%, wherein second came Ice melting with approx. 60%, then Ozone depletion by 48%.

A more detailed case summary is illustrated in Table 5-11.

Table 5-11 Severe consequences of environmental impacts

		Value	Count	Percent
Standard Attributes	Position	14		
	Label	What are the most severe consequences of environmental impacts? (choose all that apply)		
	Type	String		
	Format	A72		
	Measurement	Nominal		
	Role	Input		
Valid Values	Blizzards;Hurricanes;Global warming;Ice melting; Ozone depletion;Drought;		1	1.0%
	Drought;Hurricanes;Global warming;Ice melting;		1	1.0%
	Global warming;		27	27.3%
	Global warming;Drought;		1	1.0%
	Global warming;Drought;Ice melting;Hurricanes;		1	1.0%
	Global warming;Drought;Ice melting;Ozone depletion;		1	1.0%
	Global warming;Hurricanes;Blizzards; Drought;Ozone depletion;Ice melting;		1	1.0%
	Global warming;Hurricanes;Drought;Ice melting;		1	1.0%
	Global warming;Ice melting;		10	10.1%
	Global warming;Ice melting;Drought;		4	4.0%
	Global warming;Ice melting;Drought;Blizzards;Hurricanes;		3	3.0%

A shared connection between Global warming and Carbon dioxide was found in answers to questions 8 and 9, presented in Table 5-12.

Table 5-12 Questions 8 & 9 case summaries

			Which gases of GHG have the most environmental impact? (choose all that apply)
What are the most severe consequences of environmental impacts? (choose all that apply)	Global warming;	1	Carbon dioxide CO2;
		2	Carbon dioxide CO2;
	Global warming;Ice melting;	1	Carbon dioxide CO2;Methan CH4;Sulfur dioxide SO2;Nitrous oxide N2O;Sulfur hexafluoride (SF6);
	Global warming;Ice melting;Ozone depletion;	1	Methan CH4;Sulfur dioxide SO2;Nitrous oxide N2O;Carbon dioxide CO2;
	Global warming;Ice melting;Ozone depletion;Drought;Blizzards; Hurricanes;	1	Carbon dioxide CO2;Nitrous oxide N2O;Sulfur dioxide SO2;
		2	Carbon dioxide CO2;Methan CH4;Nitrous oxide N2O;Sulfur dioxide SO2;Sulfur hexafluoride (SF6);
	Global warming;Ozone depletion;	1	Carbon dioxide CO2;Sulfur dioxide SO2;
		2	Methan CH4;Carbon dioxide CO2;Sulfur dioxide SO2;
	Global warming;Ozone depletion;Ice melting;	1	Methan CH4;Carbon dioxide CO2;
	Ice melting;Global warming;Ozone depletion;	1	Carbon dioxide CO2;Methan CH4;Sulfur hexafluoride (SF6);

a. Limited to first 10 cases.

Q.10 Considering that all life cycle of construction projects is important, what is the most important phase in the life cycle of construction project in terms of environmental sustainability? (*choose all that apply)*

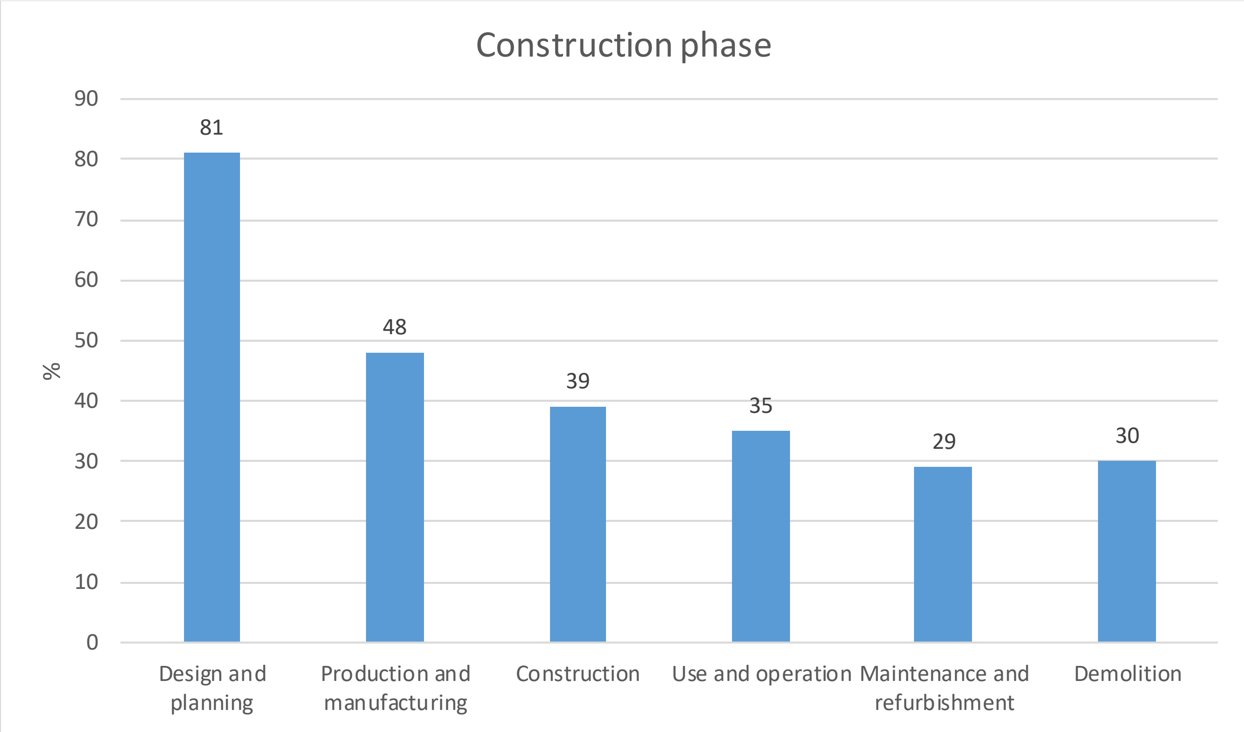


Figure 5-19 Important phase in the life cycle of construction project answers

The design and planning phase took the lead by 81%, and production and manufacturing succeeded 48%. The design selection came with the literature data generated by the research, especially emphasised by (Orr John, Gibbons, Orlando, 2020) and will be compared and justified by the qualitative data later.

Q.11 Which carbon emissions are most important throughout the whole life cycle of construction projects?

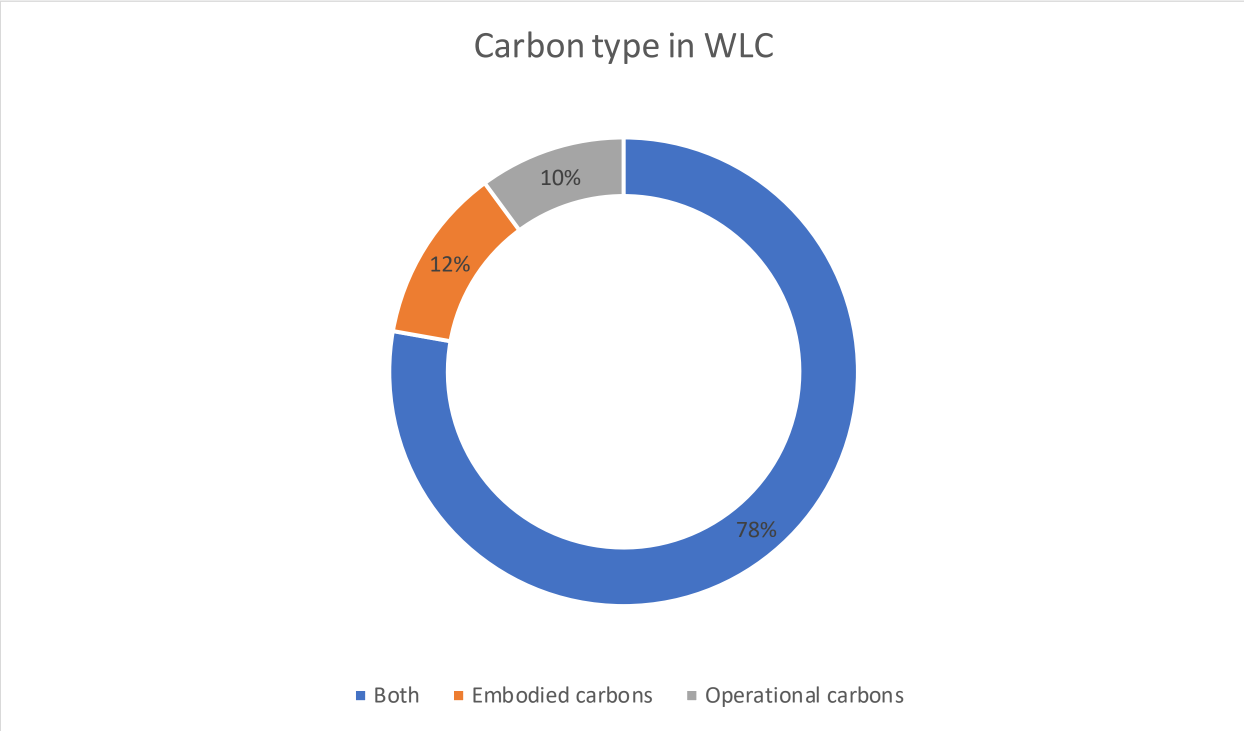


Figure 5-20 Emissions of the life cycle of construction projects

As elucidated by numerous studies, the respondents demonstrated a robust comprehension of the significance of operational and embodied carbon emissions across the entire life cycle of projects. These respondents acknowledged the distinction between these two types of carbon emissions and recognised the concurrent importance of both throughout the project's life cycle. While emphasising the equal significance of both operational and embodied carbons, the optimal approach ideally entails addressing and mitigating 100% of both carbon types for comprehensive sustainability in the project's life cycle.

Q.12 In the construction phase of projects, which carbon emissions should be considered more?

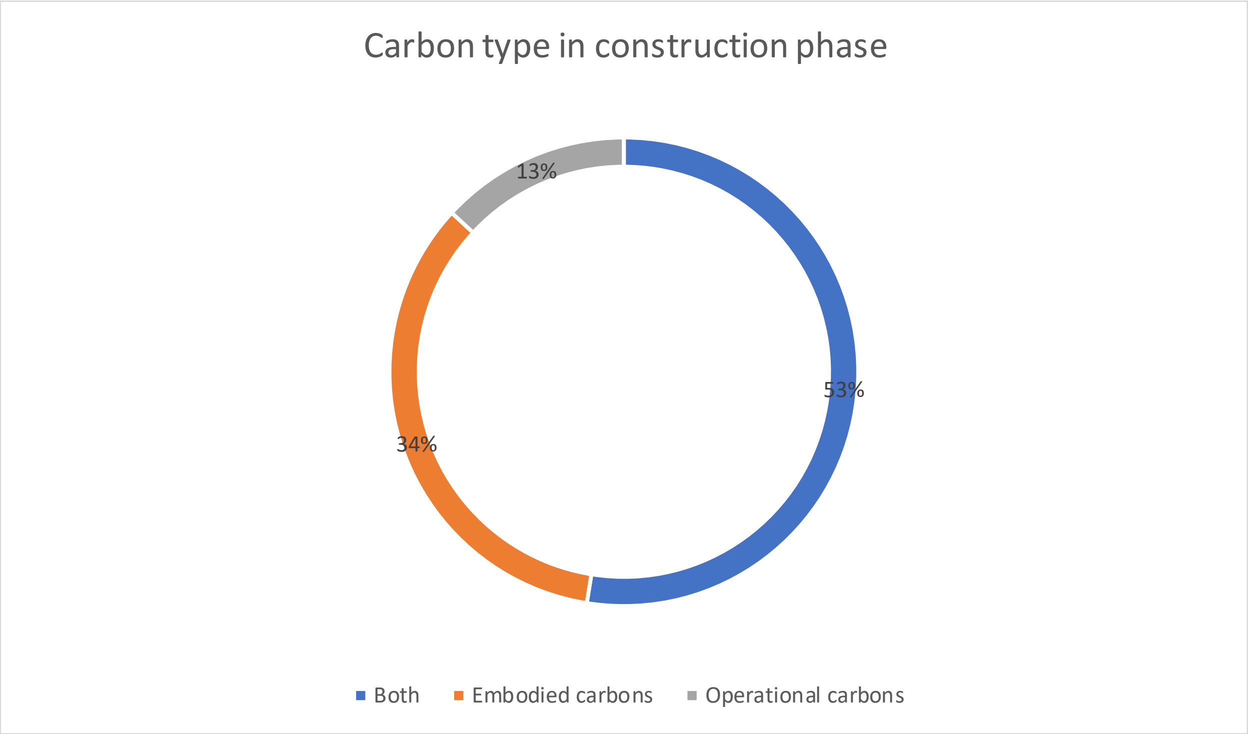


Figure 5-21 Carbon emissions associated with construction

This question showed less understanding and not fully aware of the difference between emissions through the life cycle stages, where here the perfect answer would be 100 % embodied carbons, as operational carbons, as explained through this research, for the use and operation stages of the building.

Q.13 In which unit is it best to measure carbon emissions in construction projects

Respondents were given specific choices, the only units that can measure carbon emissions. They were:

Kg. CO_2/M^2 (carbons per square meter of constructed buildings)

Kg. CO_2/Capita (carbons per individual for all humankind)

Kg. CO_2/Annual (construction industry)

Kg. CO_2/M^3 (carbons per volume of materials)

Kg.CO_2/ Kg (carbons per weight of materials)

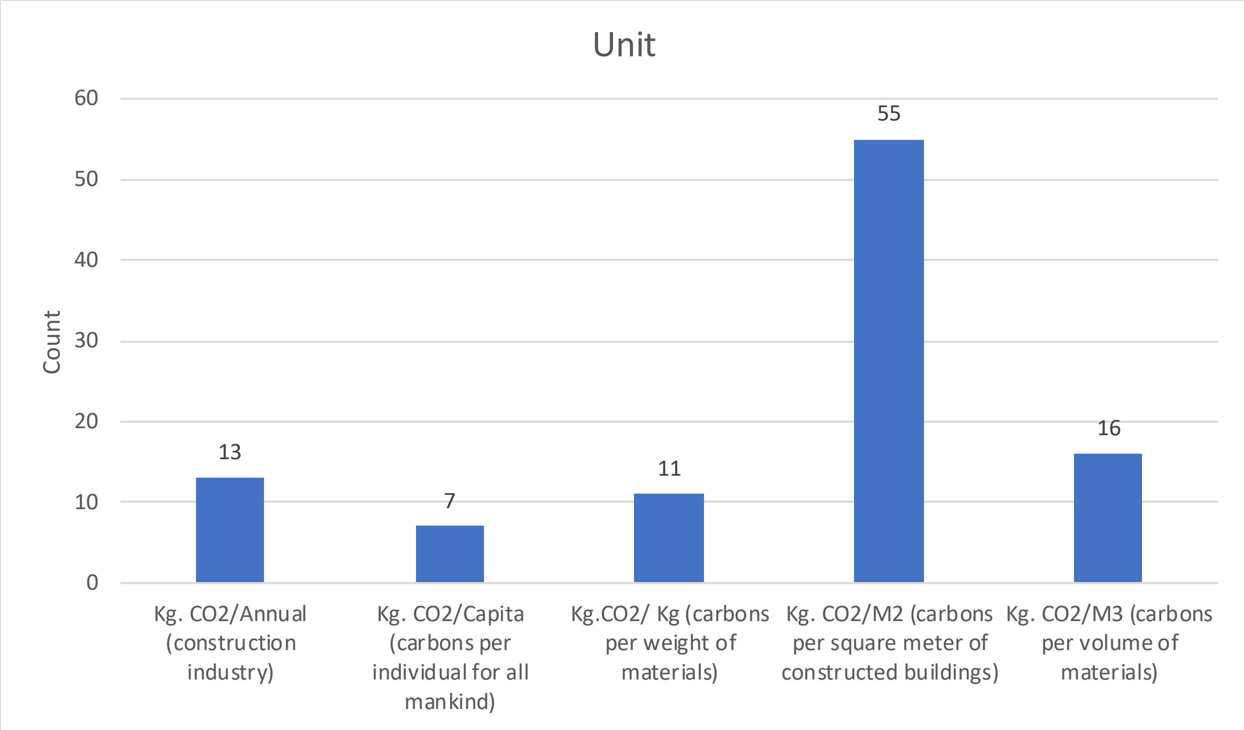


Figure 5-22 Carbon emissions best measuring unit

Table 5-13 It is best to measure carbon emissions in construction projects

	N	%
Kg. CO2/Annual (construction industry)	13	13.1%
Kg. CO2/Capita (carbons per individual for all humankind)	7	7.1%
Kg. CO2/M2 (carbons per square meter of constructed buildings)	52	52.5%
Kg. CO2/M3 (carbons per volume of materials)	16	16.2%
Kg.CO2/ Kg (carbons per weight of materials)	11	11.1%

Merging Question 13 with Questions 1 and 2 resulted in Table 5-14.

Table 5-14 Convergence occupation and preferable measuring unit (kg, CO_2/m^2)

	N	%
Architect	5	5.1%
Civil Engineer	18	18.2%
Construction	2	2.0%
Engineer	2	2.0%
Engineering	2	2.0%
Mechanical Engineer	3	3.0%
PhD candidate	3	3.0%
Professor	3	3.0%
Project Manager	2	2.0%
Structural Engineer	3	3.0%

Table 5-14 was extracted by eliminating values less than 2%, showing the advancement of civil engineers by 18.2 %, and then Architects by 5.1%. They are believed to be more capable of defining the most suitable unit to measure embodied carbon emissions. This is supported by the phenomenon that most studies regarding measuring the best unit for EC were conducted by civil engineering departments, such as (Hao et al., 2020), (Ullah et al., 2023), (Jeong et al., 2017), (De Wolf et al., 2017), and (Teng and Pan, 2019). Moreover, most studies in this research's bibliometric study used kilogram per square meter in their assessments (Table 5-2).

The 52% is not a high percentage, which suggests no strong preference for a particular measuring unit. The variance in measurement units stems from several factors, such as project type, material variations, required quantities, and adopted methodologies. This absence of a standardised preference for a specific measurement unit can result in issues like calculation errors and challenges in effective communication among construction stakeholders. Understanding the factors contributing to measurement unit inconsistencies is crucial to proactively addressing and mitigating associated risks.

Q.14 Which stage or stages of construction works are the highest for emitting carbon emissions?

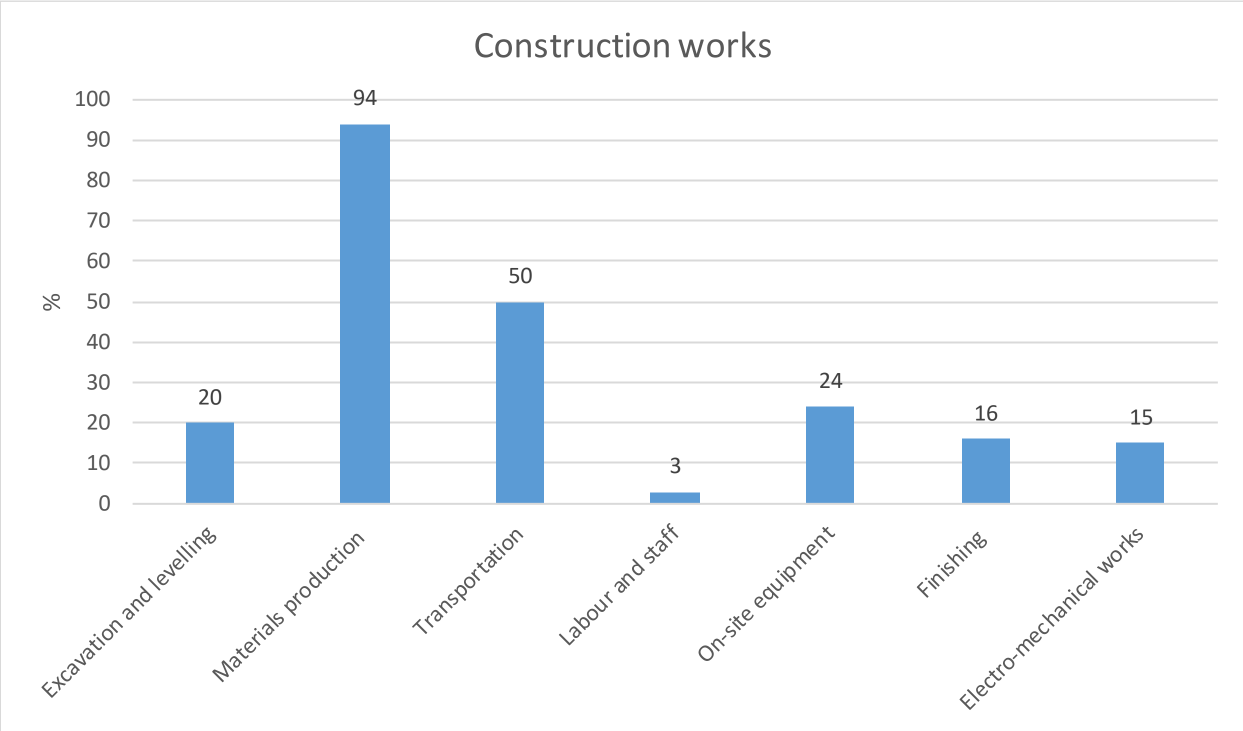


Figure 5-23 Construction stage answers

The respondents identified material production and transportation as the most important stages of the construction process, with 94% and 50% of respondents, respectively. However, on-site activities were only identified by 24% of respondents, despite being a significant part of the construction process. This finding is supported by the research conducted through bibliometric and systematic reviews, Produced previously in Tables 2-1 and 2-7.

Q.15 According to a construction project's life cycle assessment (LCA), which is the most environmentally important nowadays?

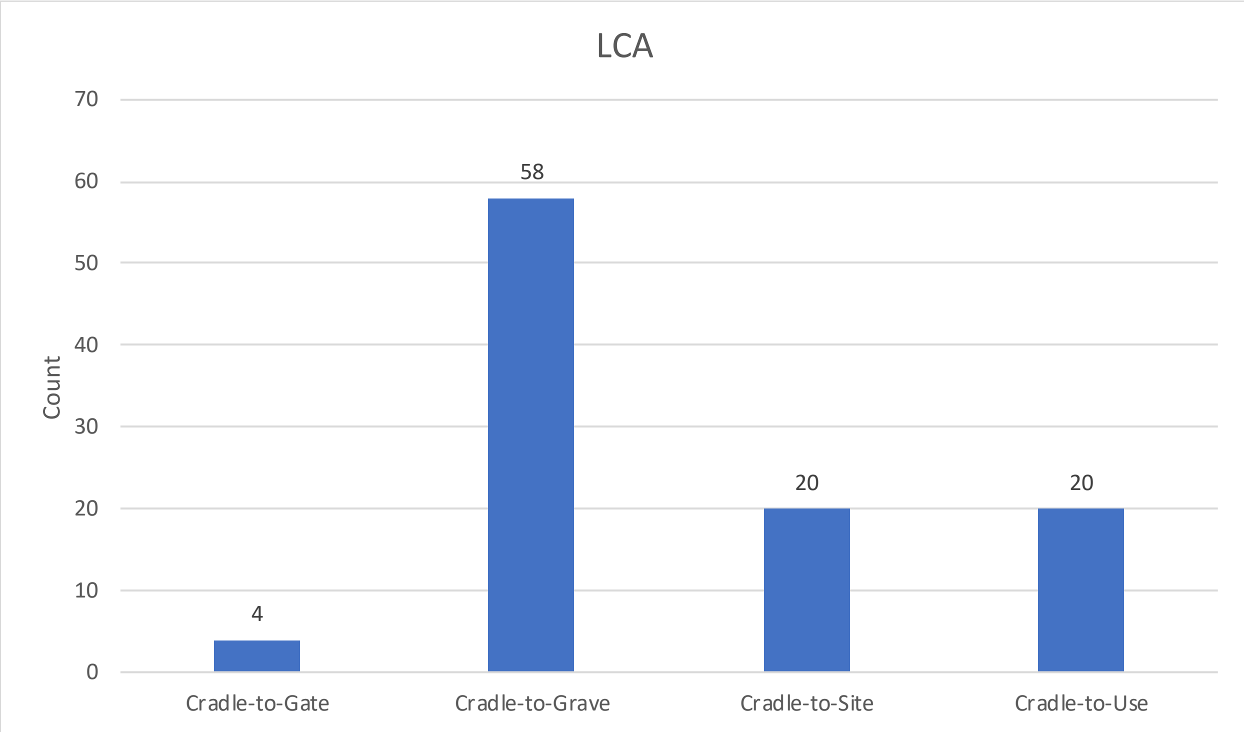


Figure 5-24 Most environmentally LCA

Figure 5-24 presents some contradictions related to the most selected stage for prioritising the environment in construction. Previously, most respondents selected the material production process (Q.14), which is majorly located in the cradle-to-gate stage. Nevertheless, they have chosen the cradle-to-grave stage, perhaps because it is more holistic than other stages.

First, most people see material production as the most significant contributor to environmental impacts, as confirmed by the study of (Zhang et al., 2023), which found that 85% of carbon emissions are emitted in the production phase of high-rise buildings. Second, the cradle-to-grave stage is a more comprehensive and holistic approach to evaluating and measuring environmental impacts.

Q.16 Which practice can help reduce embodied carbon emissions during the construction phase?

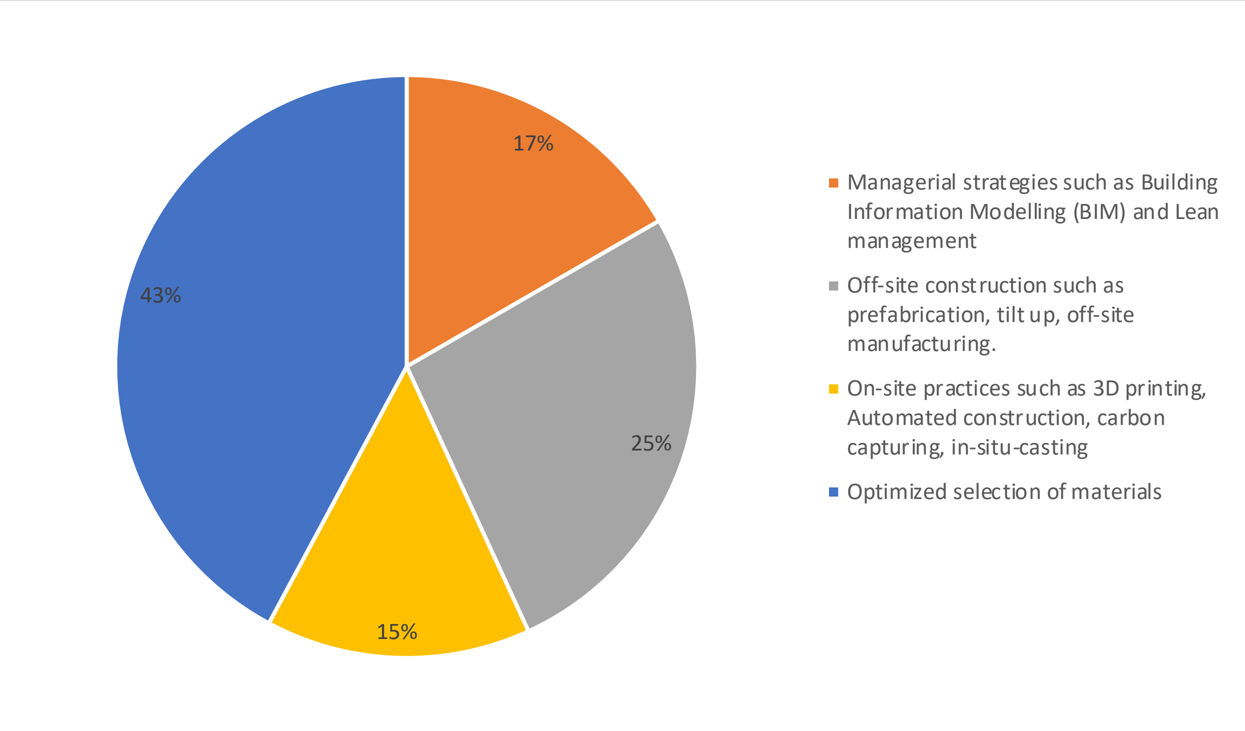


Figure 5-25 Best practices to reduce embodied carbons

Optimised selection of materials was the most popular method among the respondents, having more than 42 %, whereas OSC and prefabrication came second with 25 %. These results challenged the bibliometric studies presented in this research and defied most recent studies such as those of (Abey and Anand, 2019; Bei et al., 2021; Han et al., 2022; Hao et al., 2020; Lu et al., 2021) . However, (Zhang et al., 2023) stated that the production of building materials makes a 23% contribution to global carbon emissions. (To investigate this debate further, the qualitative data will explain this phenomenon in the convergent analysis section).

To understand the relationship between the practices and phase of construction in matters of environmental sustainability, Figure 5-26 presents the relationship map between questions 10 and 16.

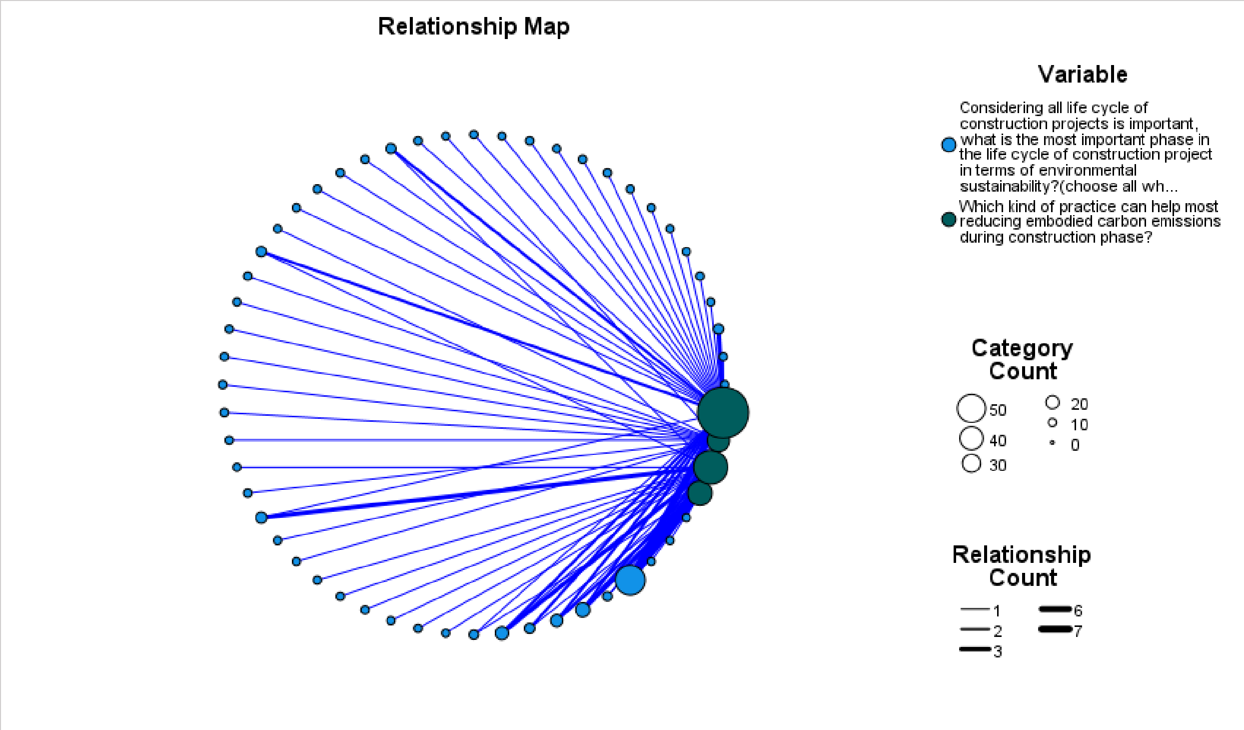


Figure 5-26 Relationship map between most important phase and best practices

The answers came logically concerning Question 10, in which more than 80% of respondents selected the design phase in promoting sustainability, where the optimised selection of materials and optimised design occur.

This question concluded two parts, which are about finding the most sustainable material and being suitable for high-rise projects; most respondents understood the question because there is almost a consensus that concrete and timber are better environmental materials than steel, supported by this research's bibliometric and systematic studies. However, steel could be more sustainable in large-scale projects and when considering the cradle-to-cradle stage.

Q.17 Which of the following materials promote (mostly) environmentally sustainable high-rise project?

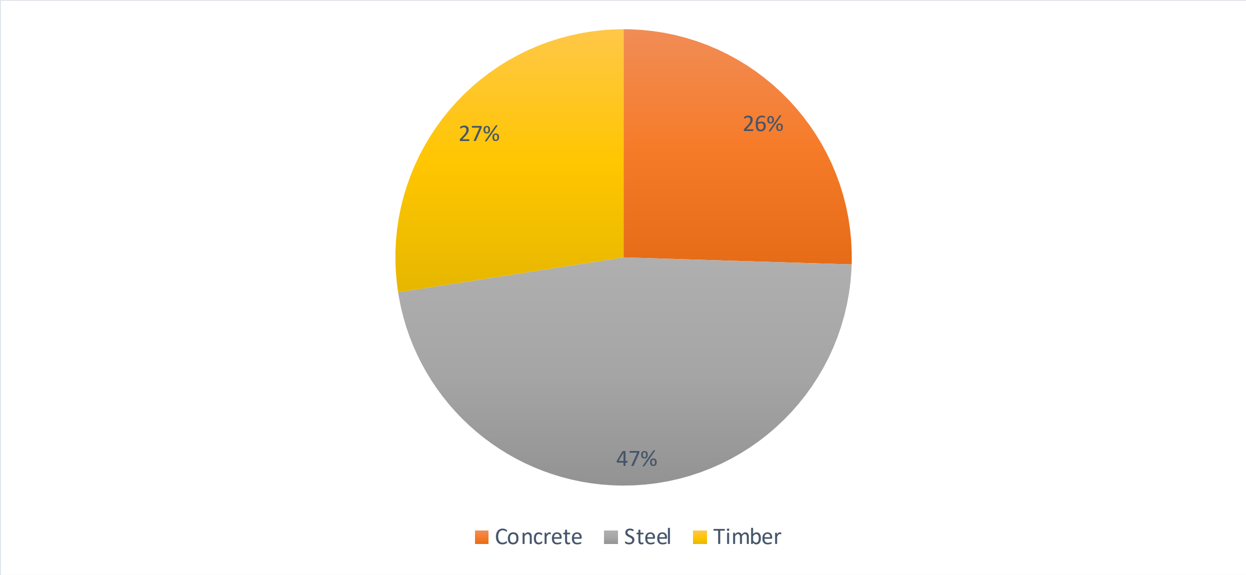


Figure 5-27 Best materials to apply sustainability

More than 47% of respondents selected steel, where concrete and timber came second, almost sharing the exact percentages of 25.74 and 26.73, respectively.

Q.18 Are high-rise building projects capable of achieving environmentally sustainable construction in the design, construction, and operation (use) phases?

This question explored the role and popularity of high-rise buildings in terms of environmental sustainability, which had already been investigated in the research through case studies, bibliometric studies, and qualitative interviews. The answers are presented in Figure 5-28.

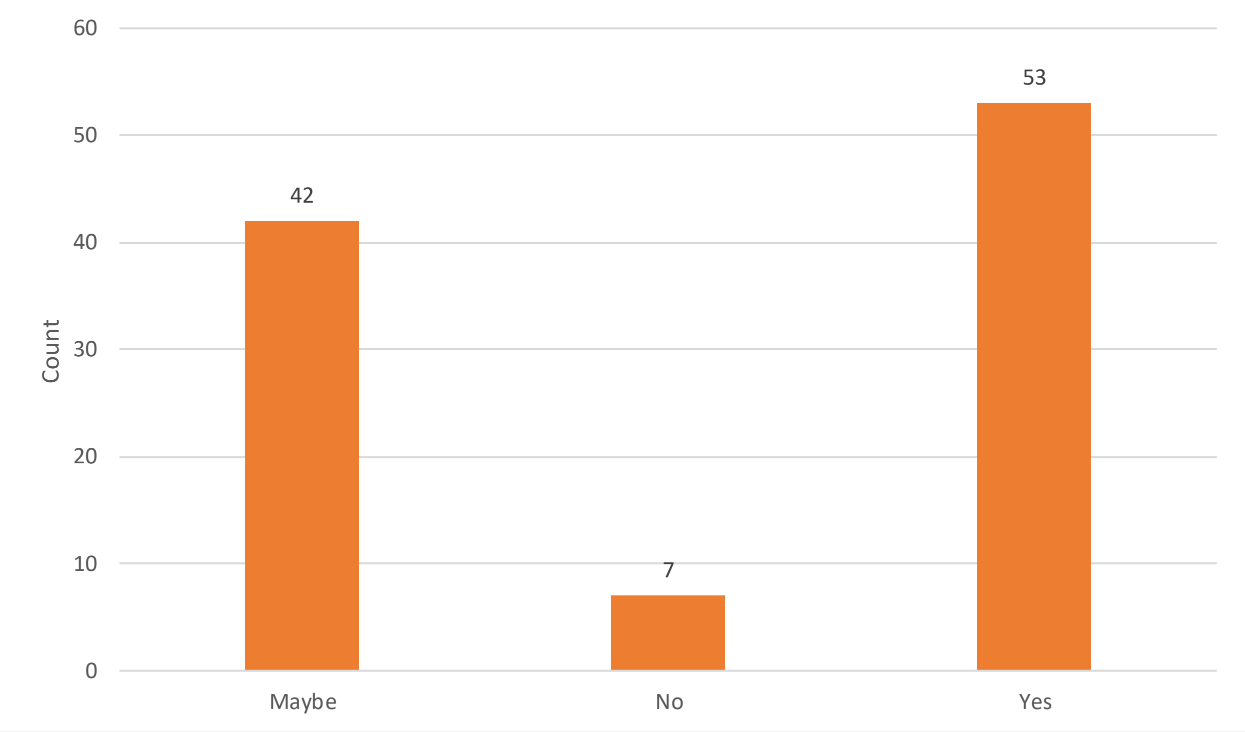


Figure 5-28 High-rise buildings' sustainability status

The tendency, the likelihood of having high-rise projects, and the potential to promote sustainability were among most of the respondents. Table 5-15 illustrates the same results.

Table 5-15 High-rise buildings sustainability percentages

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Maybe	42	41.2	41.2	41.2
	No	7	6.9	6.9	48.0
	Yes	53	52.0	52.0	100.0
	Total	102	100.0	100.0	

Q.19 What type of construction projects can be the best to apply sustainable solutions and have the best tangible outcomes? (*Choose all that apply)*

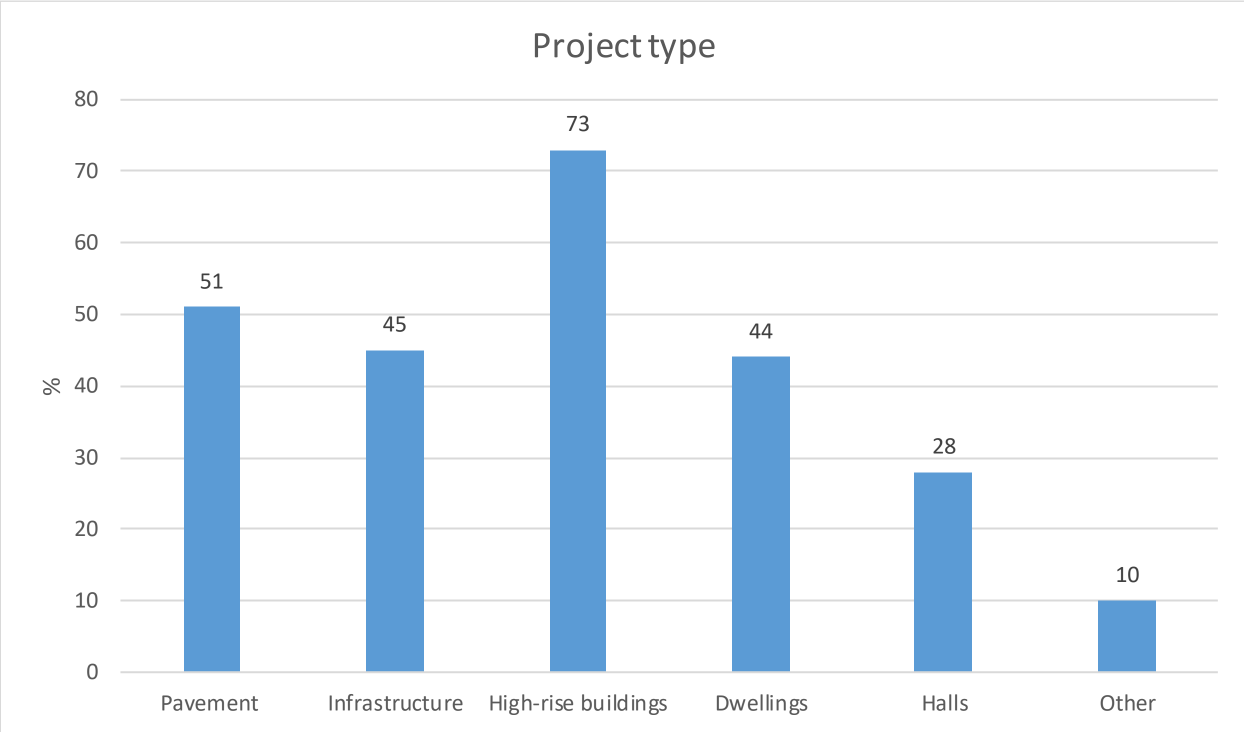


Figure 5-29 Types of construction projects

In accumulative percentage, high-rise projects led the answers with more than 70%, followed by pavement projects at 52%, and then infrastructure and dwelling projects almost shared a proportion of 44+ %. Table 5-16 below was extracted to understand the distribution and modified by excluding 1% of the results.

According to (Zheng et al., 2019), pavement projects significantly impact sustainability, and transportation agencies are actively working on eco-friendly designs. These include technologies like warm-mix asphalt (WMA) and reclaimed asphalt pavement (RAP), WMA and half-WMA, RAP implementation, utilisation of industrial by-products, and cold-in-place recycling. These approaches minimise energy consumption and emissions during material extraction and construction processes.

More explanations will be concluded in the convergent analysis of data and the results.

Table 5-16 Types of construction projects percentages

	N	%
Dwellings (houses, small flats);	3	3.0%
Dwellings (houses, small flats); High-rise buildings (commercial, residential, hospitals);	3	3.0%
High-rise buildings (commercial, residential, hospitals);	15	14.9%
High-rise buildings (commercial, residential, hospitals); Dwellings (houses, small flats);	3	3.0%
High-rise buildings (commercial, residential, hospitals); Infrastructure (water, sewage, cables);Pavement (roads, bridges, airport runways);	2	2.0%
High-rise buildings (commercial, residential, hospitals); Pavement (roads, bridges, airport runways);	3	3.0%
High-rise buildings (commercial, residential, hospitals); Pavement (roads, bridges, airport runways); Halls (theatres, stadiums);	2	2.0%
Infrastructure (water, sewage, cables) ;	2	2.0%
Infrastructure (water, sewage, cables);Dwellings (houses, small flats);	3	3.0%
Infrastructure (water, sewage, cables);High-rise buildings (commercial, residential, hospitals);	7	6.9%
Infrastructure (water, sewage, cables);High-rise buildings (commercial, residential, hospitals); Dwellings (houses, small flats);	2	2.0%
Infrastructure (water, sewage, cables); Pavement (roads, bridges, airport runways);	2	2.0%
Pavement (roads, bridges, airport runways);	4	4.0%
Pavement (roads, bridges, airport runways); Dwellings (houses, small flats); Infrastructure (water, sewage, cables) ;	2	2.0%
Pavement (roads, bridges, airport runways); High-rise buildings (commercial, residential, hospitals);	3	3.0%
Pavement (roads, bridges, airport runways); High-rise buildings (commercial, residential, hospitals); Dwellings (houses, small flats); Halls (theatres, stadiums);	2	2.0%
Pavement (roads, bridges, airport runways); High-rise buildings (commercial, residential, hospitals); Infrastructure (water, sewage, cables) ;	2	2.0%
Pavement (roads, bridges, airport runways); Infrastructure (water, sewage, cables);High-rise buildings (commercial, residential, hospitals); Dwellings (houses, small flats); Halls (theatres, stadiums);	5	5.0%
Refurbishment;	1	1.0%

Q.20 To what degree can construction projects' environmental impacts affect climate change and global warming potential? (1 is less and 10 is max)

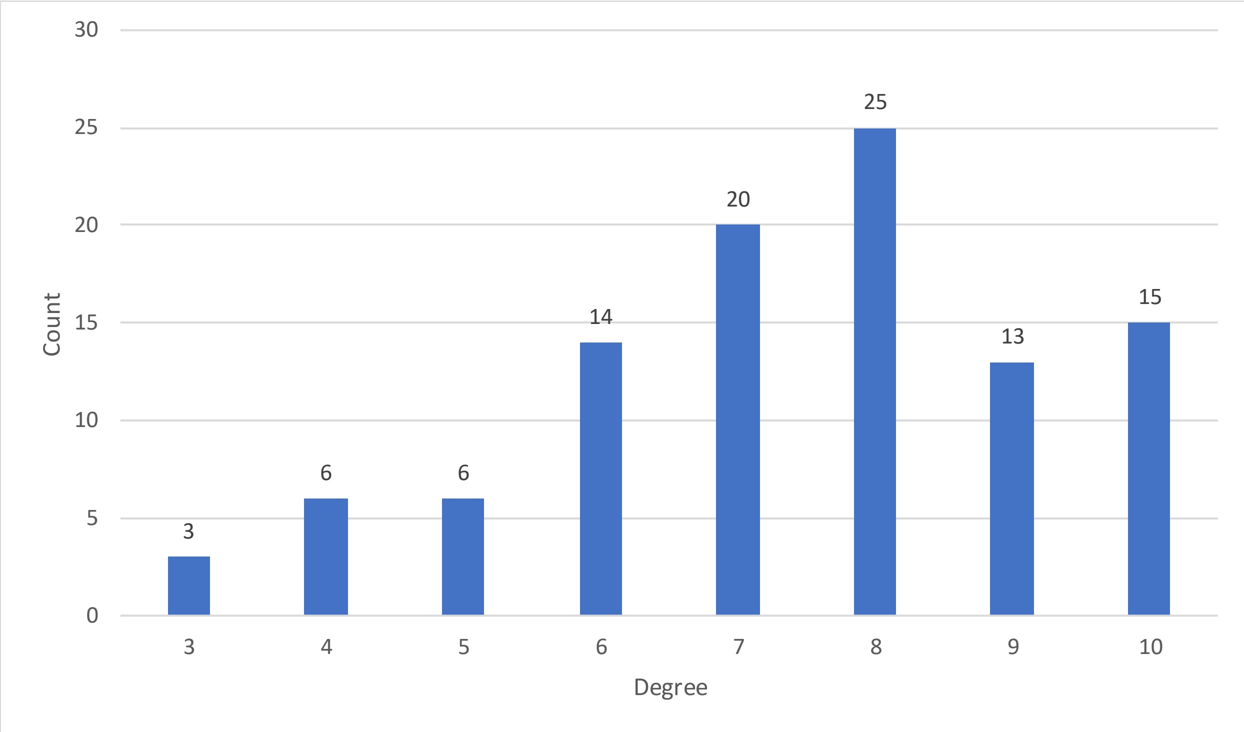


Figure 5-30 Degree of environmental impacts affecting climate change

72 % of respondents expressed concerns about climate change's association with construction activities. Climate change is the core motivation of this research.

Q.21 Is the zero net energy buildings (or GHG emissions) 2050 goal possible?

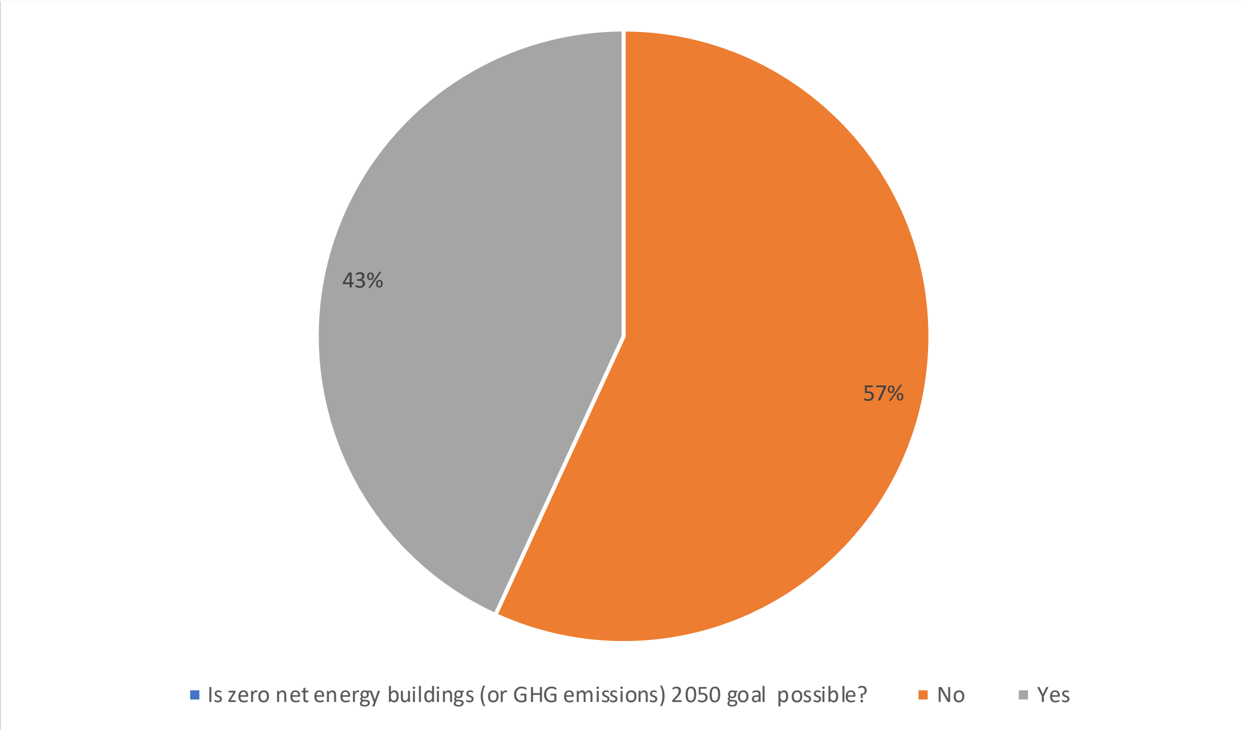


Figure 5-31 Possibility of 2050 net zero goal

Table 5-17 investigates the correlation between age groups and their viewpoints on the 2050 emissions target. Furthermore, to gain a deeper comprehension of the response.

Table 5-17 Case summaries

			Is the zero net energy buildings (or GHG emissions) 2050 goal possible?
Your age group	25-35	1	Yes
		2	No
		3	Yes
		4	No
		5	Yes
		6	No
		7	Yes
		8	Yes
		9	No
		10	No
		11	No
		12	Yes
		13	Yes
		14	Yes
		15	Yes
		16	No
		17	No
		18	No
		19	No
		20	No
		21	Yes
		22	No
		23	Yes
		24	No
		25	No
		26	Yes
		27	No
		28	Yes
		29	Yes
		30	Yes
		31	Yes
		32	Yes
		33	No
		34	No
		35	No
		36	Yes
		37	No
		38	No
		39	Yes
		40	No
		41	No
		42	No
		Total N	42
	35-45	1	Yes
		2	No
		3	Yes
		4	Yes
		5	No
		6	No
		7	No
		8	No
		9	No
		10	No
		11	Yes
		12	Yes
		13	Yes
		14	Yes
		15	Yes
		16	No
		17	Yes

		18	No
		19	Yes
		20	Yes
		21	No
		22	Yes
		23	No
		24	No
		25	No
		26	No
		Total N	26
	45-55	1	Yes
		2	No
		3	No
		4	Yes
		5	No
		6	No
		7	Yes
		8	No
		9	No
		10	Yes
		11	No
		12	No
		Total N	12
	55-65	1	Yes
		2	No
		3	No
		4	No
		5	No
		6	Yes
		7	No
		8	No
		9	No
		10	Yes
		11	Yes
		12	No
		13	Yes
		14	No
		15	Yes
		16	No
		17	Yes
		Total N	17
	65-75	1	No
		2	No
		3	Yes
		Total N	3
	Total	N	100

a. Limited to first 100 cases.

The results revealed that fewer than 45% of individuals across various age brackets endorse the 2050 objectives. These few numbers suggest that additional efforts should be directed towards persuading people, particularly those in professional capacities, to have faith in the effectiveness and trustworthiness of the measures being implemented, ultimately aiding in achieving the target.

Q.22 Name three challenges associated with having net carbon construction projects.

The qualitative approach will delve into this inquiry, presenting observed results highlighting both similarities and differences among respondents.

Similarities:

1. Common Focus Areas: Respondents express concerns about pivotal aspects of reducing carbon emissions. These include electricity consumption, high-carbon material production, and the role of technology

2. Challenges with Definitions: Many respondents stressed the need for a standardised definition of "net carbon" to measure and reduce emissions effectively

3. Political and Industry Factors: Recognised hurdles include political acceptance and industry conventions, which are substantial barriers to achieving sustainability goals

4. Cost and Efficiency Concerns: The recurring themes of cost-effectiveness and efficiency span from material production to project implementation

5. Material Lifecycle Awareness: There is a consensus on the importance of considering the entire lifecycle of materials, from production to utilisation and eventual demolition

Differences:

1. Industry-Specific Focus: Some respondents tailor their concerns to specific industries, such as construction, steel manufacturing, or energy production

2. Geographical Considerations: A few respondents note challenges specific to certain locations, such as renewable energy availability and technology suitability in distinct regions

3. Technological Solutions: Some respondents suggest specific proposals, such as green cement or carbon capture, to tackle emissions

4. Regulatory Emphasis: Updated regulations, standards, and policies are underscored by some respondents as crucial for supporting sustainable practices

5. Economic Feasibility: Economic viability, funding availability, and cost are repeatedly cited in various contexts

6. Education and Training Needs: Education and training are essential for industry professionals to comprehend and implement sustainable practices

7. Behavioural and Cultural Aspects: Some respondents consider societal acceptance and behavioural changes significant in achieving sustainability goals

Overall, respondents collectively recognise the intricate challenges in achieving net-zero carbon emissions. They acknowledge various factors ranging from technological advancements and regulatory frameworks to economic and cultural considerations.

Q.23 Will the construction industry play a positive role in climate change in the present time and the future?

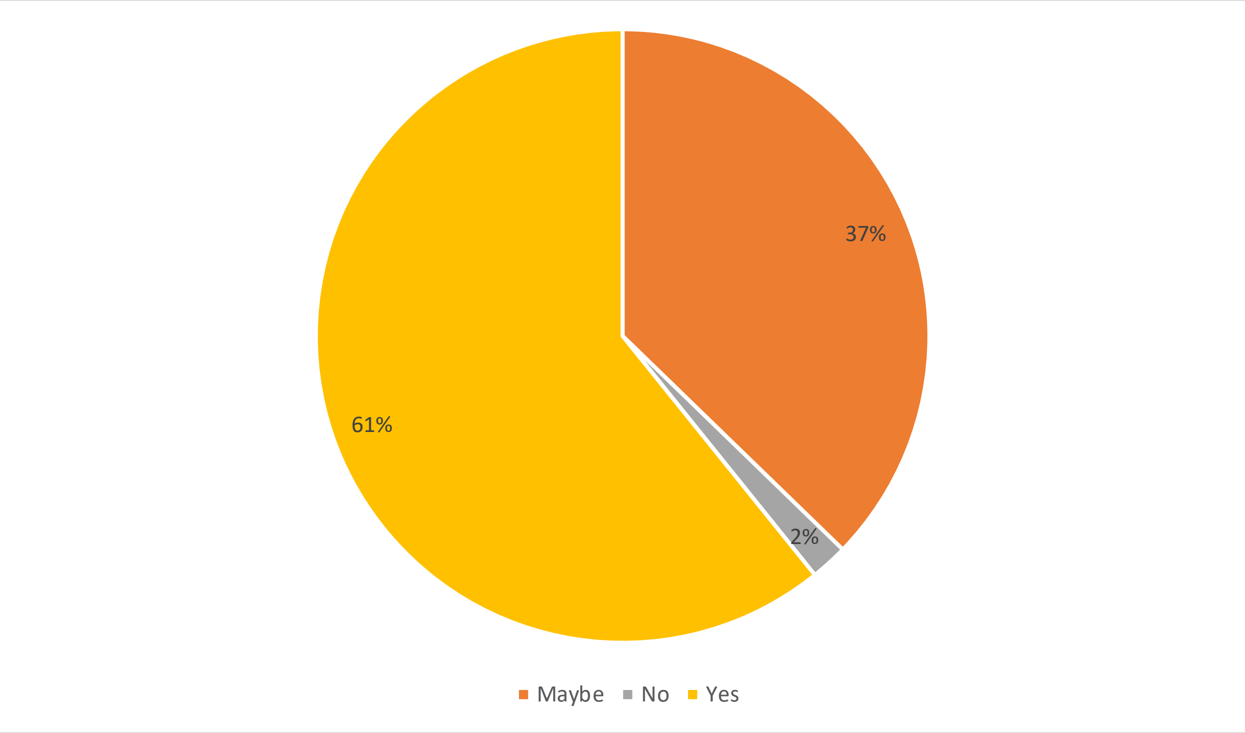


Figure 5-32 Construction role in climate change

The positiveness in this question was higher than in question 21, assuming they share the same goal of climate change ambitions concerning GHG emissions.

Q.24 Do you think that construction projects will abandon fossil fuel resources in the near future?

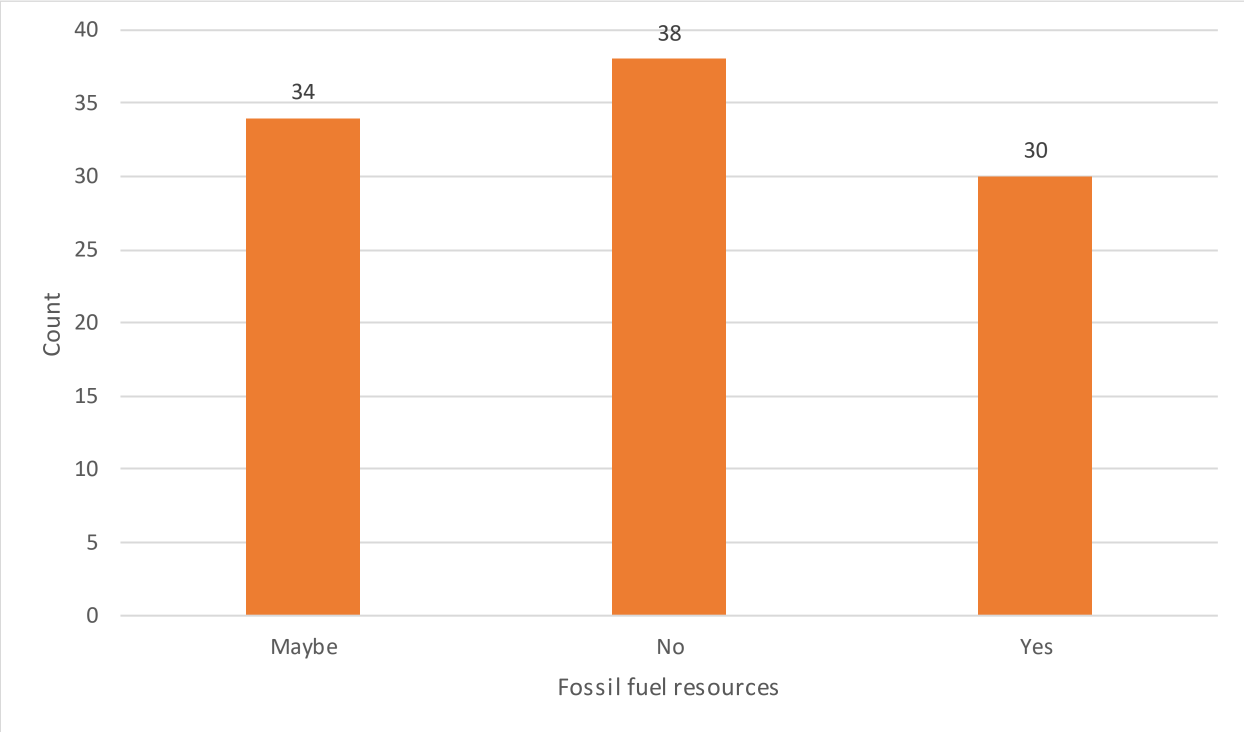


Figure 5-33 Fossil fuel dependency

Respondents expressed uncertainty about completely phasing out fossil fuels. This study recommends optimising and efficiently managing existing energy resources rather than entirely replacing them with untested or insufficiently experienced alternatives or technologies. This approach would retain fossil fuels as a backup for future replacements, incentivising ongoing innovations in their more efficient use.

However, this inquiry specifically focused on the construction industry, recognising that while other sectors may strive for independence from fossil fuels, the military and weapon industries will likely remain heavily reliant on them for an extended period.

Q.25 Which of the following organisations are most familiar to you?

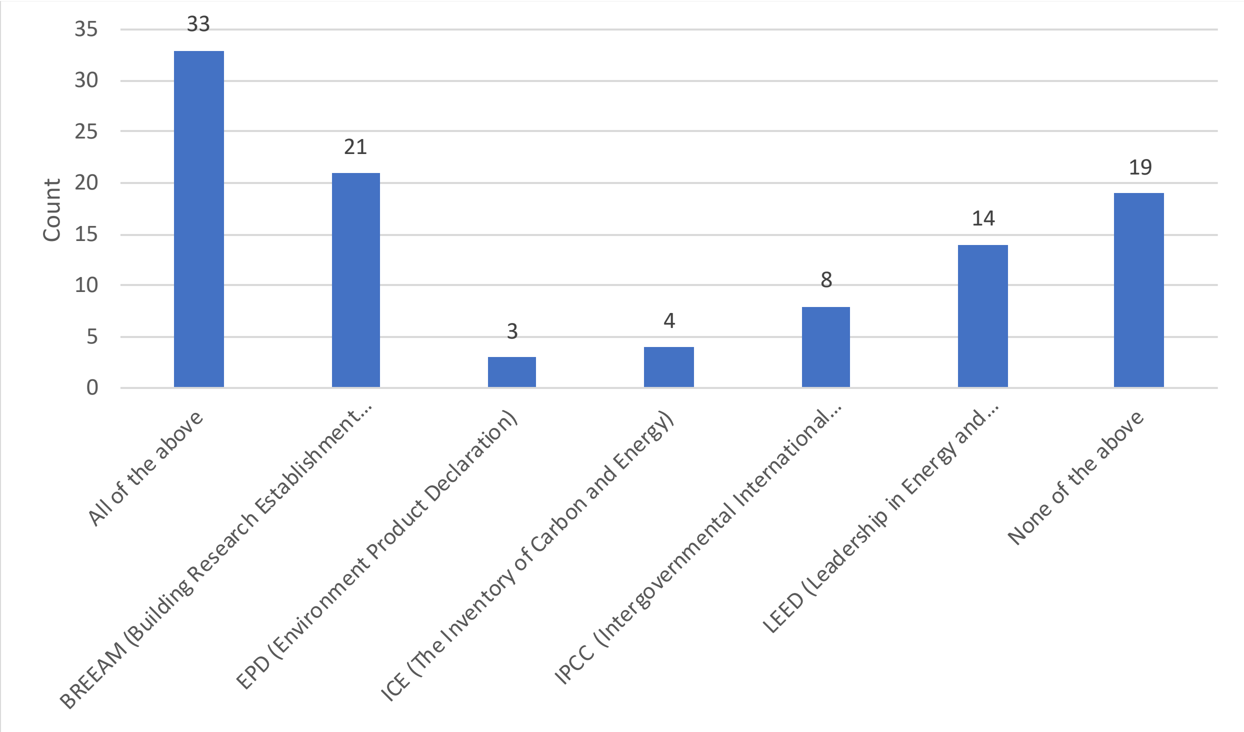


Figure 5-34 Popular organisations

To deeply understand the relevancy and importance of this question, Table 5-18 was conducted concerning the country and region of the respondents and linked to their answers.

Table 5-18 Case summaries

				Country or region of profession
Which of the following organisations are most familiar to you?	All of the above	1		United Kingdom
		2		United Kingdom
		3		Greece
		4		United Kingdom
		5		United States
		6		United Kingdom
		7		United Kingdom
		8		United Kingdom
		9		United Kingdom
		10		United Kingdom
		11		United Kingdom
		12		United Kingdom
		13		United Kingdom
		14		United Kingdom
		15		Jordan
		16		Jordan
		17		Saudi Arabia
		18		United Kingdom
		19		Jordan
		20		Egypt
		21		United Kingdom
		22		United Kingdom
		23		Jordan
		24		Switzerland
		25		Jordan
		26		United Kingdom
		27		United Kingdom
		28		United Kingdom
		29		India
		30		Jordan
		31		United Kingdom
		32		United Kingdom
		Total	N	32
	BREEAM (Building Research Establishment Energy Assessment)	1		United Kingdom
		2		United Kingdom
		3		United Kingdom
		4		Belgium

		5	United Kingdom
		6	United Kingdom
		7	United Kingdom
		8	United Kingdom
		9	United Kingdom
		10	United Kingdom
		11	United Kingdom
		12	Jordan
		13	United Kingdom
		14	Jordan
		15	United Kingdom
		16	Netherlands
		17	United Kingdom
		18	United Kingdom
		19	Jordan
		20	United Kingdom
		21	United Kingdom
		Total N	21
	EPD (Environment Product Declaration)	1	Jordan
		2	India
		Total N	2
	ICE (The Inventory of Carbon and Energy)	1	United Kingdom
		2	United Kingdom
		3	Chile
		4	United Kingdom
		Total N	4
	IPCC (Intergovernmental International Panel on Climate Change)	1	United Kingdom
		2	United Kingdom
		3	Morocco
		4	United Kingdom
		5	United Kingdom
		6	United Kingdom
		7	Bangladesh
		8	United Kingdom
		Total N	8
	LEED (Leadership in Energy and Environmental Design)	1	United States
		2	India
		3	Egypt
		4	India
		5	United Kingdom

		6	Algeria
		7	Sri Lanka
		8	United Kingdom
		9	Greece
		10	Jordan
		11	United Kingdom
		12	UAE
		13	Egypt
		14	Greece
		Total N	14
	None of the above	1	United Kingdom
		2	Netherlands
		3	Netherlands
		4	United Kingdom
		5	China Hong Kong
		6	United Kingdom
		7	Jordan
		8	Jordan
		9	Jordan
		10	United Kingdom
		11	United Kingdom
		12	Jordan
		13	United Kingdom
		14	United Kingdom
		15	United Kingdom
		16	United Kingdom
		17	Australia
		18	United Kingdom
		19	United Kingdom
		Total N	19
	Total	N	102

a. Limited to first 100 cases.

Firstly, a substantial portion (32%) of the respondents demonstrated familiarity with all the organisations. Secondly, it was evident that BREEAM enjoys more significant popularity, particularly in the UK and Europe, although its recognition is comparatively lower in the USA and China. Thirdly, LEED secured the second position with just 14% of respondents, but this figure should be considered in the context of regional variations. For instance, the responses might vary considerably if this research were conducted in the USA or China. Fourthly, 19% of respondents selected "None of the above", which is concerning, particularly given that all participants possess substantial academic or practical expertise in their field.

5.3 Qualitative Data

The qualitative data collection approach gives good validity, reliability, and generalisability to the research (Collingridge and Gantt, 2008). However, it must avoid bias, especially when analysing the collected data (LeCompte 2000). Moreover, qualitative research emphasises exploring and understanding the collected data (Almalki, 2016).

Qualitative data will have two approaches used to collect and analyse data: case studies and interviews; further, it is expected to explain and define the data collected in a quantitative approach, in a convergent parallel strategy. The map is presented in Figure 5-35.

Research Objectives 3, 4, and 5 will be reflected in this qualitative methodology, where case studies investigated the role of embodied carbon emissions in construction projects, both general large-scale projects and high-rise ones in particular, as illustrated in the next section.

Moreover, objectives 4 and 5 regarding examining high-rise projects in terms of sustainability and standardising criteria for decarbonising the construction industry will be studied in experts' opinion through semi-structured interviews.

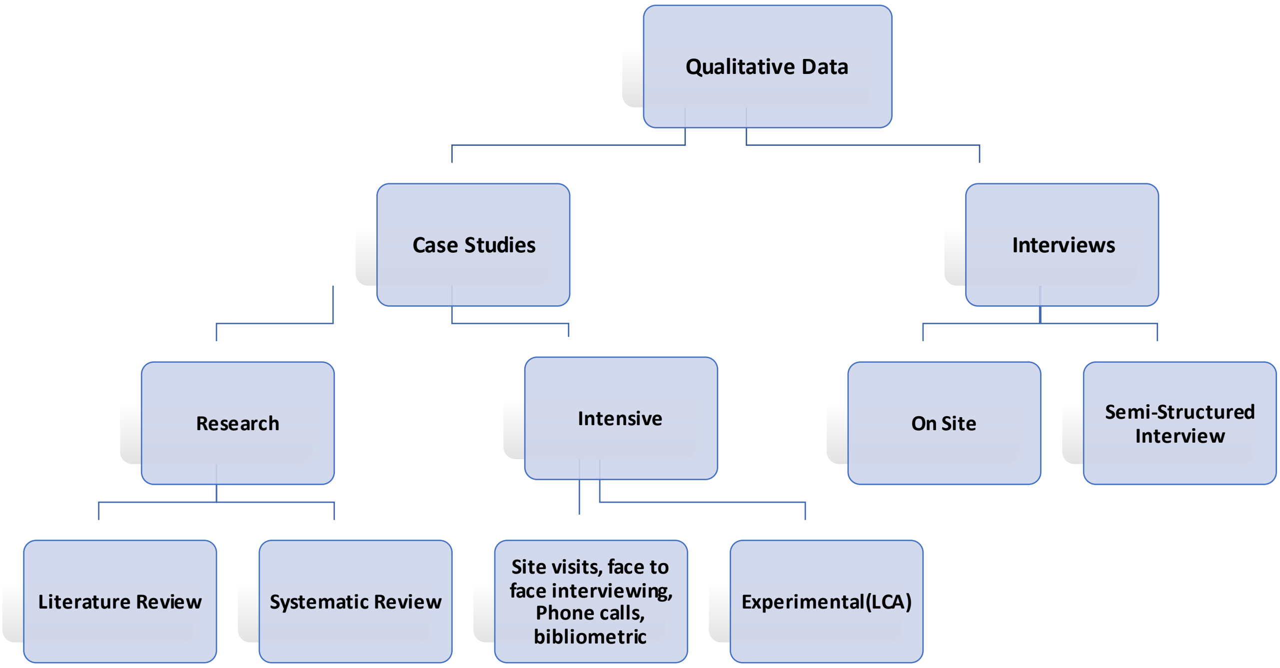


Figure 5-35 Qualitative data collection structure

5.3.1 Case Studies

(Yin, 2018) had expressed concerns about using case studies, such as many times, the case studies investigator needs to follow systematic procedures, which allows the production of a biased view that might influence the direction of the findings and conclusions. However, (Crowe, 2011) explained the benefits of the case study approach which proves highly valuable when seeking a comprehensive understanding of a specific issue or event. Additionally, it aims to provide an overview of crucial methodological considerations encompassing the design, planning, analysis, interpretation, and reporting aspects of conducting case studies.

According to Yin's book (2009), the case study is a versatile research method to enhance our understanding of individual, group, organisational, social, political, and related phenomena. Unsurprisingly, the case study has become widely utilised across multiple industries due to its unique ability to address social phenomenon complexities method effectively, permitting investigators to capture and retain the holistic and meaningful aspects of real-life events, encompassing life cycles, small group behaviour, organisational and managerial processes, and the evolution of industries, among others.

This research will prominently employ the case study methodology as a supplementary approach, serving two essential purposes. Firstly, it will be a valuable backup to corroborate and enrich the findings obtained through other data collection methods: quantitative databases generated by bibliometric studies and questionnaire surveys. By incorporating the case study method, the research aims to strengthen the validity and reliability of its conclusions by triangulating the results with different sources of evidence. Then, the qualitative interview will examine the validity of the data.

Secondly, the case study methodology will be critical in generating a more comprehensive and objective numerical database. This aspect is particularly crucial as it facilitates the incorporation of quantitative data, allowing for a more in-depth analysis of the research subject. By integrating qualitative and quantitative data from case studies, the research endeavours to attain a more robust and multifaceted understanding of the phenomenon under investigation.

The case study approach captures real-life scenarios in their natural context, allowing in-depth exploration of complexities and interactions. This qualitative method provides valuable insights and helps identify patterns and trends for a broader theoretical framework, enriching scholarly knowledge.

Incorporating the case study methodology in this research is intended to serve as a complementary approach to validate and complement other data collection methods and develop a more comprehensive and objective numerical database (Robert K. Yin, 2014). By embracing the strengths of the case study method, the research endeavours to enhance its overall rigour and contribute significantly to the existing body of knowledge within the relevant field of study.

This research's case studies unit of analysis is large-scale and prefabricated construction projects focusing on high-rise projects. Furthermore, the sampling method for case study data collection was used.

The unit of analysis in these case studies will be sophisticated to unique large-scale and high-rise building projects, focusing on environmental aspects and reduction of embodied carbon emissions.

The case studies will be divided into two types. The first type is on-site investigated projects, and the other type is based on academic literature research studies (bibliometric). Both types of environmental sustainability will be examined intensively, focusing on embodied carbon emissions.

Methods of collecting data will include site visits, interviews, emails, phone calls, reviewing old and recent research studies, conference papers, and region or country regulations. All will be utilised to examine the database's validity and reliability and reflect a credible critical analysis. See Figure 5-36.

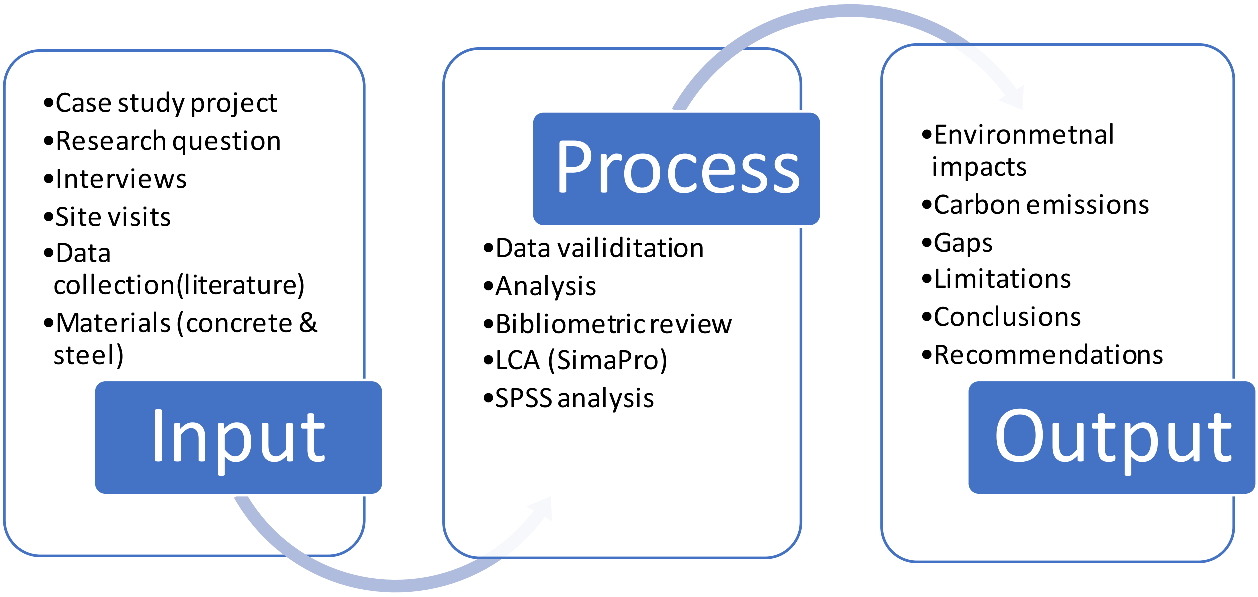


Figure 5-36 Input-Output Process

(Säynäjoki et al., 2017) discussed that integrating sectoral environmental burden data into Input-Output (IO) tables enables the evaluation of a transaction's environmental impacts across the entire economy, achieving a theoretically complete system assessment like the IO-LCA. This method considers capital and infrastructure requirements, overcoming the truncation bias observed in process LCA. However, pure IO- LCAs suffer from a distinct downward bias due to the absence of 'gate-to-grave' emissions assessments, covering the entire lifecycle from the use to the decommissioning phases.

Although (Shao et al., 2014) utilised the Bill of Quantities (BOQ) for quantifying embodied carbon through LCA and claimed to provide an accurate impact assessment, their study had certain limitations. For instance, it did not consider the indirect carbon emissions associated with construction projects and assumed that the case studies all used reinforced concrete. In contrast, the case studies discussed in this context determined not to use BOQ because it cannot determine sustainable methods or provide precise information on the carbon emissions emitted during manufacturing, transportation, or on-site practices.

Instead, the following six intensive case studies employed LCA through the SimaPro software 9.5 database. This approach was chosen to determine and analyse the environmental impacts, particularly those related to the mega projects examined in the selected case studies. Nevertheless, it is crucial to acknowledge that the reliability and usefulness of this analysis hinge on the accessibility and credibility of the utilised database. SimaPro 9.5 relies heavily on *ecoinvent*, an organisation based in Zurich, Switzerland, committed to gathering top-tier data for global sustainability evaluations (Ecoinvent, 2023). The Life Cycle Impact Assessment (LCIA) conducted in the case studies will employ the same LCA software.

They are already embedded in the LCA analysis, which focuses more on the impact of using materials on the required classifications of environmental impacts. In contrast, climate change and air emissions are the designated impacts in this research.

When using LCA software for analysis, weighting and normalisation are complementary approaches to assess the environmental impact of different processes or products. Also, there is the characterisation approach, oriented towards numbers rather than indicators, and the grouping approach (Rosenbaum et al., 2017).

In this data collection section, the research focuses more on environmental impacts from a qualitative perspective; thus, a characterisation approach was given to climate change because embodied carbons play a significant role in climate change (Globally, 2018).

Normalisation involves comparing the environmental impact of a specific process or product to a reference value, such as the average impact of all processes or products in each category, which helps to put the impact into perspective and understand its significance. Moreover, normalisation helps compare different processes or products within the same category and identify areas of improvement (Cucurachi et al., 2017).

Conversely, weighting assigns weights or importance factors to different environmental impact categories based on their relative significance. Weighting in LCA enables the identification of emissions, resources, life cycle steps, or processes that significantly contribute to the overall environmental impact, facilitating the search for technical solutions to optimise environmental performance according to the chosen method. It identifies critical areas where improvements can be made and helps determine break-even points when the ranking of different product concepts changes based on input parameters. Weighting is a valuable tool for pinpointing focus areas and making informed decisions to minimise environmental impact (Bengt, 2000).

Both weighting and normalisation are valuable tools in LCA software as they provide a more holistic understanding of the environmental impact (Prado et al., 2020). However, the selected approach when analysing the case study will depend on the weighting method. Table 5-19 summarises the essential differences among normalisation, grouping, and weighting in research conducted by (Chau et al., 2015).

Table 5-19 Processes used in LCA software analysis (Chau et al., 2015)

Aspect	Definition	Purpose	Problems
Normalisation	The calculation of the magnitude of category indicator results relative to some reference information	It helps to understand the relative importance of different impact categories in LCA studies	Uncertainties in emission data and characterisation factors can lead to uncertainties in normalisation results
Grouping	The aggregation of impact categories into one or more sets	Allows for a more concise and easier-to-understand presentation of the results	It can oversimplify the results
Weighting	The conversion of indicator results of different impact categories into a single score	Allows for a comparison of the results across different impact categories	There is no consensus on the approach or a satisfactory method to guide the assignment of weightings

However, only steel and concrete will be examined through LCA software due to their size and contribution to environmental impacts as explained through the literature of this research, particularly described by (Teng and Pan, 2020) as being traditionally critical carbon contributors. Glass for example, will be examined to present the difference compared to steel and concrete. Furthermore, (Zhang et al., 2023) describe them as dominant contributors. Moreover, they are the most critical materials affecting embodied carbon emissions. Moreover, according to (Government Commercial Function, 2022), "*over half of which is linked to construction product and materials production, particularly materials such as steel and cement, account for around 15% of global carbon emissions*". Moreover, (Shao et al., 2014) stated that: *"the steel and concrete inputs are the two largest energy consumption and carbon emission sources among the 22 related production sectors"*.

The selected approach is explained in **Appendix 7**. However, the LCA is designated to examine the whole life span of the project; thus, operational energy is included in the assessment. This research assumes that the effect of operational energy has recently been minimised within the available clean and renewable energy resources, which can reach zero operational emissions, according to many studies and projects illustrated in the literature review. Moreover, operational energy is more oriented toward using buildings rather than material processes. This hypothesis was illustrated thoroughly in Chapters One and Two.

To comprehensively assess the carbon emissions linked to climate change, targeted case studies will focus on prominent architectural landmarks with readily available data and projected significant environmental impacts.

These case studies include an examination of carbon emissions using the LCA software from the Burj Khalifa, The Shard, Empire State Building, SPECS, and The Shanghai Tower. By analysing the environmental footprints of these iconic structures, we aim to gain valuable insights into the carbon-intensive nature of large-scale construction projects and their implications for climate change mitigation efforts.

Table 5-20, extracted from Yin's book (2014), provides the main outlines for the structure and content of each case study, guiding the research process accordingly, which will be subjected implicitly and explicitly in each case study.

Table 5-20 Case studies approach (Robert K. Yin, 2014)

METHODOLOGICAL TOPIC	ILLUSTRATIVE CONTENT
1. Overall, Tone	*Thoughtful, balanced, and transparent tone*
2. Research Questions	*Suit the case study research*
3. Design	*Definitions, how selected, the logical connection, rivals that were considered*
4. Overview of rest of methodology section	*A summary of the data collection and analysis methods*
5. Data Collected	*Verifying the data, unexpected difficulties, case study protocol*
6. Analysis Methods	*Description of tools and software*
7. Caveats About Study	*Inherent shortcomings in the design and analysis and how the shortcomings might have influenced the findings*

Figure 5-37 was designed to explain the framework for collection and analysis of the database of case studies, while Figure 5-38 is the framework specified for LCA calculation and analysis process.

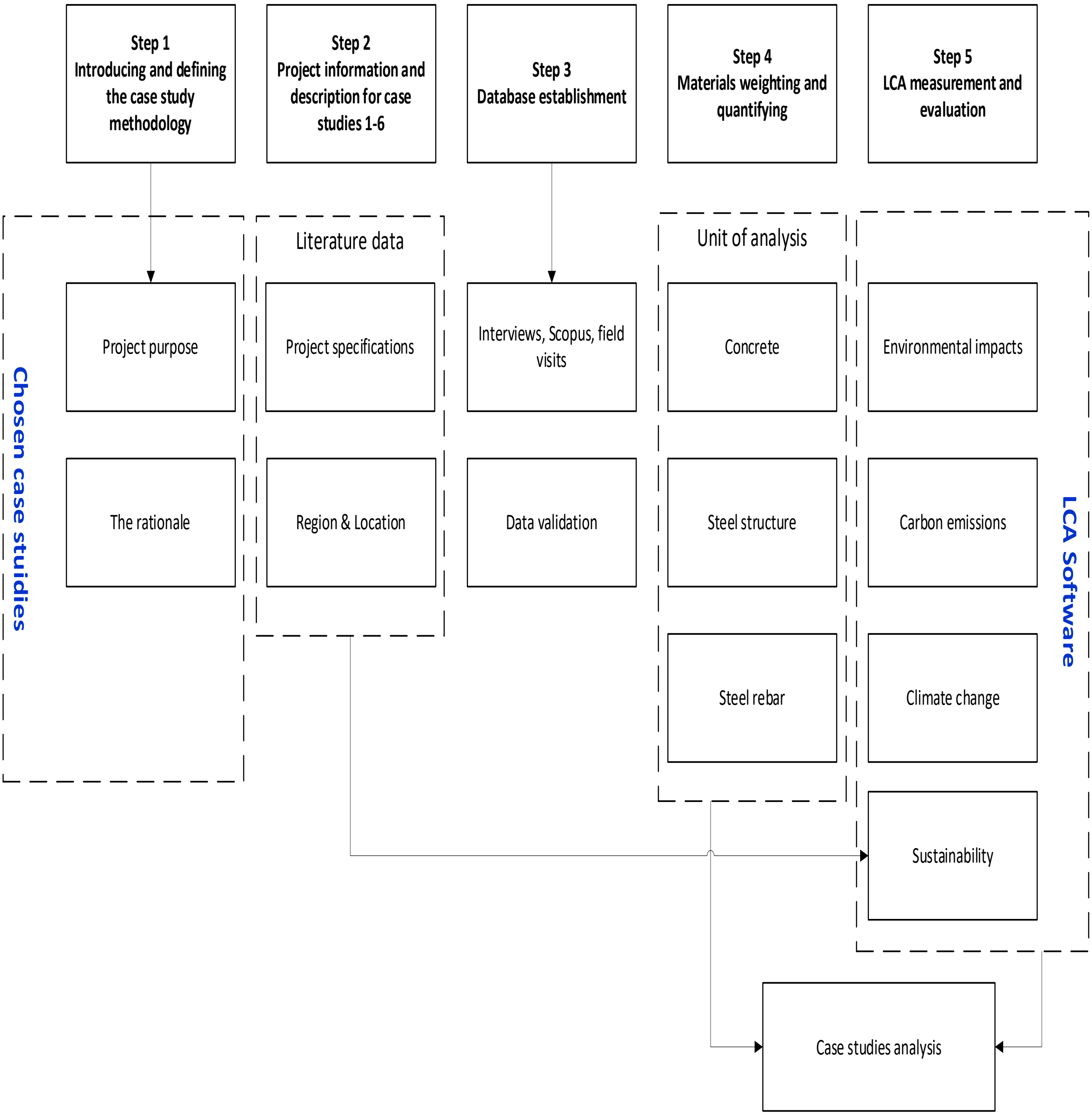


Figure 5-37 Case studies process

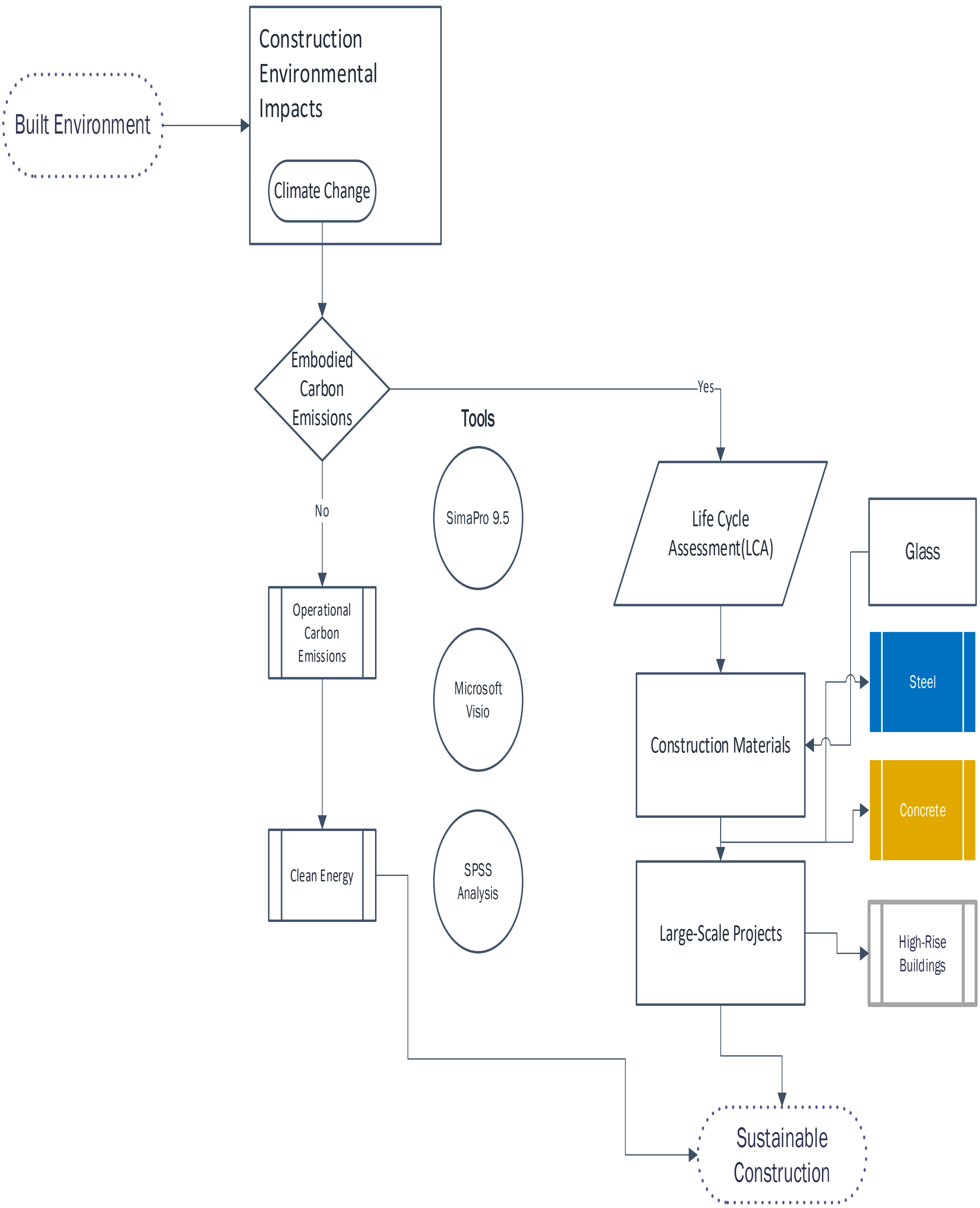


Figure 5-38 LCA application process on case studies

1. Intensive Case Studies

Case Study 1: University of Hertfordshire SPECS Project

Figure 5-39 SPECS Project (University of Hertfordshire, 2022)

Project details

Location	Hatfield/UK
Size	15,000 m^2
Budget	£ 89M
Building type	Five-storey steel frame
Building purpose	To host the School of Physics, Engineering and Computer Science.
Date of commencing	2022
Date of completion	2024
Main contractor	Morgan Sindall
Designer	Morgan Sindall

1. Project Background

The project is located at the University of Hertfordshire. The University's new building for the School of Physics, Engineering, and Computer Science (SPECS) will transform students' education. It will respond directly to the UK skills gap, inspiring and investing in the next generation of engineers, computer scientists, and physicists.

Moreover, this research is interested in the construction and engineering of the project, which will be explored through multiple tools, such as site visits, interviews, and literature review.

2. The Rationale

Designing and aiming to build a unique modern large-scale project should give a good reason for the SPECS project to be a case study; moreover, the researcher had exclusive access to the project.

The SPECS project will be examined to see how it concludes innovative design and state-of-the-art construction techniques that can be used to create sustainable buildings that meet the needs of modern society. The project focuses on energy efficiency, water conservation, and waste reduction to set a new standard for sustainable construction practices. As a result, it shall provide a valuable case study for students, architects, engineers, and researchers to learn from and apply to future projects.

Furthermore, like the research location, the project's location provides a unique opportunity to gather first-hand data on the building's performance, energy consumption, and environmental impact. This valuable information can further optimise the building's system and inform future sustainable building practices.

The United Kingdom has a significant advantage in implementing sustainable solutions, particularly in the construction sector. This sector is dedicated to reducing carbon emissions, minimising environmental impacts, and addressing climate change (Defra, 2019; Government Commercial Function, 2022; Marvin and Weetman, 2008; Mayor of London, 2015; UK Green Building Council, 2021).

3. Introduction

The SPECS project was taken as a case study in this research for several reasons, specifically that it applies to most of the research topic, as it is a large-scale project in terms of size, cost, and complexity, and it is claiming to be a sustainable project from cradle-to-grave, which has been investigated.

The project is a large-scale endeavour in size, cost, and complexity. Additionally, the SPECS project claims to be sustainable throughout its life cycle, from inception to disposal. Further investigation and explanations regarding its sustainability will be provided later in the research.

As mentioned in the rational section, it was a preferable case study project mainly due to its location, which is just the exact location of the research. This location gives it better follow-ups and accesses, in addition to the reasons mentioned earlier.

The United Kingdom is at the forefront of the decarbonisation process in the construction industry, actively and rapidly taking steps to mitigate environmental impacts, particularly those related to embodied carbon, to address climate change (Globally, 2018).

Morgan Sindall, the first tear UK construction company, will ensure that the development will be delivered under the Southern Construction Framework (SCF), a quality-managed collaborative construction framework for public bodies to procure major building works using a two-stage open book process to deliver the best value (Morgan Sindall, 2022).

As part of the Considerate Contractors Scheme, the construction company must deliver the project using best practices beyond statutory requirements. Considerate Contractors Scheme is "*a not-for-profit, independently run organisation that supports and guides positive change in the construction industry*" (Considerate Contractors Scheme, 2022).

4. Construction

The construction phase, as described by the cradle-to-site scenester, will be the centre of the SPECS case study. Furthermore, as explored in the research, the embodied carbons associated with construction activities in the cradle-to-site phase, and even with destruction and recycling works, were the critical engine of the research. Especially that embodied carbon impacts continue being ignored, as (Moncaster and Malmqvist, 2020) stated that this carbon impact has pushed governments, institutions, and construction companies to deliver environmentally sustainable projects.

Since the design and planning of the SPECS project, and through the construction works, the project has aimed to deliver environmental and sustainable practices in materials selection, concrete mixing and casting, steel framework, excavation, site offices, health and safety, and many others. All will be assessed and explored intensively during site visits, meetings, and interviews with project staff members.

Therefore, this case study focuses on the SPECS project's construction phase, specifically its embodied carbon impacts. The aim is to identify and analyse the project's sustainable practices, challenges encountered, and lessons learned. The findings of this study will contribute to developing a more sustainable construction industry by providing insights into the practical implementation of sustainable practices.

5. Planning and Design

The project's planning was set to deliver a sustainable construction project as introduced by using all possible technologies and practices on-site and off-site, all of which will be illustrated later in this case study.

The project's design, presented externally in Figure 5-40, aims to deliver a sustainable operating building in terms of air quality, clean energy, waste reduction, natural lighting, and thermal insulation.

Figure 5-40 Project external design

6. Construction Process

According to the designers, engineers, and construction managers, the project is socially, economically, and environmentally sustainable, as shown in their plan to achieve an excellent grade in the BREEAM classification. Additionally, constructing a building for engineering faculty requires setting an excellent example of sustainability and eco-friendly construction methods.

The sustainability applications were set from the beginning phase of planning and design, shown in the building design and drawings, through the construction practices, and into the building's operating functions by creating a world-leading facility that completes the building to the highest possible standards.

7. Site Preparation and Excavations

All necessary field tests, especially soil and ground tests, were examined before the land preparation and foundation installation. Then, concrete pile foundations were made using high-graded concrete specifications to deliver the best bearing capacity for the building's structural loads.

The foundation process and 17 cm floor slabs were the only ones that required casting concrete in situ, while the remaining concrete works were done off-site, as will be explored afterwards.

Figures 5-41 and 5-42 present the construction preparation process before the foundation installation.

Figure 5-41 Excavation and site preparation

Figure 5-42 Site preparation and levelling the ground

8. Material Selection

The SPECS project will assess material selection due to its vital role in environmental impacts, especially embodied carbon emissions, as introduced in the research.

The main structure consists of steel columns and beams, while shear walls used for lefts used prefabricated reinforced concrete elements.

8.1 Concrete

The building floor slab design was made to use the minimum amount of concrete to deliver a sustainable practice and minimise the weight load of the building. At the same time, steel corrugated sheets were installed beneath each floor slab. Such a system had the following advantages:

1. No formwork is required, eliminating wasting time and materials

2. Making a concrete slab of 17.5 cm reduces the embodied carbons associated with producing large amounts of concrete, especially when a minimum of 30 MPa concrete mixes are used

3. Less concrete means better handling by workers, assuring the best compatibility of finishing

4. Water usage is reduced in concrete production by excluding any in-situ concrete works

5. Less concrete transportation is used, according to the location of ready-mix concrete plants

Figure 5-43 shows the concrete slabs installed.

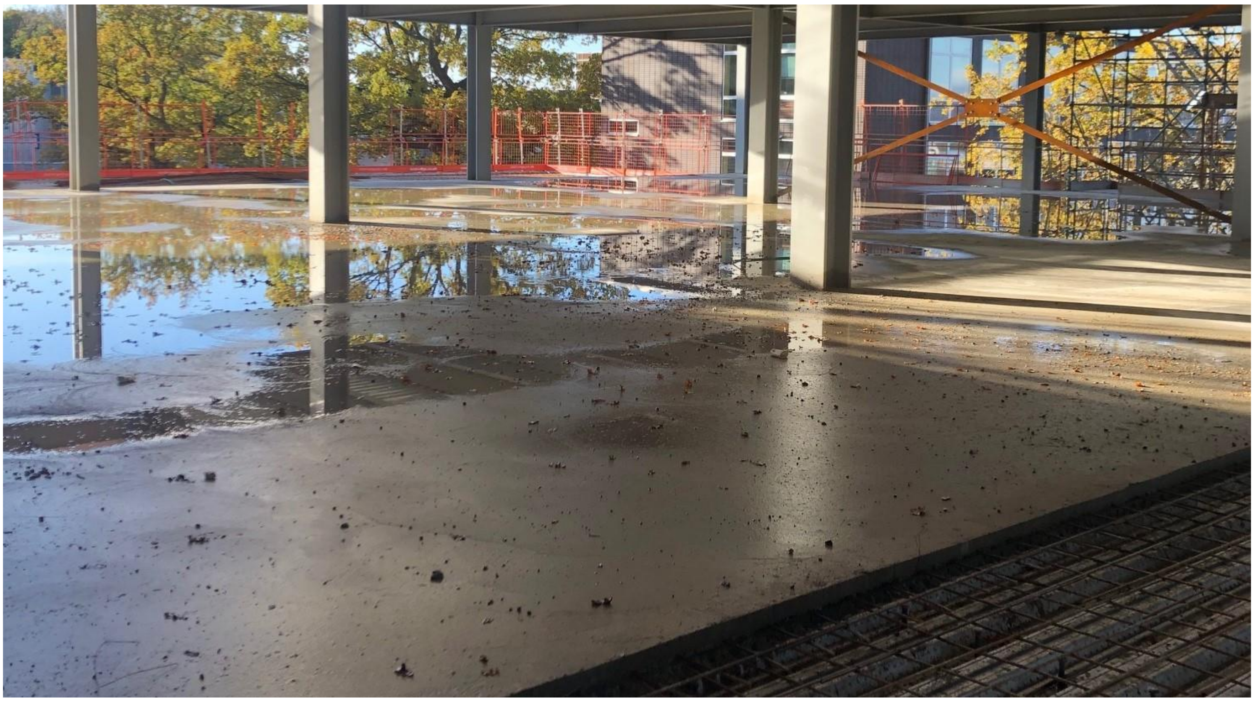


Figure 5-43 Typical floor slab in SPECS Project

Lifts had two separate towers containing shearing walls, using an off-site system as introduced. They were designed and manufactured before usage, upon the required design and specifications.

The installation of two main (concrete towers), dependency delivering the precast ready wall elements on site by special lorries, transferred to the prepared location, then stacked upon each other, depending on steel rods already planted in each wall. This procedure reduces the time, materials, and workers, resulting in a sustainable construction method because it reduces the environmental impacts, including carbon emissions.

Figure 5-44 presents the process of concrete wall installation.

Figure 5-44 Prefabricated concrete transporting

After installing each concrete wall, project staff used grout materials to fix and fill the gaps between each wall, which resulted in a smooth, straight surface of the concrete towers.

Figure 5-45 Concrete towers

The project’s security walls were installed environmentally and sustainably, and no in-situ cement or concrete was used as a foundation. Instead, portable concrete foundation units were used, giving the advantage of removing them after finishing the project without the need to demolish anything. See Figure 5-46.

Figure 5-46 Temporarily foundation supporters for the site wall

The SPECS project implemented sustainable practices in the building floor slab design, lifts, and security walls. Using minimum concrete and installing steel corrugated sheets helped minimise the weight load of the building and reduce the environmental impact associated with large amounts of concrete production.

Additionally, using prefabricated shearing walls and portable concrete foundation units reduced the usage of materials, time, and workers, resulting in a sustainable construction process. These practices demonstrate the project's commitment to sustainability and the importance of considering environmental impacts in construction projects.

8.2 Steel

The incorporation of steel in construction has emerged as a pivotal advancement. Not only does steel offer remarkable versatility, but it also undergoes off-site manufacturing through sophisticated fabrication technologies. This allows for the precise and uniform production of all necessary building components, encompassing slab sheets, columns, beams, and staircases (Refer to Figure 5-47).

Using off-site manufacturing significantly slashes construction timelines, facilitating projects to achieve unprecedented completion speeds. Furthermore, steel's complete recyclability enables any generated waste during fabrication to be easily repurposed or sold, thereby reducing the environmental footprint of the construction process.

The benefits of OSC practices are multi-dimensional. By minimising material waste and labour costs, construction expenses plummet while enhancing the final product's quality. Additionally, manufacturing components within a controlled environment drastically diminishes error probabilities, ensuring a more consistent and dependable end product.

Adopting OSC practices in steel construction has transformed the construction sector. By saving time and curbing environmental impacts, this technology empowers builders to erect efficient and environmentally conscious structures. Through this process, steel emerges as an even more appealing choice for constructing resilient and sustainable buildings for the future.

Figure 5-47 Steel columns and beams installation

8.3 Construction Practices

As shown in using concrete or steel elements, most of the possible sustainable practices were used besides the following methods.

8.3.1 Transportation and Machines

HVO and hybrid machines were used throughout the project, significantly mitigating carbon emissions.

8.3.2 Site Offices

The temporary site offices showed a highly sustainable practice, starting with prefabricated offices installed on a non-concrete foundation of reusable rubber mats. Shown in Figure 5-48.

Figure 5-48 Site offices

8.4 Health and Safety

Health and safety equipment, including safety boots, glasses, reflective vests, and helmets, were always mandatory for labourers and visitors. Moreover, the following safety procedures were noticed at the construction site:

1. Safety guardrails were installed simultaneously with the steel H beams located on the edges of the building
2. Noise pollution was minimised
3. Emergency kits were available everywhere

4. Fire extinguishers and hoses were provided sufficiently
5. Welding workers were provided with extra protective shields

Safety nets with unique designs that disallow objects to rebound if they fall on them. See Figure 5-49.

Figure 5-49 Typical floors safety net

8.5 External Façade

The cladding process of aluminium frames and glass was dynamic and fast, and mechanical scaffolds were used to install the elements at the right time and place. Figure 5-50 shows the process of cladding in the front façade.

Figure 5-50 Façade claddings

9. Sustainability and Carbon Footprint

The SPECS project aims to achieve an Excellence rating by BREEAM, which was noticed by the project's sustainable practices and attention to detail. This case study believes that an Excellence rating will probably be granted. No environmental impacts were noticed, and very available sustainable practices were adopted in the construction phase, such as OSC for concrete, steel, site offices, and others.

In the operational phase of the building, many sustainable practices will be used, as introduced at the beginning of this case study, such as renewable energy resources, grey water systems, natural ventilation, smart lighting systems, and others.

The concrete used in floor slabs will be subjected to the LCA software to evaluate this.

The slab concrete volume is:

$$\boldsymbol{Vs = A \times D}$$

Equation 6

V= 15000 m^2 × 17.5 cm = 2625m^3

Where A is the flat area, D is the depth of the concrete slab, V is the volume of concrete, and the concrete used in slab design is grade 30MPa.

Figure 5-51 presents the results of LCA analysis using LCA software, adopting the method of Environmental Footprint 3.1. There were two types of concrete: the first was based on unit and referred to by (U), and the second was based on system and referred to by (S).

System analysis was adopted in this database, which was justified by having a more general approach. Also, the results were minor between the unit and system approaches. This process is applied to the rest of the case studies.

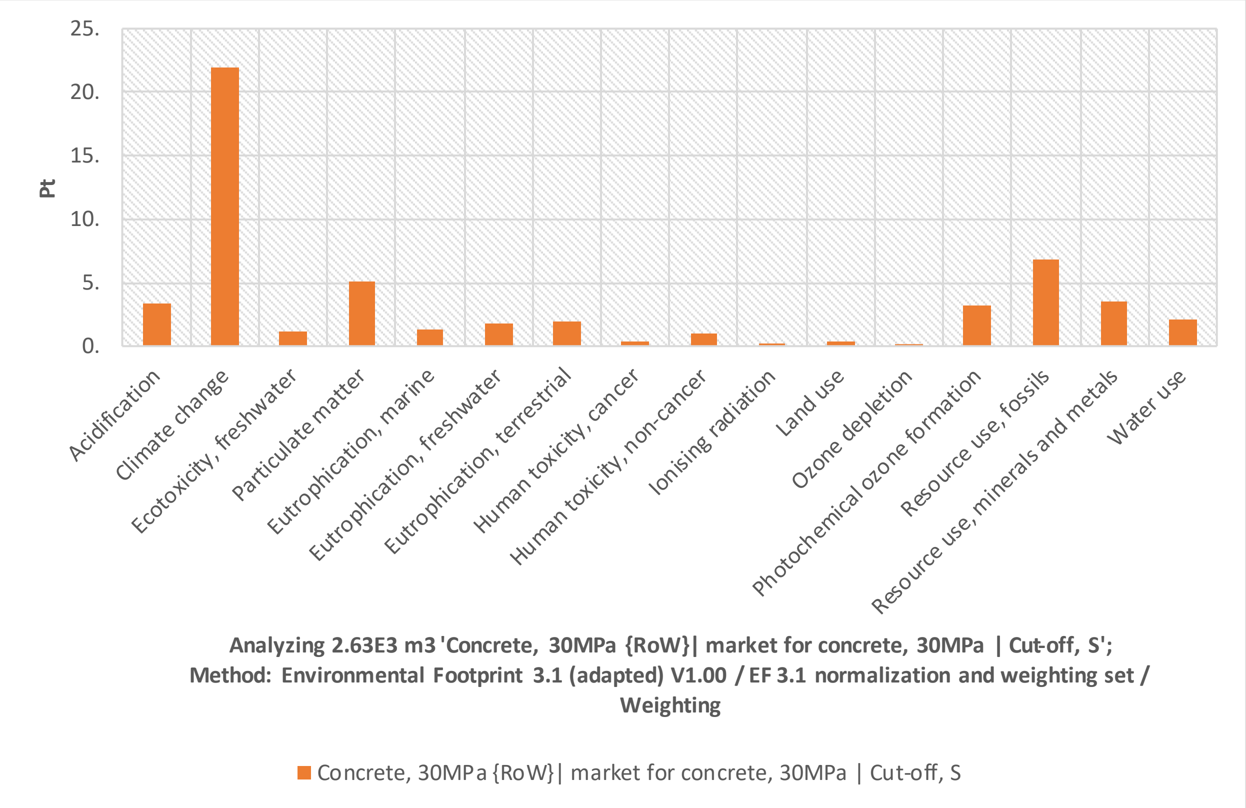


Figure 5-51 Concrete LCA

Climate change impact was the highest according to the LCA analysis of concrete using LCA software, where (pt) is the indicator used by the software to measure and compare the impacts of materials through LCA. So far, the results comply with the literature and data collected in this research. Moreover, Table 5-21 was extracted from the same software to address the most influential impacts associated with climate change.

Table 5-21 Climate change airborne emissions

Compartment: Airborne emission | Indicator: Weighting | Cut-off: 0% | ☐ Default units
☐ Per sub-compartment | Category: Climate change | ◉ Standard | ☐ Exclude long-term emissions
☑ Skip unused | ○ Group | ☐ Per impact category

No	Substance	Compartr	Unit	Total	Concrete, 30MPa
	Total of all compartments		Pt	22	22
	Total of airborne emission		Pt	22	22
1	Carbon dioxide, fossil	Air	Pt	20.7	20.7
2	Methane, fossil	Air	Pt	1.13	1.13
3	Dinitrogen monoxide	Air	Pt	0.0643	0.0643
4	Methane, biogenic	Air	Pt	0.0206	0.0206
5	Sulfur hexafluoride	Air	Pt	0.017	0.017
6	Carbon dioxide, land transformation	Air	Pt	0.0112	0.0112
7	Methane, tetrafluoro-, CFC-14	Air	Pt	0.00341	0.00341
8	Methane, trifluoro-, HFC-23	Air	Pt	0.000564	0.000564
9	Ethane, hexafluoro-, HFC-116	Air	Pt	0.000407	0.000407
10	Methane, chlorodifluoro-, HCFC-22	Air	Pt	0.000367	0.000367
11	Methane, land transformation	Air	Pt	0.000111	0.000111
12	Ethane	Air	Pt	6.67E-5	6.67E-5
13	Methane, bromotrifluoro-, Halon 1301	Air	Pt	4.95E-5	4.95E-5
14	Methane, tetrachloro-, CFC-10	Air	Pt	3.12E-5	3.12E-5
15	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	Pt	2.38E-5	2.38E-5
16	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	Pt	9.69E-6	9.69E-6
17	Methane, dichloro-, HCC-30	Air	Pt	8.69E-6	8.69E-6
18	Ethane, 1,1-difluoro-, HFC-152a	Air	Pt	8.39E-6	8.39E-6
19	Propane	Air	Pt	2.5E-6	2.5E-6
20	Methane, dichlorodifluoro-, CFC-12	Air	Pt	2.48E-6	2.48E-6
21	Butane	Air	Pt	1.31E-6	1.31E-6
22	Methane, bromochlorodifluoro-, Halon 1211	Air	Pt	7.22E-7	7.22E-7
23	Chloroform	Air	Pt	5.78E-7	5.78E-7
24	Ethane, 1,1,1-trichloro-, HCFC-140	Air	Pt	5.31E-7	5.31E-7
25	Methane, monochloro-, R-40	Air	Pt	4.83E-7	4.83E-7
26	Ethane, 1,2-dichloro-	Air	Pt	2.99E-7	2.99E-7
27	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	Pt	1.66E-7	1.66E-7
28	Tetrachloroethylene	Air	Pt	1.46E-7	1.46E-7
29	Methane, trichlorofluoro-, CFC-11	Air	Pt	9.86E-9	9.86E-9
30	Methane, bromo-, Halon 1001	Air	Pt	8.68E-9	8.68E-9

10. Summary and Conclusion

The construction site manager stated that more focus is required for the design phase of the project rather than the construction phase to implement sustainable practices. However, the construction site management must monitor and apply any planned and designed regulations or systems to ensure that the LCA-designated output is achieved. Also, any sustainable practices should consider the cradle-to-site stage, especially when dealing with embodied carbon reductions.

Moreover, the project is based in the UK, where there is a governmental construction 2025 strategy, which includes a report outlining the strategy to digitalise the construction sector by 2025 by promoting intelligent technologies and sustainable growth that includes reduction of the whole-life greenhouse emissions in the built environment by 50% (Koronaki, 2020). SPECS building project can be considered a highly sustainable project from cradle-to-use stages.

Case Study 2: Amman Gate Towers

Figure 5-52 Amman Gate Towers

Location	Amman/ Jordan
Size (floor area)	220,000m^2
Budget	$563 M
Building type	High-Rise towers
Building purpose	Commercial, Hotel
Number of floors	44
Hight	185,160 meters
Date of commencing	2005
Date of completion	2024
Owner	Al Bayan Holding Company Kuwait
Structural engineer	Al Nasser Partners
Main contractor	Al Hamad Contracting Company

1. Introduction

The Amman Gate Towers (AGT) project was chosen as a real-time and on-site case study. They represent an iconic project, the tallest building in Jordan so far—Jordan, where the researcher had a long experience working in the Middle Eastern country as a practicing engineer.

As a modern high-rise project and the highest towers in Jordan, it has had some problems and obstacles throughout its life cycle, which explains the delay in opening the project so far. However, this research assumes that additional environmental issues are being considered, with or without the delay in finishing the construction works. At the same time, this case study will examine and explain these concerns.

Before visiting the project and meeting the project manager and some site engineers, some research papers and news articles were explored to create a base point for investigating the case study, such as safety and health problems that happened during the construction phase, starting with the fire that happened on the eighth floor of the north tower, and the collapsing of three floors of the same tower (Abu-Hamdi, 2017).

LCA analysis was not subjected to this case study because of the scarcity and outdated quantitative database.

2. The Rationale of the Case Study

This project was chosen to demonstrate a complex case study of high-rise projects, especially in the planning and construction phase, and how many challenges and difficulties can counter such projects.

Moreover, being a member of the Jordan Construction Contractors Association (JCCA) and Jordan Engineers Association (JEA), the researcher has a good knowledge of the status of construction in the country of this case study project.

3. Project Problem

The first issue encountered in the research was the need for more research papers or scientific articles about the project, shown clearly in Figure 5-53 in the data collection section. Nevertheless, the project's problems can be divided into economic, political, engineering, planning, and design issues.

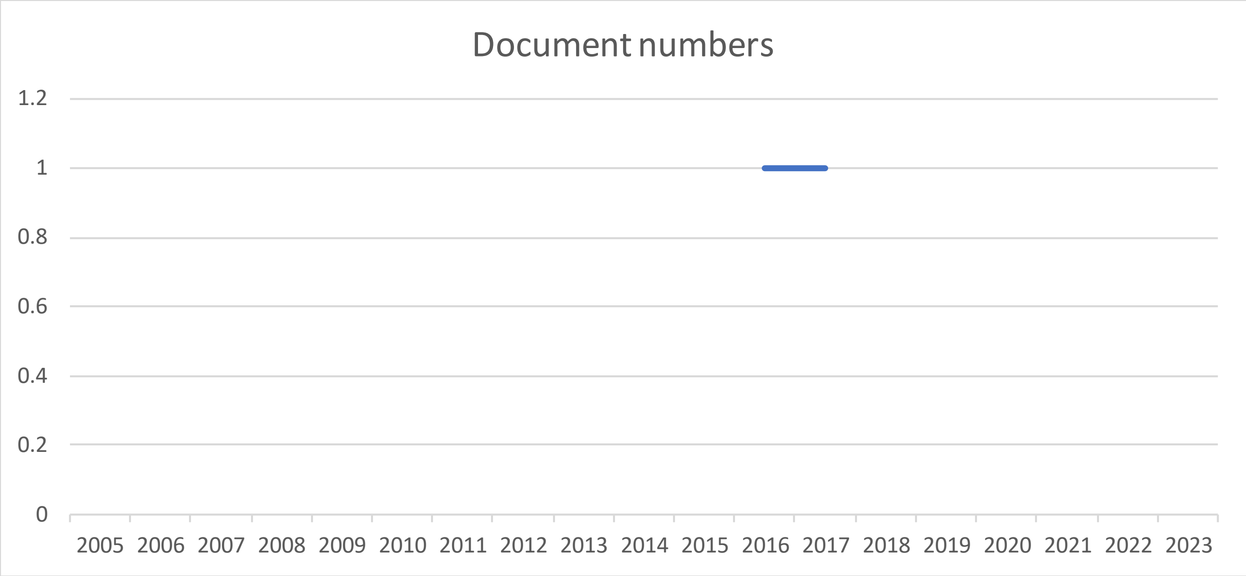


Figure 5-53 Scopus search for AGT project

Only two documents appeared in the Scopus search, showing the role of region or country in research studies. No matter how many sophisticated projects or construction technologies these regions contain, more research still needs to be conducted. The following case studies will demonstrate this.

4. Site Visit

It took much work to be granted permission to visit the project site or meet someone from the project staff, clearly because of the sensitive case of the project, which has faced several financial and planning obstacles since the beginning.

After meeting some residents living near the project location (Om-Uthina), it was learned that they complained about how the project depleted a large area that was initially a green park. Most of them also complained about the daily traffic issues they had to deal with, even before the project was opened.

Moreover, on the political and financial level, the project had several funding problems and a legal tendering process, with Amman Greater Municipality (AGM), Al Hamad Contracting Company, and AL Bayan Holding Company as the parties involved. However, this research is more concerned with the construction and environmental concerns, which started when planning the project location.

The project location, as introduced, was chosen in a quiet residential area without enough access to main highways or services of utilities such as water, electricity, and sewage systems. However, the project insisted on being built, and the estimated completion percentage at the time this case study was written was about 75%, including the total completion of structural works.

The current project manager refused to be interviewed for political reasons even though the Mayor of Amman was contacted to pursue him. The project is now in the finishing stage. However, fortunately, the site civil engineer was interviewed during the construction stage of the project years 2005 to 2007 and stated that the project witnessed both environmental and non-environmental practices during the construction phase.

Environmental practices, according to the site engineer, included the following:

1. Pouring ready mix concrete was done at night to mitigate transportation delays
2. Most concrete casting in situ was monitored, and minimal waste was generated
3. Reusable wood formwork was used most of the time
4. Steel rebars were prepared in cuttings and bending off-site and delivered to the location upon need, which reduced inventory issues

Non-environmental practices, according to the site engineer, were the following:

1. Less recyclable materials were used
2. Electricity used in the construction process was from fossil fuels
3. Cement on-site mixers were old and produced high carbon emissions
4. Delays from consultant engineer checking caused materials stacking, project delays and affected productivity

Figure 5-54 shows the problem of the location of the Amman Gate project.

Figure 5-54 Towers neighbourhood area

5. Construction Phase

Standard construction methods were used in land preparation, excavation, sub-structure, and super-structure works. Moreover, wood formwork was used for columns and slab preparations.

Different concrete grades were used, mainly C50 and C60. In comparison, steel rebars in different diameters were used, including S20, S25, S30, S35, and S40.

6. Sustainability and Carbon Footprint

The interview with the site engineer indicated several things regarding sustainability in the project. It showed a general lack of awareness of environmental concerns in the construction process of all types of buildings, especially high-rise ones.

When asked about the level of awareness, the site engineer answered at a minimal level. Furthermore, questions regarding the type of construction projects that mostly need sustainable solutions were answered that high-rise buildings should apply environmentally sustainable solutions because, according to the site engineer, they are not currently a sustainable method of construction from the cradle to the grave.

The site engineer was needed to discuss embodied and operational carbon emissions; however, he indicated that both should be considered in construction projects. Furthermore, only a few expectations were made regarding reaching net zero emissions by 2050.

Nevertheless, the construction projects in Jordan do not necessarily reflect the status of green building and sustainable construction awareness among academics and engineers because only the cradle-to-gate phase was undertaken in the case study.

Furthermore, as a member of the Jordan Renewable Energy Organization, the author attended the MENA Conference organized by the Jordan Green Building Council (JGBC) in December 2021, which was held in Amman. The author noticed a good level of awareness of environmental impacts and green buildings among the attendants.

Moreover, JGBC is associated with the World Building Green Council (WBGC) and is committed to applying sustainable solutions to carbon emissions in the construction industry (Nugent et al., 2023). However, no interest was shown regarding embodied carbon emissions on any scale, where the word “embodied” has not been found on all JGBC booklets (JGBC, 2018, 2017; Jordan Green Building Council and Friedrich-Ebert-Stiftung Amman Office, 2016), despite that the Global Status Report of Building and Construction 2022 had put Jordan in developed position in terms of energy and sustainability (UN, 2022).

Figure 5-55 shows the main boundaries of interest for environmental sustainability in construction in Jordan.

Feature	Sub-feature	Aspect	Requirement
Sustainable Sites	Pollution	Protecting surrounding environment	Avoiding construction material disposal on streets.
	Management	General safety	All safety standards must be implemented on site.
	Site Design	Green areas	A minimum of **15%** of land area must be planted.
	Heat Islands	Roof area	**50%** of roof - light colored, UV absorption constant, planted and a minimum solar reflection index of **0.7.**

Figure 5-55 Jordan GBC mandatory requirements for Green Buildings (JGBC, 2017)

Jordan GBC is focusing on some materials; however, they are general and broad, see Figure 5-56. However, GBC could consider establishing a foundation for embodied carbon reduction during the construction process of buildings, especially high-rise buildings.

Feature	Sub-feature	Aspect	Requirement
Materials	% of volatile organic matter (VOC)	Concrete	**VOC <100 g/l**
		Brick	**VOC <100 g/l**
		Adhesives	**<65 g/l**
		Leak-proof material	**<250 g/l**
		Ceiling paint	**<50 g/l**
		Internal walls paint	**<150 g/l**
		Water resistance	**<100 g/l**

Source: Jordan Green Building Council – Mini Checklist, mandatory fields

Figure 5-56 Materials requirements according to JGBC (JGBC, 2017)

(Globally, 2018) report provides a database of tables showing solid evidence supporting the established conclusions about Jordan's status. The report was mainly focused on showcasing the regulations and systems related to the embodied carbon of countries.

This project was not subjected to the LCA approach because of the need for more data validity, plus the project's long duration, which must distort the created database.

7. Summary and Conclusion

This project case study shows a clear idea about the location's role in the research, where research data, interviewing, and site visiting indicated flopping in understanding the importance of environmental sustainability and applications of sustainable construction methods.

By giving a credible evaluation of the selected country and location in the AGT case study, it is obsereved that many successful high-rise buildings have been built in Jordan. They are still under construction and presumed to be sustainable, such as the Abdali new downtown. See Figure 5-57. This shows that there has been progress in sustainability since 2005.

This case study focused on the Amman Gate Towers project in Jordan, the country's tallest building. Throughout its life cycle, the project faced several challenges and obstacles, including economic, political, engineering, planning, and design issues.

The lack of research papers or scientific articles about the project made it difficult to collect data. However, a site visit was conducted, and an interview with a site engineer revealed some environmental and non-environmental practices during the construction phase. The project also raised concerns about the sustainability of high-rise buildings, with a poor level of awareness about environmental concerns in the construction process.

In conclusion, this case study demonstrates the importance of considering environmental concerns in constructing high-rise buildings and the need for increased awareness and sustainable solutions. It also highlights the challenges and difficulties encountered in the planning and construction phase of such projects, including economic and political factors. More research and attention are needed to address these issues and promote sustainable construction practices in the future.

However, some academics showed a good understanding. Furthermore, this must be reflected by enforcing more restrictions or implementing new codes on construction sites.

No LCA assessment was conducted in this case study because the material quantity was not available or reliable.

Figure 5-57 Abdali town centre in Amman (Hourani, 2014)

Case Study 3: Burj Khalifa

Project details

Location	Dubai
Size	465,000m^2
Budget	$1.5 billion M
Building type	Skyscraper
Building purpose	Luxury apartments, shopping mall
Number of floors	165
Hight	823 m
Date of commencing	2004
Date of completion	2009
Architect	Adrian Smith
Structural engineer	Bill Baker
Developer	Emmar

Figure 5-58 Burj Khalifa (2023)

1. Introduction

When mentioning any building worldwide, the Burj Khalifa Tower comes to mind since it is the highest building man has ever made, which adds significant value to this research.

The building was designed to be the centrepiece of a large-scale, mixed-use development that includes residential, commercial, and hospitality ventures, parkland, residential skyscrapers, and the Dubai Mall.

Burj Khalifa is a popular tourist attraction in Dubai, with several observation decks near the top offering stunning city views. The tower holds many records, including the Tallest Building in the World and the Highest Number of Stories in the World (Burj Khalifa Facts and Information, 2023; The World Tallest Building:Burj Dubai, 2023).

Containing 1000 luxurious apartments and a vast shopping mall, this state-of-the-art building will house more than 12,000 people who will be working or living in it. According to (Ponzini and Alawadi, 2022), skyscrapers became a typical modernisation and globalisation narrative.

2. The Rationale of the Case Study

The primary logical reason for choosing this project was to construct the world's largest tower in the harsh environment of the Gulf Region in the Middle East. Moreover, constructing such a project requires many modern and sustainable methods to deliver a successful project.

Burj Khalifa is an innovative endeavour among various civil engineering projects (Brockmann et al., 2016).

3. Design and Planning

The planning of the enormous tower was established upon the desire to add an iconic building to the booming development of Dubai, which is in the United Arab Emirates south of the Arabian Peninsula.

The design of Burj Khalifa was derived from the geometries of the desert flower, which is popular in the region, and the patterning systems were inspired by Islamic architecture (Abdelrazaq, 2012).

The design concept was buttressed building shape, with a central core that provides the necessary resistance with wings to provide shear resistance and increased moment of inertia (Baker and Pawlikowski, 2015), Where early integration of aerodynamic shaping and wind engineering played a significant role in the architectural massing and design of this multi-use tower (Abdelrazaq, 2012). This factor is believed to have played a crucial role in enhancing the structure's ability to withstand lateral winds, which can pose severe threats or cause partial damage, such as to the glass façade. This resilience is directly linked to the sustainability of maintenance and repair efforts for the building, which, over time, can lead to increased carbon emissions due to the frequent need for parts and repairs.

Most of the building consists of reinforced concrete structure, supported by a steel braced frame on a 230 m tall spire. In comparison, the foundation was built on a 3.7 m thick solid RC raft foundation, using 194 of 1.5 m piles (Baker and Pawlikowski, 2015), In which massive reinforced-concrete core and wings extend 600 m above ground level (Aldred, 2010).

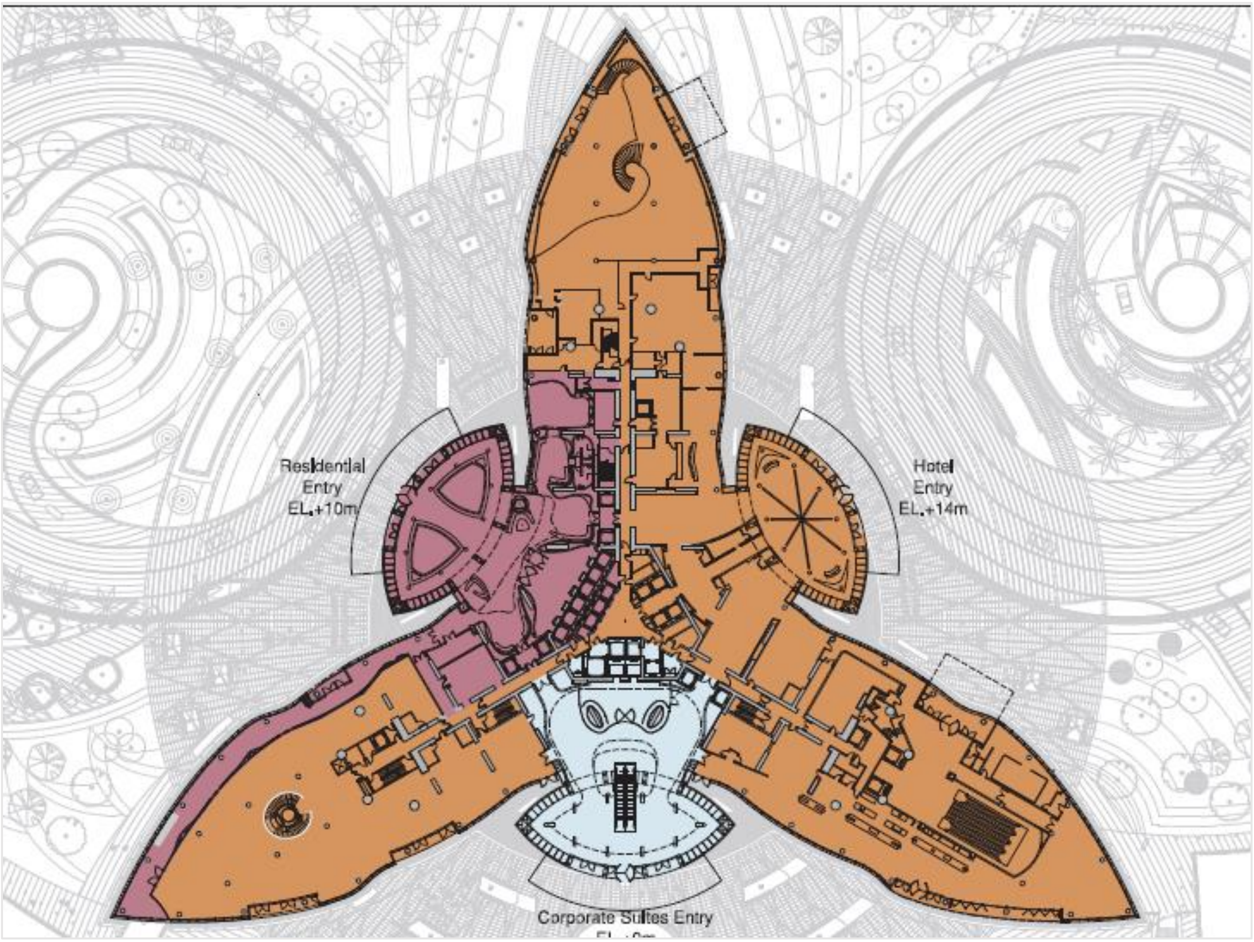


Figure 5-59 Building top view design (Bogomil, 2020)

4. Construction methods

According to (Baker and Pawlikowski, 2015), when construction started in 2004, 3 tonnes of cranes of various heights were distributed and used to speed and facilitate the construction process, minimising the time. Figure 5-60 presents the early stages of the building after the foundation process.

Figure 5-60 Foundation process (Burj Khalifa Facts and Information, 2023)

(Baker and Pawlikowski, 2015) stated that the construction had a rapid "up-up" system for vertical concrete deliveries in several stories and perimeter columns that required outriggers to tie with the system, simplifying and accelerating the construction processes.

The prime contractor utilised advanced construction techniques and materials for the Burj Khalifa. Three main tower cranes were positioned strategically near the central core and extended to different heights as needed. To expedite construction, self-climbing formwork streamlined the forming of walls and perimeter columns. Prefabricated wall reinforcement segments were employed for swift placement, and high-speed construction hoists efficiently transported workers and materials. Circular steel forms were used for the nose columns, while panel formwork supported the placement of floor slabs. A specialised GPS monitoring system was also implemented to ensure the structure's verticality (Baker and Pawlikowski, 2015).

The project manager responsible for constructing the Armani Hotel, located in the Burj Khalifa, was interviewed in this case study. Dubai has the second Armani hotel after Milan, presented in Figure 5-61.

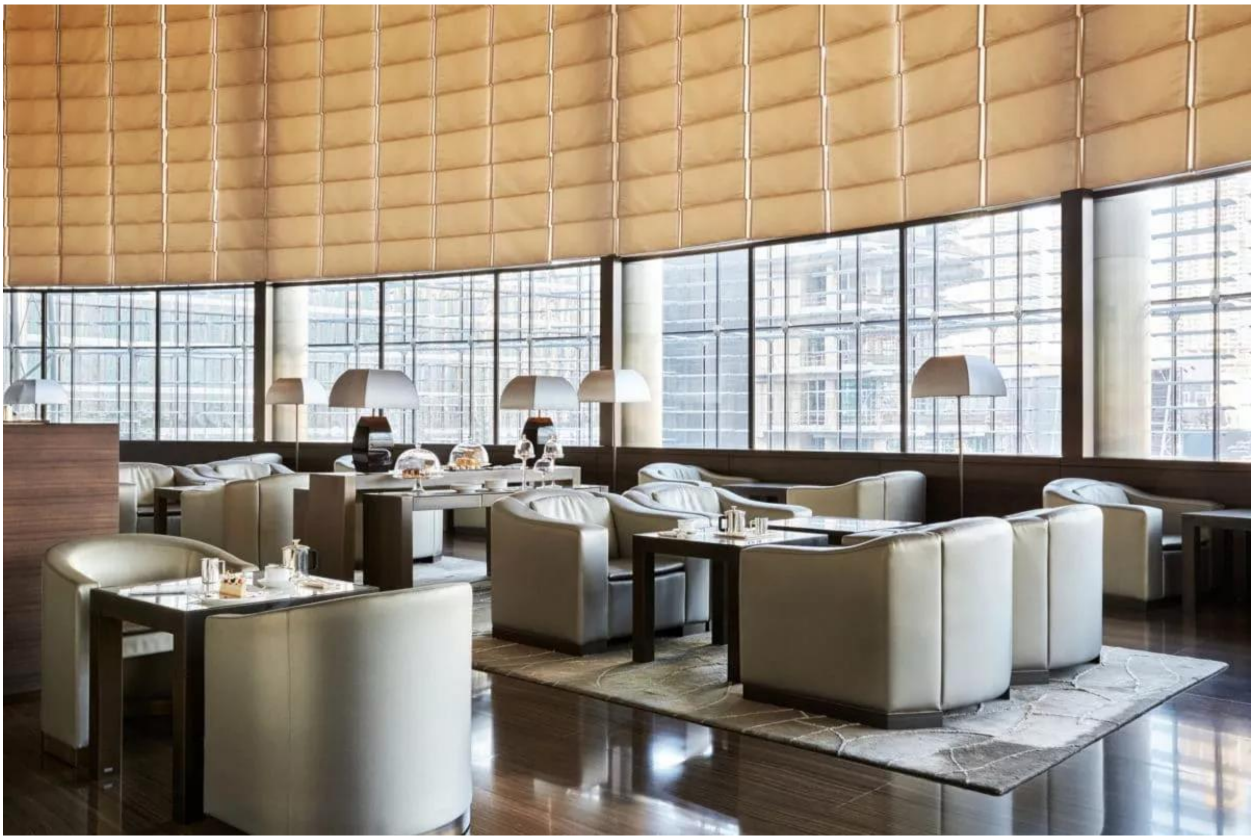


Figure 5-61 Armani Hotel/ Dubai

Located on floors 1 to 8, 38, and 39 of Burj Khalifa, the project manager indicated that building the hotel phase was the most difficult, as it was the superstructure starting point of the project. However, speed and rapid construction methods were used to cope with the project procurement plan, just as (Baker and Pawlikowski, 2015) stated.

(Aldred, 2010) discussed that the combination of high-performance concrete's pumpability and high early strength, along with the prefabrication of reinforcing cages and advancements in slip- and climb-form technology, allows for the rapid construction of large and intricate reinforced concrete structures at a rate of two to three levels per week. As a result, adequately designed reinforced concrete is increasingly competitive with structural steel in terms of construction speed. Figure 5-62 presents construction works.

When building large-scale projects, agile and lean construction systems must be adopted. Otherwise, it will cause significant environmental impacts and quality problems. As introduced in this research, these systems provoke sustainability and must be used in building the Burj Khalifa Tower.

Figure 5-62 Construction stage of the tower (Burj Khalifa Facts and Information, 2023)

5. Materials

Fly ash was used intensively with C80 to C60 concrete strengths; specifically, the raft foundation used C50 mix concrete that contained up to 40% fly ash (Baker and Pawlikowski, 2015), but (Aldred, 2010) claimed that fly ash was used as a replacement level of 13 to 20 % combined, which perhaps is true since no accurate numbers where showed in the C60 and C80 concrete mixed that was used in the rest of the tower. However, the matter is that environmentally sustainable materials were used in the project.

In total, 330,000m^3 of concrete and 39,000 tons of steel rebar were used, alongside reflective glazing, aluminium, textured stainless steel, and many others (Abraham O, 2019), such as crushed aggregated of Gabbro and high-quality limestone were used in producing the concrete. However, using them in the Middle East was a slight challenge (Aldred, 2010). See Figure 5-63.

In the Middle East, where numerous super-tall structures and significant infrastructure projects are underway, the durability of high-performance concrete is crucial in ensuring the required service life is achieved, particularly in hot and chemically aggressive environments (Aldred 2010).

Figure 5-63 World record concrete pumping height of 601 m was achieved on 8 November 2007 (Aldred 2010)

Steel played a crucial role in the construction of the Burj Khalifa. Circular steel forms created the nose columns, providing structural support and stability. Additionally, steel was utilised as wall reinforcement, which was prefabricated in 8-meter segments on the ground—this prefabricated method allowed for quick and efficient placement, contributing to the overall speed of construction. Using steel in these critical areas helped ensure the strength and integrity of the building (Baker and Pawlikowski, 2015).

In summary, fly ash was extensively used in the construction project, primarily in the raft foundation, with varying proportions in different concrete mixes. While the specific fly ash percentages for C60 and C80 concretes were not provided, it is evident that environmentally sustainable materials, including fly ash, reflective glazing, aluminium, stainless steel, and high-quality crushed aggregates, were prioritised in the project's design and execution.

6. Challenges and Critiques

The Khalifa Burj project faced many challenges, including the region's high temperature, its location on seashore land, the availability of construction materials, finance, skilled workers, and others.

Moreover, the project had a financing problem that led the governor of Abu Dhabi state in the UAE to pay 2.7 billion USD to help Dubai with its outstanding debts; in return, the tower was renamed after the Sheik Khalifa Bin Zayed, the ruler of Abu Dhabi (Sotoudehnia and Rose-Redwood, 2019).

One of many criticisms of the Burj Khalifa project is that the city's real estate sector focused on luxurious high-end departments while ignoring the rest of the population in the centre and downtown areas (Ponzini and Alawadi, 2022) while other concerns were made regarding the risk of evacuation process during smoke or fire (Barreiro-Gomez et al., 2021). Moreover, risks of weather, wind, workers' safety, and natural catastrophes were significant concerns (Abraham O, 2019).

Regarding sustainability and decarbonisation status, the UAE government entity aimed to reduce carbon emissions and address climate change concerns. They sought to understand their carbon footprint and find ways to reduce the impact of their operations while also cutting costs. The exercise involved developing a carbon footprint calculation tool and forecasting scenarios, identifying potential carbon savings of over 2.3 million tCO_2e/year by 2030. This data would provide carbon performance information to internal and external stakeholders (Suryan et al., 2020). However, the sustainability of the largest project in UAE is evaluated afterwards.

7. Data Collection Analysis

Only sixty-three general research documents were found in Scopus, downsized to 24 documents regarding construction within scopes of engineering, materials science, and environmental science. They were presented in Figure 5-64.

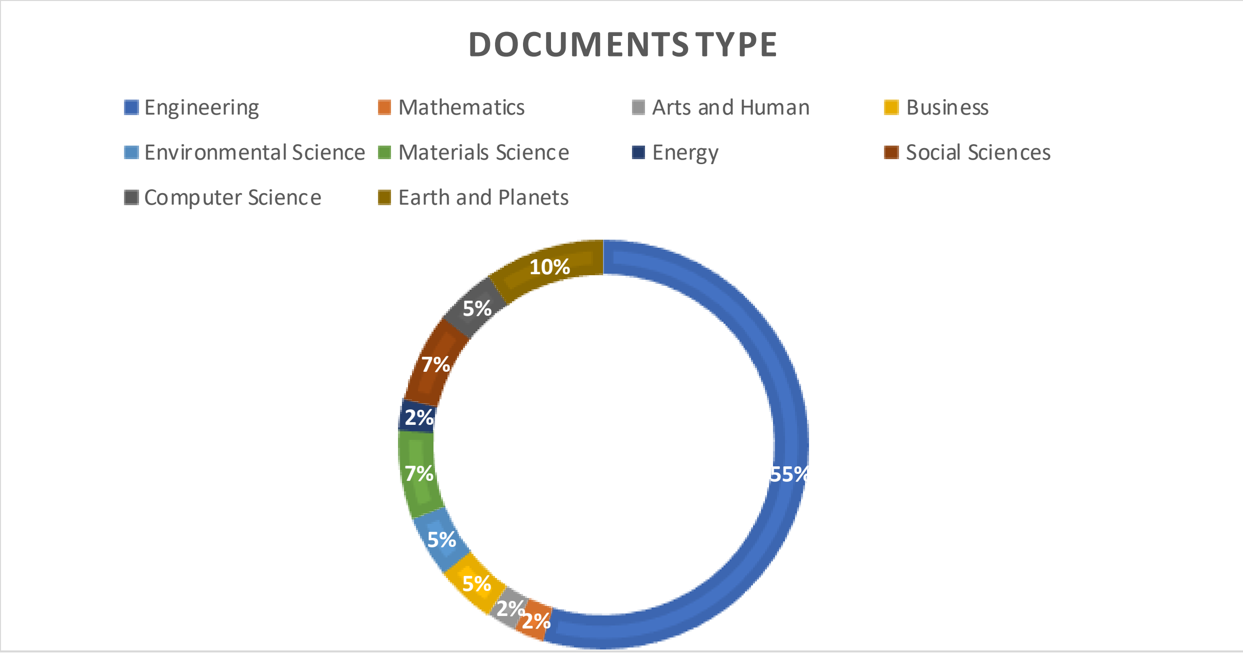


Figure 5-64 Research documents (Scopus)

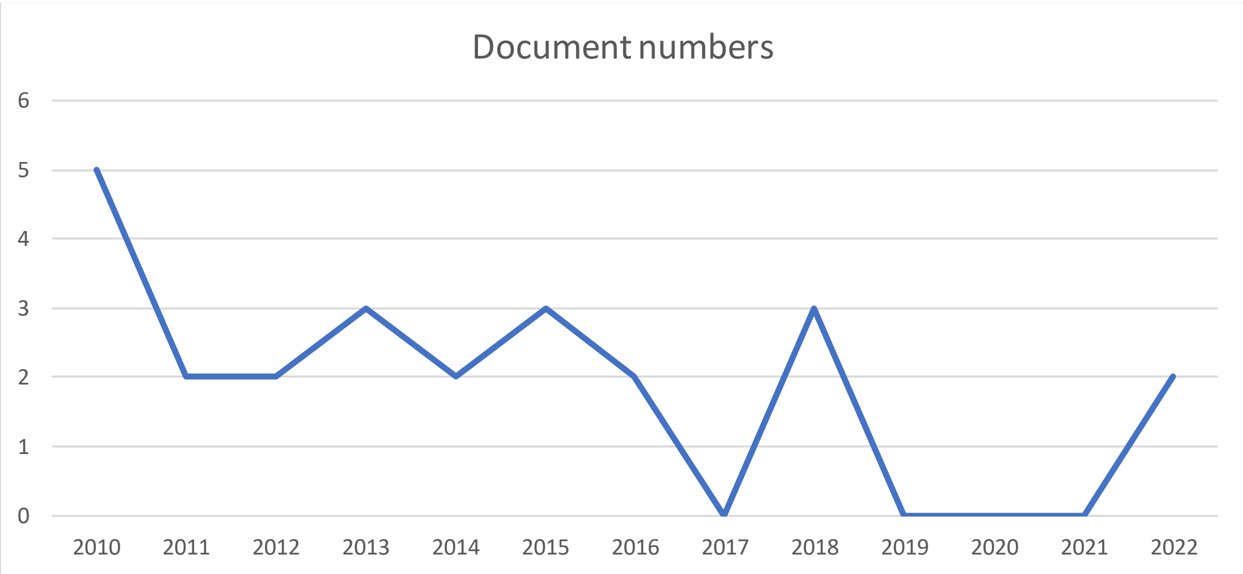


Figure 5-65 Number of documents (Scopus)

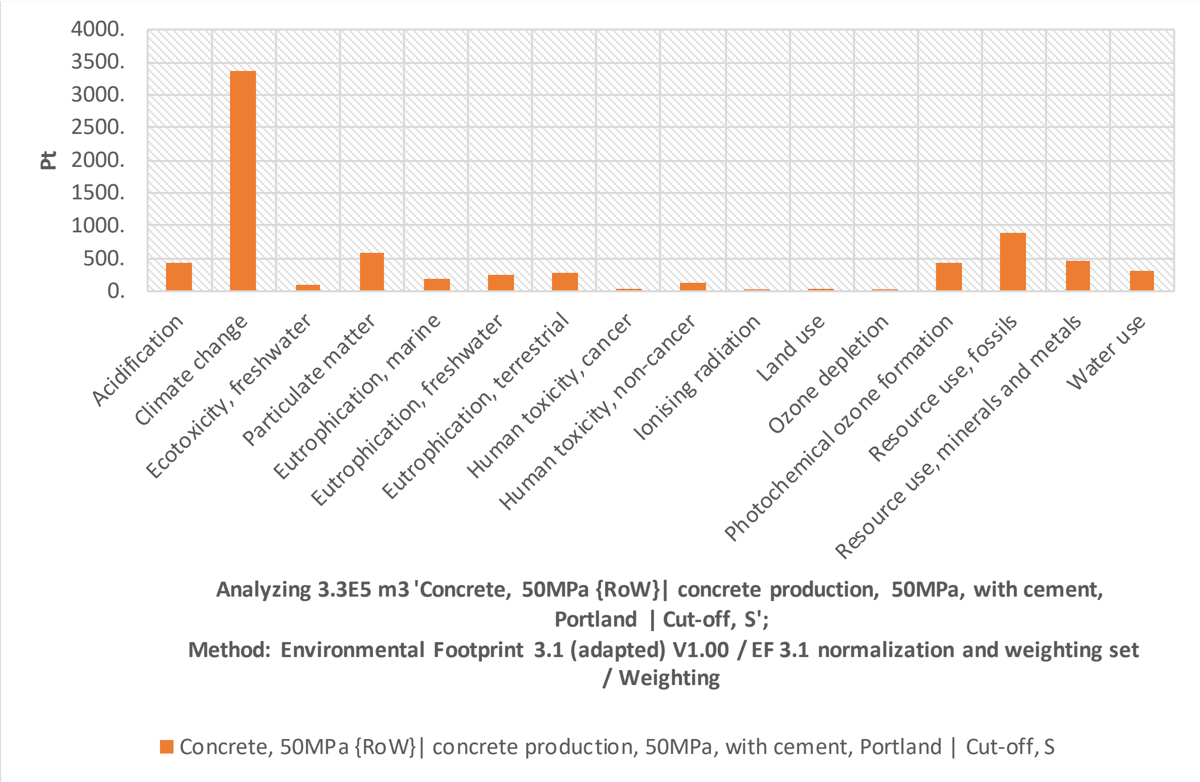
Logically, the research interest was at its peak during the start and delivery of the project. However, the massive drop in research in the following years could be more convenient, especially compared to the other case study projects. See Figure 5-65.

8. Sustainability and Carbon Footprint

The main structural bulk components in this research were analysed using the LCA method to discuss the environmental impact and sustainability of the Khalifa project concrete and steel.

Concrete was analysed using the LCA software database according to the Ecoinvent 3 classification. Furthermore, it was assumed to be an average grade of C50.

The results are presented in Figure 5-66.



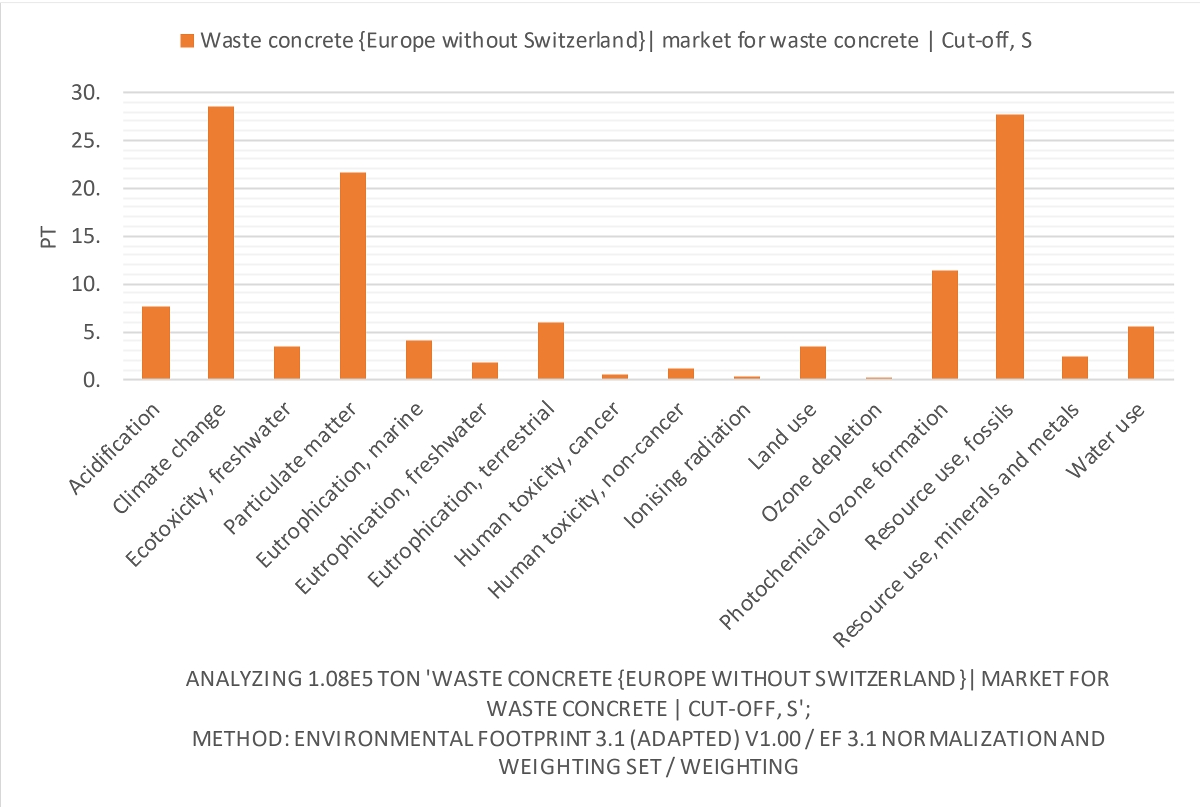


Figure 5-66.a) Concrete LCA environmental impacts, b) Waste concrete environmental impacts

Fossil use, resources, water, land use, and others were maintained at minimal stages, providing a good sustainability index. Nevertheless, climate change is the highest, which could be explained by the enormous usage of materials in the project; if no sustainable materials were used, such as Fly Ash or sustainable construction methods, the climate change numbers would be much higher. Table 5-22 addresses all environmental impacts.

LCA analysis revealed that concrete's waste impacts are minimal compared to the impacts of concrete. It also showed that the software analyses most construction materials in terms of waste, except for steel. This could be an advantage for steel, as it likely has minimal production and processing waste, largely because it is manufactured off-site, this was supported by (Burgan and Sansom, 2006; Che Hasan et al., 2013).

Table 5-22 Concrete environmental impacts

Impact category	Unit	Concrete, 50MPa
Acidification	mol H+ eq	4.465
Climate change	kg CO2 eq	1.31E8
Climate change - Biogenic	kg C02 eq	1.08E5
Climate change - Fossil	kg CO2 eq	1.3E8
Climate change - Land use	kg CO2 eq	2.04E5
Ecotoxicity, freshwater - pa	CTUe	3.48
Ecotoxicity, freshwater - pa	CTUe	1.478
Ecotoxicity, freshwater - in	CTUe	3.638
Ecotoxicity, freshwater - or	CTUe	1.08E8
Ecotoxicity, freshwater - or	CTUe	16E7
Particulate matter	disease inc.	4.55
Eutrophication, marine	kg N eq	1.34E5
Eutrophication, freshwater	kg P eq	1.4984
Eutrophication, terrestrial	mol Neg	1.476
Human toxicity, cancer	CTUh	0.0431
Human toxicity, cancer - in	CTUh	0.0186
Human toxicity, cancer - or	CTUh	0.0245
Human toxicity, non-cancer	CTUh	1.03
Human toxicity, non-cancer	CTUh	0.984
Human toxicity, non-cancer	CTUh	0.0498
lionising radiation	kBq U-235 eq	1.66E6
Land use	Pt	5.618
Ozone depletion	kg CFC11 eq	0.782
Photochemical ozone form	kg NMVOC eq	4.29E5
Resource use, fossils	M.J	8.39E8
Resource use, minerals	kg Sb eg	433

To understand the climate change results, the carbon emissions associated with the project are addressed in Table 5-23, which is extracted from the inventory provided by the LCA software database.

Table 5-23 Concrete climate change impacts

Compartment: All compartments | Indicator: Weighting | Cut-off: 0% | ☑ Default units
☐ Per sub-compartment | Category: Climate change | ◉ Standard | ☐ Exclude long-term emissions
☑ Skip unused | ○ Group | ☐ Per impact category

No	Substance	Compartr	Unit	Total	Concrete, 50MPa
	Total of all compartments		Pt	3.35E3	3.35E3
1	Carbon dioxide, fossil	Air	Pt	3.18E3	3.18E3
2	Methane, fossil	Air	Pt	155	155
3	Dinitrogen monoxide	Air	Pt	7.14	7.14
4	Methane, biogenic	Air	Pt	2.86	2.86
5	Carbon dioxide, land transformation	Air	Pt	2.74	2.74
6	Sulfur hexafluoride	Air	Pt	2.05	2.05
7	Methane, tetrafluoro-, CFC-14	Air	Pt	0.361	0.361
8	Methane, trifluoro-, HFC-23	Air	Pt	0.0666	0.0666
9	Ethane, hexafluoro-, HFC-116	Air	Pt	0.0448	0.0448
10	Methane, chlorodifluoro-, HCFC-22	Air	Pt	0.0386	0.0386
11	Methane, land transformation	Air	Pt	0.0271	0.0271
12	Ethane	Air	Pt	0.0098	0.0098
13	Methane, bromotrifluoro-, Halon 1301	Air	Pt	0.00574	0.00574
14	Methane, tetrachloro-, CFC-10	Air	Pt	0.00548	0.00548
15	Methane, dichloro-, HCC-30	Air	Pt	0.00157	0.00157
16	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	Pt	0.00153	0.00153
17	Ethane, 1,1-difluoro-, HFC-152a	Air	Pt	0.00142	0.00142
18	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	Pt	0.00137	0.00137
19	Propane	Air	Pt	0.000301	0.000301
20	Methane, dichlorodifluoro-, CFC-12	Air	Pt	0.000262	0.000262
21	Butane	Air	Pt	0.000158	0.000158
22	Methane, bromochlorodifluoro-, Halon 1211	Air	Pt	8.95E-5	8.95E-5
23	Chloroform	Air	Pt	8.01E-5	8.01E-5
24	Ethane, 1,1,1-trichloro-, HCFC-140	Air	Pt	6.71E-5	6.71E-5
25	Methane, monochloro-, R-40	Air	Pt	6.11E-5	6.11E-5
26	Ethane, 1,2-dichloro-	Air	Pt	5.46E-5	5.46E-5
27	Tetrachloroethylene	Air	Pt	1.81E-5	1.81E-5
28	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	Pt	1.58E-5	1.58E-5
29	Methane, trichlorofluoro-, CFC-11	Air	Pt	1.16E-6	1.16E-6
30	Methane, bromo-, Halon 1001	Air	Pt	9.11E-7	9.11E-7

The table presented the superiority of carbons in contributing more than 90% to climate change.

The following equation calculates the carbon emissions caused by concrete in terms of climate change during the life cycle of the project:

$$\boldsymbol{CE = \frac{CC}{a}}$$

Equation 7

CE is the carbon emissions per square meter, CC is the climate change emissions in kg CO_2, and a is the area of the building.

$$\boldsymbol{CE} = \frac{\mathbf{1310000000}}{\mathbf{465000}}$$

The result is **281.7** kg CO_2 /m^2 for the concrete impact.

Steel was analysed according to the Environmental Footprint 3.1. the results are presented in Figure 5-68.

Moreover, to explore the amount of GHG emissions, Table 5-24 was extracted from LCA software to illustrate the amount of carbon emissions in kilograms associated with steel production and installation of the project.

Table 5-24 Steel airborne emissions

Compartment: Airborne emission | Indicator: Amount | Cut-off: 0% | ☑ Default units
☐ Per sub-compartment | Category | ◉ Standard | ☑ Exclude long-term emissions
☑ Skip unused | ○ Group | ☐ Per impact category

No	Substance	Compartr	Unit	Total	Reinforcing steel {GLO}|
61	Beta-cyfluthrin	Air	kg	0.00113	0.00113
62	Bifenthrin	Air	kg	0.00272	0.00272
63	Boric acid	Air	kg	2.85E-11	2.85E-11
64	Boron	Air	kg	90.3	90.3
65	Boron trifluoride	Air	kg	1.93E-7	1.93E-7
66	Bromine	Air	kg	34.9	34.9
67	Bromoxynil	Air	kg	5.14E-12	5.14E-12
68	Butadiene	Air	kg	0.000139	0.000139
69	Butane	Air	kg	552	552
70	Butene	Air	kg	0.0792	0.0792
71	Butyric acid, 4-(2,4-dichlorophenoxy)-	Air	kg	2.47E-13	2.47E-13
72	Cadmium (II)	Air	kg	2.89	2.89
73	Calcium	Air	kg	116	116
74	Carbaryl	Air	kg	2.16E-5	2.16E-5
75	Carbendazim	Air	kg	0.091	0.091
76	Carbon	Air	kg	0.112	0.112
77	Carbon dioxide, biogenic	Air	kg	1.14E6	1.14E6
78	Carbon dioxide, fossil	Air	kg	7.44E7	7.44E7
79	Carbon dioxide, land transformation	Air	kg	5.66E4	5.66E4
80	Carbon disulfide	Air	kg	282	282
81	Carbon monoxide, biogenic	Air	kg	2.92E3	2.92E3
82	Carbon monoxide, fossil	Air	kg	9.93E5	9.93E5
83	Carbon monoxide, land transformation	Air	kg	247	247
84	Carbonyl sulfide	Air	kg	2.9	2.9
85	Carfentrazone-ethyl	Air	kg	0.000708	0.000708
86	Chloramine	Air	kg	0.00136	0.00136

To understand the table from a numerical perspective, if we only calculated the Carbon dioxide (fossil) in the reinforced steel that is used in the Khalifa building, it will be equal to the:

$$\boldsymbol{Dioxide\ carbons\ per\ square\ meter = \frac{emissions}{area}}$$

Where emissions are the air carbon dioxide fossil in kg, taken from Table 5-24, and the area of the Khalifa building in square meters. It is essential to highlight that these carbon emissions refer to CO_2 and do not include equivalent emissions. This distinction is necessary to understand the variations and differences in emissions better.

$$\boldsymbol{\frac{7,440,000,000}{465,000} = 160\ kg.CO2\ per\ m2}$$

The emissions database obtained from this study represents only a single type of emission (fossil carbon dioxide) within a specific material (reinforced steel) from a single building. This data primarily reflects the embodied carbon emissions associated with large-scale projects, which are the direct carbons rather than indirect carbons (land transformation), providing valuable insights into their environmental impacts. Next, Table 5-25 presents the impacts of climate change.

Table 5-25 Steel environmental impacts

Damage category	Unit	Total	Reinforcing steel (GLO)
Resource use, fossils	MJ	8.94E8	8.94E8
Ecotoxicity, freshwater	CTUe	3.73E8	3.738
Land use	Pt	2.51E8	2.518
Climate change	kg CO2 eq	8.37E7	8.37E7
Water use	m3 depriv.	1.75E7	1.75E7
Iionising radiation	kBq U-235 eq	2.56E6	2.56E6
Eutrophication, terrestrial	mol N eq	8.73E5	8.73E5
Photochemical ozone form	kg NMVOC eq	4.23E5	4.235
Acidification	mol H+ eq	3.495	3.49E5
Eutrophication, marine	kg Neg	8.39E4	8.39E4
Eutrophication, freshwater	kg P eq	3.77E4	3.77E4
Resource use, minerals and	kg Sb eq	261	261
Particulate matter	disease inc.	6.79	6.79
Ozone depletion	kg CFC11 eq	1.59	1.59
Human toxicity, non-cancer	CTUh	0.997	0.997
Human toxicity, cancer	CTUh	0.53	0.53

To validate the previous results and make them consistent with the concrete calculation approach, the climate change impact in Table 5-25 was used. It resulted in 180 kg CO_2 /m^2 of carbon associated with steel impacts on climate change. This higher amount of 20 kg CO_2 contributes to the holistic category of climate change emissions, including different types of carbon and non-carbon emissions. Furthermore, it is approximate to the numbers presented in Table 3-2, which was generated by Gan et al. 2018.

Moreover, the number is approximate when using Table 3-2 (direct embodied carbon factors), presented by (Gan et al., 2018), which quantifies embodied carbon emissions to steel rebar to (2.25 kg CO_2 e/kg), which is:

$$\boldsymbol{CE = SR \times CEf}$$

Equation 8

Where CE is carbon emissions (embodied), SR is steel rebar, and CEf is factor of carbon emissions.

$$\boldsymbol{CE = 39{,}000{,}000 \times 2.25 = 87{,}750{,}000}$$

$$\boldsymbol{CE(per\ m2) = \frac{CE}{A}}$$

The resulting carbon emissions per square meter equals 188.7 kg CO_2/m^2. This number represents the carbon emissions in the cradle-to-gate stage, or from A1 to A3, according to (Gan et al., 2018). These numbers are similar to the previous LCA carbon calculations.

So, the rest of the case studies will be subjected to climate change equivalent carbons because they seem more holistic, consistent, and rational. In contrast, this research objective focuses on mitigating carbon emissions in specific embodied ones. After all, as explained earlier, they are more controllable and better measured; however, climate change will not be excluded.

When adding more air carbon emissions to the calculation, the LCA amount will be much higher than the calculated one because LCA is more holistic. There are a few reasons why the amount of carbon emissions calculated using LCA software is higher.

First, LCA software typically calculates the whole life impact of a building, which includes the operational emissions from heating, cooling, and lighting (This is not entirely applicable to steel). Second, the project's location can significantly impact carbon emissions, and LCA software typically needs to consider this. Third, the LCA software concludes waste and recycability of materials (Figure 5-66. b). Fourth, LCA includes all types of air and ground emissions, and finally, the duration of the project is also not typically taken into account by LCA software.

While the LCA (Life Cycle Assessment) software explicitly mentions the recyclability of materials in each section, it does not clearly demonstrate the calculation process for recyclability. This lack of transparency in how recyclability is quantified can make it challenging to understand its impact within the overall assessment.

To validate the number of embodied carbons provided by Table 5-25, a more detailed table was provided by (Pomponi and Moncaster, 2018), presented in Table 5-26.

Table 5-26 Construction steel embodied emission factors (Pomponi and Moncaster, 2018)

Source	Macro category	Further description"	Boundaries of the assessment (EN 15978)	Boundaries of EC coefficients	Material boundaries of the assessment	ECCs
[44]	Steel	Reinforcing	A + B4 +C	A1-43	(4)	1.340
[46]	Steel	Reinforcing	A1-A4	A1-43	(4)	1.526
[54]	Steel		A+ C	A1-43	(1)	1.53
[41]	Steel	Crude DRI	A1-44	A1-A3	(1)	1.540
[56]	Steel	Galvanized	A + 35	A1-A3	(3)	1.75
[56]	Steel	Tubing	A + B5	A1-A3	(3)	1.8
[61]	Steel	Rebar	A1-45 + B3 + C	AL-A3	(3)	1.86
[61]	Steel	Sections	A1-45 + B3 + C	AL-A3	(1)	1.95
[62)	Steel	Lean	A1-45 + C2	Al-A5	(1)	1.950
[62)	Steel	Standard	A1-45 + C2	Al-A5	(1)	2.015
[41]	Steel	Crude pig iron	A1-A4	Al-A3	(1)	2.090
[49)	Steel		A + C1, C3	Al-A3	(3)	2.208
147)	Steel		A + CI	Al-A3	(2)	2.210
150]	Steel	10% recycled content	A+ C	Al-A3	(1)	2.210
[581	Steel	Rebar	A1-44 + B4 + C1, 02	Al-A3	(3)	2.27
[53]	Steel	Galvanized	A1-A4 + B4 + C1, 02	A1-A3	(3)	2.82
(48)	Steel	Bar	A + B2, B5 +C	A1-A3	(4)	3.15
[42)	Steel		A1-44	A1-A3	(3)	3.809

The carbon factors for steel are similar to the previous tables, which is 2.27, a little bit more because it contains more stages (B4, C1, C2). Figure 5-67 provide a reminder of the life assessment stages.

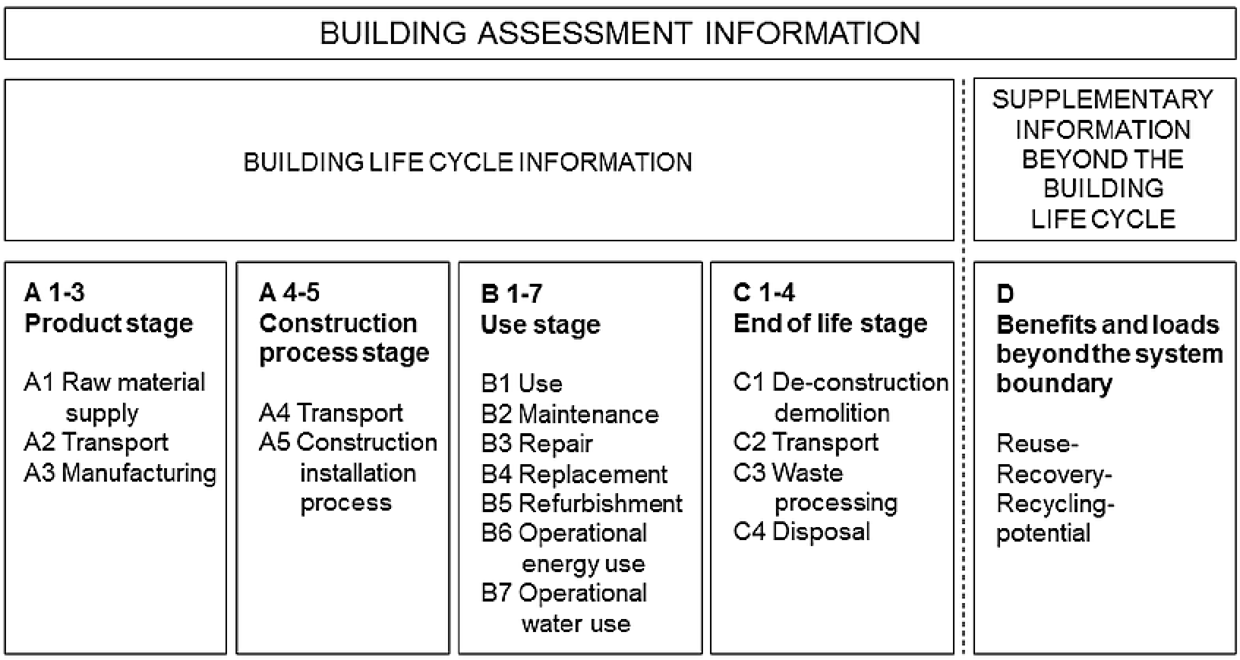


Figure 5-67 Life cycle stages modified after (Alotaibi et al., 2022)

The analysis conducted in this case study reveals that the embodied carbon emissions attributed to steel and concrete are significant compared to other materials. Concrete, in particular, stands out as a major contributor to these emissions. The bibliometric study supports these findings, highlighting the substantial environmental impact associated with these materials in terms of embodied carbon. This comprehensive assessment underscores the need for focused efforts to mitigate the carbon footprint associated with steel and concrete. It emphasises the importance of exploring alternative materials and sustainable construction practices to reduce environmental impact.

It is worth mentioning that this research primarily focuses on qualitative explanations supported by quantitative data. The case studies included in the research aim to provide comprehensive insights into the subject matter, allowing for detailed qualitative analysis based on the numerical findings.

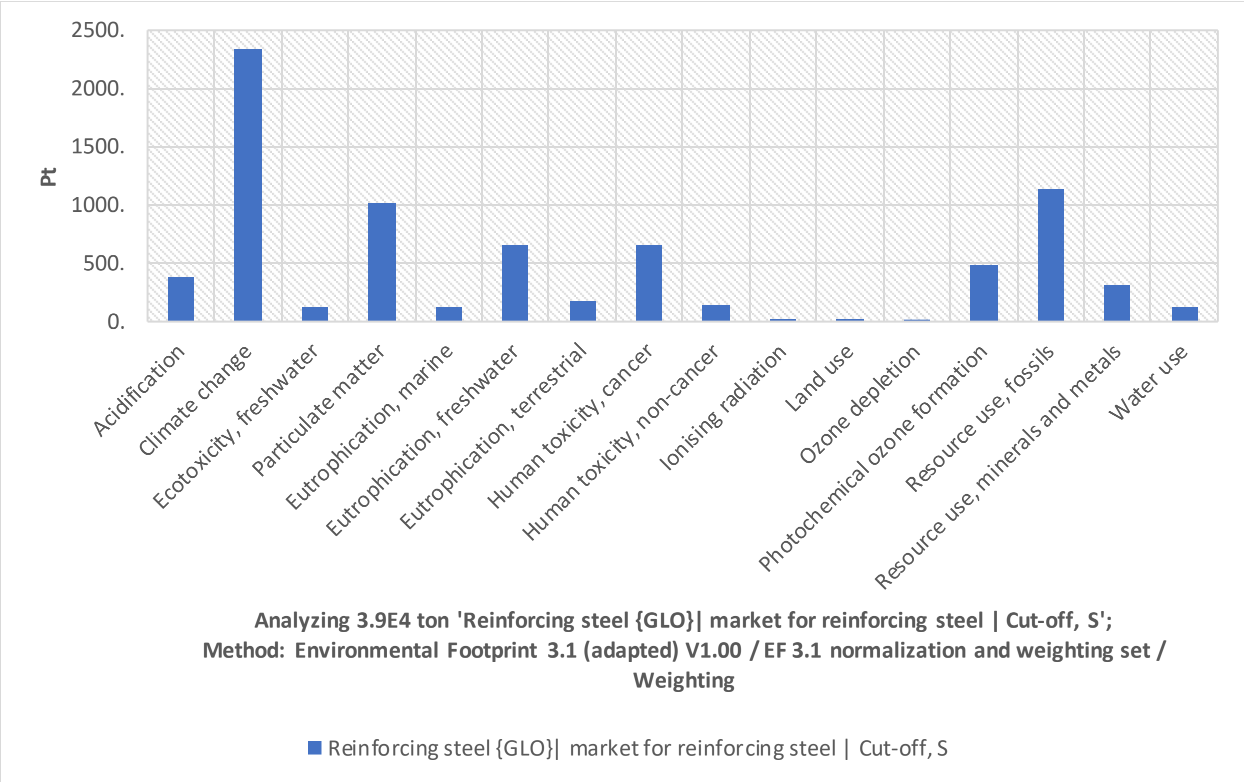


Figure 5-68 Reinforced steel LCA environmental impacts

Again, climate change had the highest impacts, but less than concrete. Moreover, Figure 5-69 illustrates the steel rebar production process.

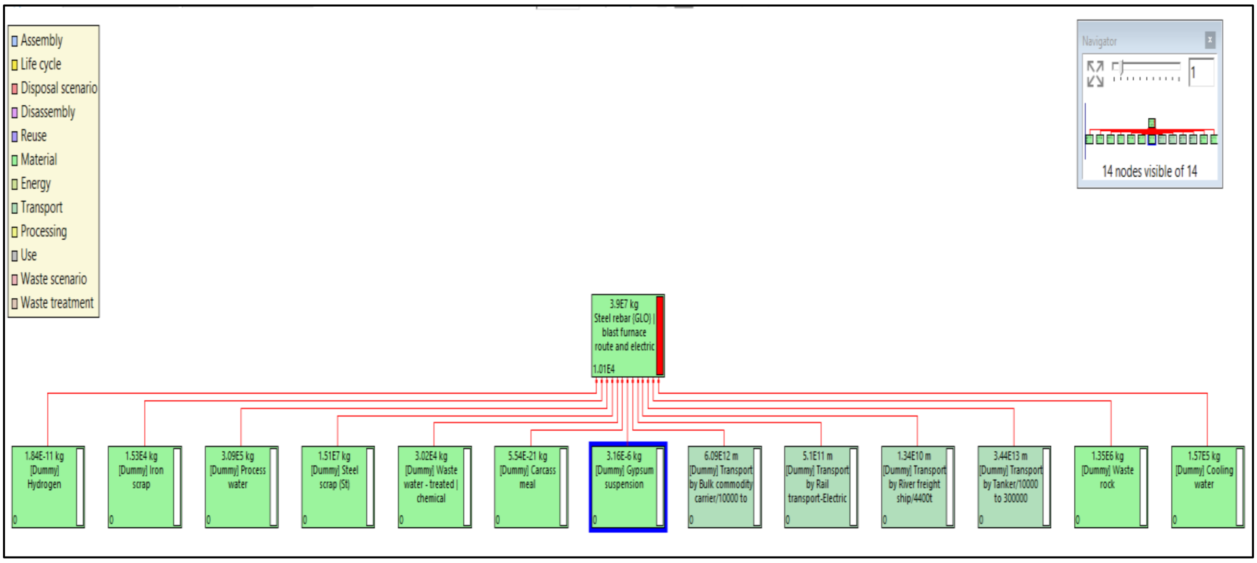


Figure 5-69 Steel LCA production process

Figure 5-69 introduces the contribution of Hydrogen, Iron scrap, process water, wastewater, carcass meal, gypsum suspension, transport of bulk commodity carrier, transport by rail, transport by river freight ship, transport by tanker, waste rock, and cooling water.

Table 5-27 provides the calculations of climate change emissions associated with the steel rebar usage in the Khalifa project.

Table 5-27 Steel climate change impacts

Compartment: All compartments | Indicator: Weighting | Cut-off: 0% | ☑ Default units
☐ Per sub-compartment | Category: Climate change | ◉ Standard | ☐ Exclude long-term emissions
☑ Skip unused | ○ Group | ☐ Per impact category

No	Substance	Compartr	Unit	Total	Reinforcing steel {RoW}|
1	Carbon dioxide, fossil	Air	Pt	2.06E3	2.06E3
2	Methane, fossil	Air	Pt	244	244
3	Dinitrogen monoxide	Air	Pt	8.34	8.34
4	Sulfur hexafluoride	Air	Pt	2.28	2.28
5	Methane, chlorodifluoro-, HCFC-22	Air	Pt	1.88	1.88
6	Carbon dioxide, land transformation	Air	Pt	1.49	1.49
7	Methane, biogenic	Air	Pt	1.42	1.42
8	Methane, tetrafluoro-, CFC-14	Air	Pt	0.228	0.228
9	Methane, trifluoro-, HFC-23	Air	Pt	0.0641	0.0641
10	Ethane	Air	Pt	0.0422	0.0422
11	Ethane, hexafluoro-, HFC-116	Air	Pt	0.0287	0.0287
12	Methane, land transformation	Air	Pt	0.0105	0.0105
13	Methane, tetrachloro-, CFC-10	Air	Pt	0.00491	0.00491
14	Methane, bromotrifluoro-, Halon 1301	Air	Pt	0.00386	0.00386
15	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	Pt	0.00184	0.00184
16	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	Pt	0.000801	0.000801
17	Methane, dichlorodifluoro-, CFC-12	Air	Pt	0.000675	0.000675
18	Ethane, 1,1-difluoro-, HFC-152a	Air	Pt	0.000615	0.000615
19	Propane	Air	Pt	0.00021	0.00021
20	Methane, bromochlorodifluoro-, Halon 1211	Air	Pt	0.000132	0.000132
21	Methane, dichloro-, HCC-30	Air	Pt	0.000108	0.000108
22	Butane	Air	Pt	8.4E-5	8.4E-5
23	Chloroform	Air	Pt	7.86E-5	7.86E-5
24	Ethane, 1,1,1-trichloro-, HCFC-140	Air	Pt	7.66E-5	7.66E-5
25	Methane, monochloro-, R-40	Air	Pt	6.98E-5	6.98E-5
26	Tetrachloroethylene	Air	Pt	2.92E-5	2.92E-5
27	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	Pt	2.48E-5	2.48E-5
28	Ethane, 1,2-dichloro-	Air	Pt	1.08E-5	1.08E-5
29	Methane, trichlorofluoro-, CFC-11	Air	Pt	3.92E-6	3.92E-6
30	Methane, bromo-, Halon 1001	Air	Pt	1.04E-6	1.04E-6
31	Trichloroethylene	Air	Pt	2.43E-7	2.43E-7
32	Methane, dichlorofluoro-, HCFC-21	Air	Pt	9.14E-8	9.14E-8

Table 5-27 addressed the climate change-associated emissions with steel through LCA of the Khalifa Project. However, they show different measurements than the one referred to embodied carbon emissions in the BSRIA Table; for example, in terms of carbon emissions per unit, most probably because the LCA software database uses a more extensive scope that includes the life cycle assessment stages of the product, and this might include more carbons associated such as land usage and others.

"SimaPro simplifies the process by providing the necessary tools to calculate carbon footprints effectively. It offers a comprehensive database and carbon dioxide equivalence factors for

greenhouse gas emissions. SimaPro also enables separate reporting of different types of emissions, including biogenic methane and land-use change. Additionally, its grouping analysis feature allows activities to be categorised by business function or department, facilitating transparency and identifying opportunities for reducing the overall carbon footprint" (SimaPro, 2023).

The critical point to highlight at this stage is the consistent discovery that carbon emissions exert the most substantial influence throughout the project's construction phase.

9. Summary and Conclusion

Burj Khalifa project was and still is a successful construction project in terms of economic, social, and urbanisation scales. However, many points should be considered when evaluating its environmentally sustainable results.

First, the project contained many social solutions, including residential flats, luxury hotels, commercial offices, and a mall in the same tower. These types of buildings will inevitably reduce traffic problems or concentrate on the transportation direction; consequently, this will reduce the emissions associated with transportation.

Second, building this tall building will reduce the need to build more high-rise buildings, reducing the environmental impacts caused by constructing more new buildings, especially embodied carbon impacts.

Third, on a larger scale and nationwide, UAE shares a high amount of carbon emissions, despite the sustainable and modern construction methods adopted, knowing that UAE is not considered an industrial country in terms of factories and production lines; however, it is still an oil resource country, which eventually relies on fossil fuels extensively. According to the World Bank (2023), it is 20.5 Metric tons /capita. However, the population of UAE is not as high as the USA or China, but it is still an indicator of carbon status.

In conclusion, the Burj Khalifa Tower is a remarkable and iconic structure that showcases modern engineering, construction, and sustainability methods. The tower's design was derived from geometries of the desert flower and inspired by Islamic architecture, with early integration of aerodynamic shaping and wind engineering. The construction process utilised modern methods such as rapid vertical concrete delivery and perimeter columns requiring outriggers to tie the system, simplifying and accelerating the construction processes.

Concrete was produced using sustainable materials such as fly ash, Gabbro crushed aggregates, and high-quality limestone. A prefabricated steel structure also functioned. However, the project faced numerous challenges, including financing, construction material availability, high temperatures, and risks of natural catastrophes. In addition, criticisms have been made about the project's focus on luxurious high-end departments while ignoring the rest of the population in the city's centre and downtown areas.

Overall, the Burj Khalifa Tower is an impressive feat of engineering, construction, and sustainability that showcases the potential for modern high-rise buildings. Despite the challenges and critiques, the tower remains an iconic symbol of Dubai and the Middle East, attracting millions of visitors annually.

Summary and Conclusion of On-site Real Case Studies

The case studies examined three expansive high-rise building endeavours: the SPECS Project at the University of Hertfordshire, the Amman Gate Towers in Jordan, and Dubai's Burj Khalifa in the UAE. Each project underwent scrutiny, explicitly delving into its environmental sustainability and emphasising the assessment of embodied carbon emissions.

The projects were examined using on-site case studies and academic research studies. The SPECS Project employed various sustainable practices to reduce its environmental impact, such as using high-grade concrete mixes, minimising concrete usage, and using off-site production methods. The Amman Gate Towers showed limited awareness of environmental concerns, and the Burj Khalifa employed a range of sustainable construction methods, such as using fly ash in concrete mixes, rapid construction methods, and environmentally friendly materials.

It was discovered that the research interest in these projects required enhancement, especially post-project completion. This study delved into three case studies involving expansive high-rise building projects to assess their environmental sustainability by explicitly concentrating on embodied carbon emissions. The University of Hertfordshire's SPECS Project entailed an on-site investigation focused on environmental sustainability.

Amman Gate Towers was a case study that demonstrated a failure in planning and construction, which caused massive delays in delivering the project. Burj Khalifa was taken as the most giant tower in the world, and the construction methods and materials used were studied.

It was concluded that large-scale high-rise building projects have the potential to be environmentally sustainable. However, they must be constructed with environmental concerns and use sustainable construction methods and materials.

2. Research Case Studies (literature)

Case Study 4: The Shard

Project details

Location	London
Size	398,490 m^2
Budget	425 million pounds
Building type	Skyscraper
Building purpose	Residential, public observation deck, hotel
Number of floors	95
Hight	309.6 meters
Date of commencing construction	2009
Date of construction completion	2012
Architect	Renzo Piano
Structural engineer	Arup (structure and services)
Developer	Qatar Investment

Figure 5-70 The Shard (London 2023)

1. Introduction

London mega-projects can be a good case study for sustainable construction and technologies that can be adopted, especially since the Shard project is considered a critical approach to sustainable construction of large-scale projects (Brooks and Rich, 2016), especially when it is the tallest tower in Europe (Bogomil, 2020), despite that the Federation Tower suppressed it in Moscow, perhaps the author meant in western Europe region, never the less, this research is not taking the highest buildings in consideration more than sustainable construction approach for large-scale towers. Moreover, Western Europe considers it the most qualified skyscraper structure (Sungur et al., 2021).

Despite the refusal in Europe, mainly the UK, to adopt high-rise buildings since their spread in the early 1920s, especially in the USA, most European countries in the late 1960s and 1970s started to construct large-scale towers to cope with urbanisation development.

London started to construct several high-rise buildings in the centre and edges of the capital, such towers as Signature by Regus (183m), One Canada Square (235m), Heron Tower (230m), Twenty-two (278m), One Park Drive (205m), 30 St Mary Axe (The Gherkin) (180m) and many others. The Shard is part of The Shard Quarter development and was designed to be a "little vertical city" with a transportation hub, offices, restaurants, a hotel, and a public gallery (Jones, 2023).

Church spires and ship's masts inspired the building's unique design, which has been described as statement architecture.

2. The Rationale

The United Kingdom has been at the forefront of standardising and ensuring consistent assessments for various engineering industries, particularly civil engineering. British Standards have been widely adopted as codes for significant global projects, attesting to their influence and credibility (bsi, 2023). Given this reputation, selecting an iconic construction project in the UK's capital city would be a well-justified choice for research.

However, the UK has recently faced challenges concerning sustainable construction and decarbonisation (Polli, 2020; UK Green Building Council, 2021). One of the issues is the need for more consistency in regulations and guidelines related to these areas. Additionally, there is a high number of institutions and agents involved in dealing with sustainable construction and decarbonisation (bre, 2022; *BREEAM In-Use International*, 2016; Government Commercial Function, 2022; Marvin and Weetman, 2008; Suryan et al., 2020), leading to a somewhat fragmented approach to tackling the problem.

The research aims to identify and establish more consistent regulations to address the challenges of decarbonising construction. The goal is to streamline the efforts and create a unified approach to sustainable construction and decarbonisation by reducing the number of entities involved.

Additionally, building a skyscraper in the densely populated city of London posed considerable challenges, particularly in aligning with efforts to enhance its environmental sustainability. This was further compounded by the project's initiation following the implementation of the ultra-low emissions zone (ULEZ) regulations in 2007, as noted by (Hajmohammadi and Heydecker, 2022).

3. **Design and Planning**

After studying the vortex power and turbulence created by building structures (Sungur et al., 2021), a Buttressed-core system was adopted (Brooks and Rich, 2016), where the design of a lighter construction load-bearing system was used through the principles of wind engineering dynamics and fluid mechanics systems (Sungur et al., 2021). Such systems will eventually reduce the usage of materials and the generated waste, mitigating environmental impacts caused by the project during construction works.

4. **Construction Methods and Materials**

A top-down construction method was adopted, enabling the first three stories and the underground structure to be built simultaneously. A second pile wall was built with steel columns to form bearing piles, and then a rig was attached to the columns to support the concrete core (Bogomil, 2020). See Figure 5-71.

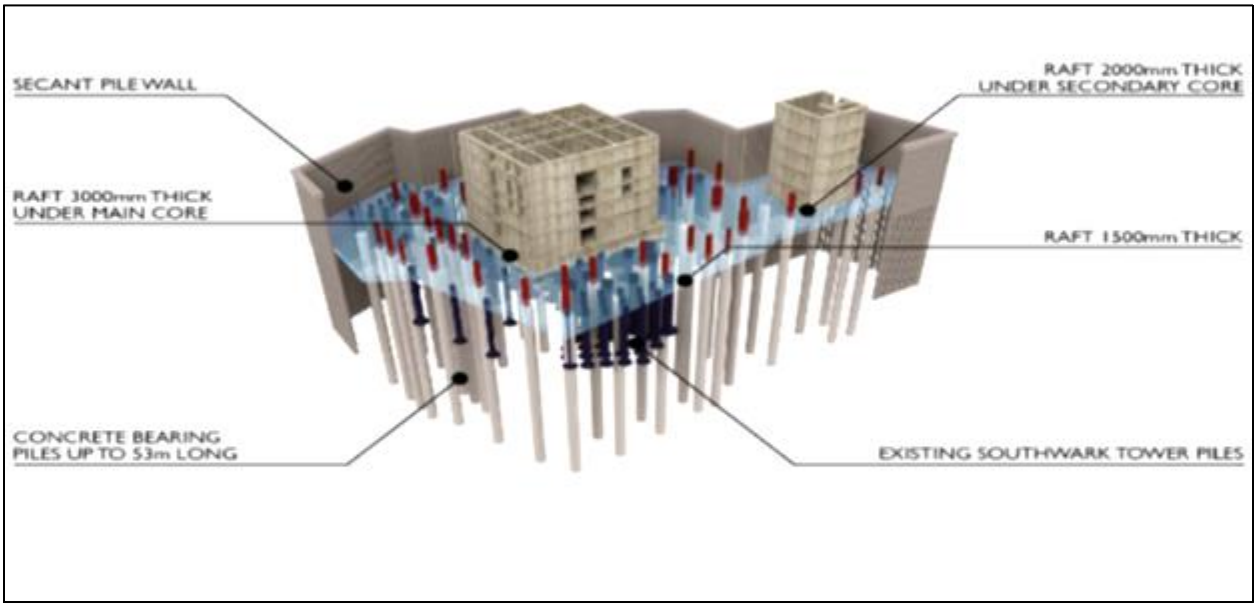


Figure 5-71 Shard design (Bogomil, 2020)

Constructing 460 pieces of steel weighing 530 tonnes (Galvanized type), structured in a 1.5m grid framework (STEEL FOCUS: THE SHARD-Some pointers on reaching the top, 2022) has given the dynamic design and optimised usage of materials, especially in steel, alongside with glass and steel which were combined like a mesh made of layers, reaching its apex between the 72 and 95th floors with the steel structure to look like a crown (Sungur et al., 2021).

The spire of the building features a triple-height enclosed viewing gallery on level 69 and an external platform on level 72, designed to resemble a ship's deck with a hardwood timber floor. The plant and chillers are located on level 75, while the lift goes up to level 78, maintaining the same level of finishes throughout (Intelligence for Architects, 2023).

The Shard is a notable structure despite its relatively light weight of 530 tons compared to the building's total weight of 12,500 tons. Standing at 60 meters and spanning 23 storeys, it required careful construction due to its elevated position 300 meters above the ground, where wind speeds can reach 100 mph (Parker, 2012).

The spire was assembled in modules to ensure safety and efficiency, with steelwork and flooring built-in segments small enough to fit on trailers. These segments were then bolted together on-site, minimising the number of crane lifts and reducing potential delays. Before final assembly, a dry run was conducted at a separate location, allowing for risk assessment, issue identification, and aesthetic adjustments. This strategic approach proved successful, especially considering the challenging weather conditions that limited crane operations during the construction of the upper levels (Parker, 2012).

During the design of the viewing levels, the architects were mindful of minimising visible connections, through limiting the structure segments to 23 out of 95 storeys as mentioned before, this benefits the tower of having better views especially after the floor 23. They aimed to enhance the steelwork's refinement, considering that people would look upwards and outwards through the structure. Giles Reid, the London representative of the Renzo Piano Building Workshop, emphasised the importance of achieving a high standard and pushing the boundaries.

Figure 5-72 presents the Shard spire erected in three sections at Severfield-Reeve's Dalton plant.

Figure 5-72 Trial assembly (Intelligence for Architects, 2023)

For The Shard in London, the project primarily used hot-dip galvanized steel. This process entails dipping the steel into molten zinc, creating a thick, durable coating that is highly resistant to corrosion. This type of galvanization is particularly suitable for large, exposed structural elements, such as those in The Shard, which require robust protection against the elements. Given the building's significant exposure and the need for long-term durability, hot-dip galvanizing was selected over electro-galvanizing. The latter provides a thinner zinc layer, making it more appropriate for smaller items with less exposure to harsh condition (History of galvanizing, 2024).

To validate this, a comparison assessment will be made between using hot dipped steel and normal galvanized steel will is produced in Figure 5-76.

A comprehensive analysis is necessary to determine whether utilizing recycled materials alone is sufficient to achieve significant reductions in environmental impacts and whether it qualifies as a sustainable construction method. The short answer is yes, as embodied impacts result from the energy consumed in extracting, processing, and delivering new materials. However, uncertainties exist regarding recycled materials, such as demolition techniques, transportation, and waste management. A thorough research study, incorporating solid data and critical analysis, will provide a more accurate and integrated answer to these questions, considering the latest research in the field.

Despite its impressive dimensions, with a thickness of 3 meters and four layers of reinforcement in each direction, the construction of this slab was a significant undertaking. It required the largest continuous concrete pour in the UK, involving three concrete pumps and 700 truckloads over 36 hours, resulting in a massive volume of 5,500 m^3, part of the whole 54,000m^3 of concrete used (Parker, 2012).

According to (Parker, 2012), to mitigate environmental impact, the concrete utilised ground-granulated blast furnace slag (GGBS), a by-product of steelmaking, as a substitute for 70% of the traditionally used Portland cement. This substitution significantly reduced the carbon footprint, eliminating approximately 700 tonnes of CO_2 emissions from the base slab alone. Additionally, using slag resulted in less heat generation during the curing process. However, even with these measures, the base slab's temperature during curing still exceeded 60°C.

Regarding the environmental sustainability of the Shard, (Brooks and Rich, 2016) described the project as "symbolising sustainable development, mainly through sustainably procured materials, and the incubator for sustainable construction". Furthermore, (Sungur et al., 2021) have pointed out five main parameters:

1. To decrease the traffic load of the city in terms of CO_2 emissions
2. Steel spire will eliminate the three-million-pound damper system
3. Triple glazed blue panel systems
4. Tapering against the wind aerodynamic
5. Reuse of recycled materials in terms of construction

Only number five is the most relevant to this research because it was the only point considering embodied energy and embodied carbons.

5. Challenges and Gaps

The main challenge of the Shard project started before the construction works commenced due to the reasons discussed in the introduction and rationale of this case study. Still, it should be referred to that this project was the ignition and motivation to build more high-rise buildings, particularly in London because it represented the critical role in creating a sustainable built environment; moreover, a delay was caused by the Chartered Association of Building Engineers (CABE), and English Heritage who believed that this project would ruin the culture and historical view of London (Bogomil, 2020).

Gaps of knowledge in the project can be presented by a need for direct information on the construction phase, prefabrication methods besides steel and glass installation, transportation environmental impacts, and carbon emissions numbers.

6. Data Collection Analysis

Since the project is relevantly new, the charts analysed will be based on document type and subject area.

A general Scopus search resulted in 2,847 documents, and then after refining it to Engineering, Environmental Science, and Materials Science, the results narrowed down to 787 documents. Then, the keyword "Construction" was used to filter the results into 97 documents. Only ten relevant ones were used. See Figures 5-73 and 5-74.

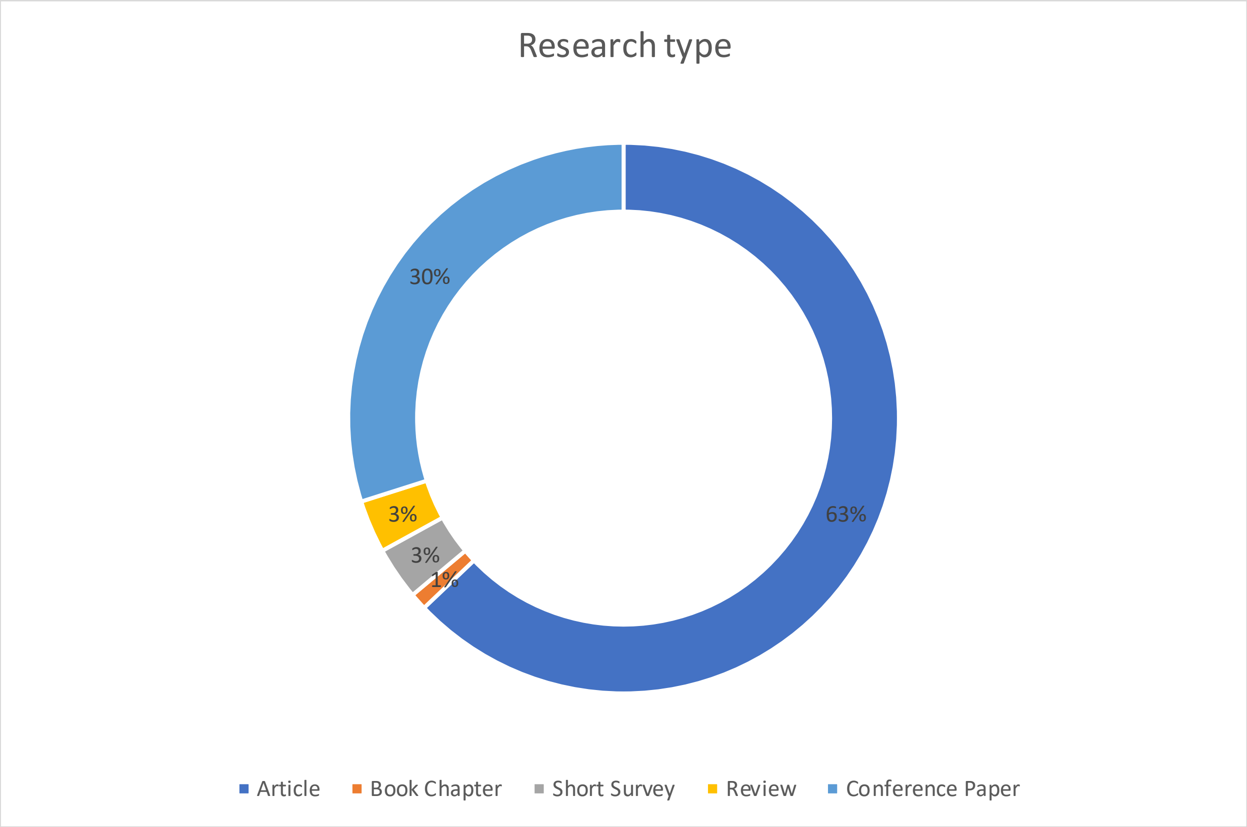


Figure 5-73 Types of research

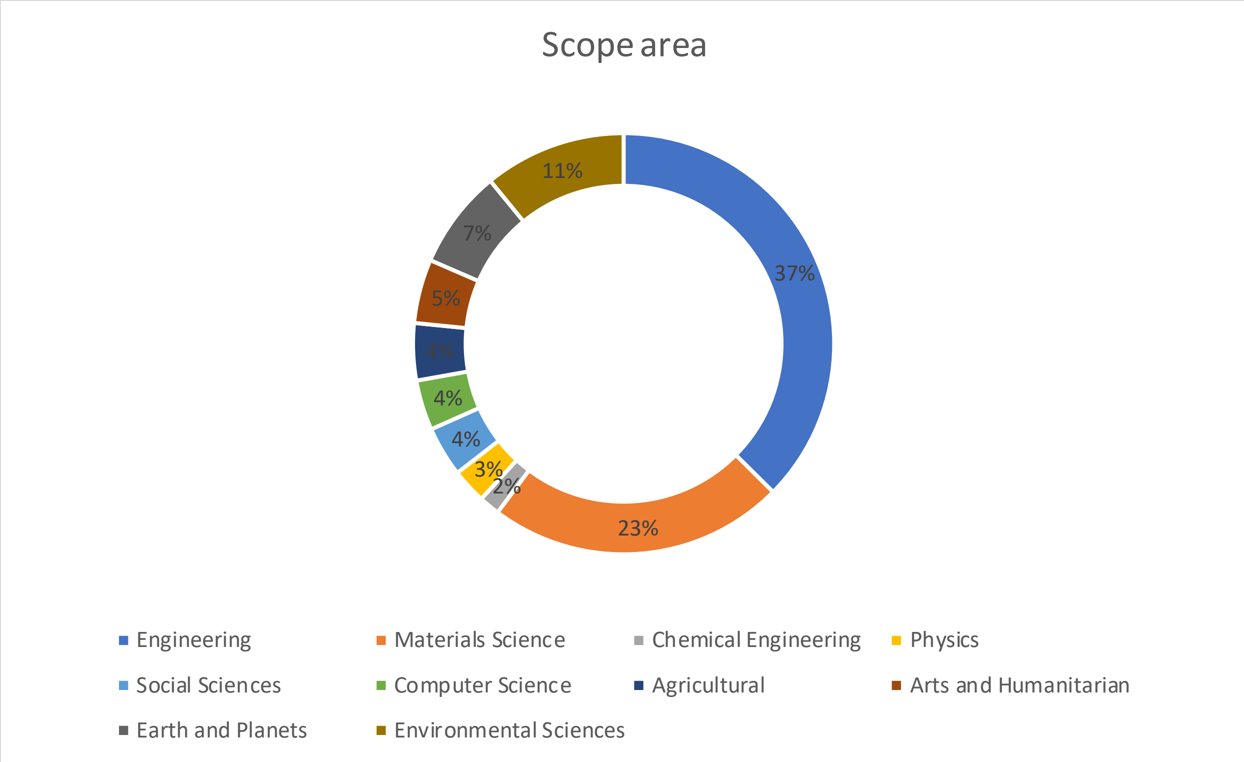


Figure 5-74 Data scope areas

7. Sustainability and Carbon Footprint

Steel, the primary material used in structuring the Shard, was analysed using the LCA software database by Environmental Footprint 3.1 (adapted for SimaPro substances). The LCA approach was used. Concrete was substantial in the project, so it was analysed in Figure 5-77.

The Environmental Footprint method is the impact assessment method adopted in the Environmental Footprint (EF) transition phase of the European Commission. The implementation is based on the Environmental Footprint 3.1 method published during the EF transition phase. It includes the normalisation and weighting factors published in July 2022. The steel LCA process is explained in Figure 5-75.

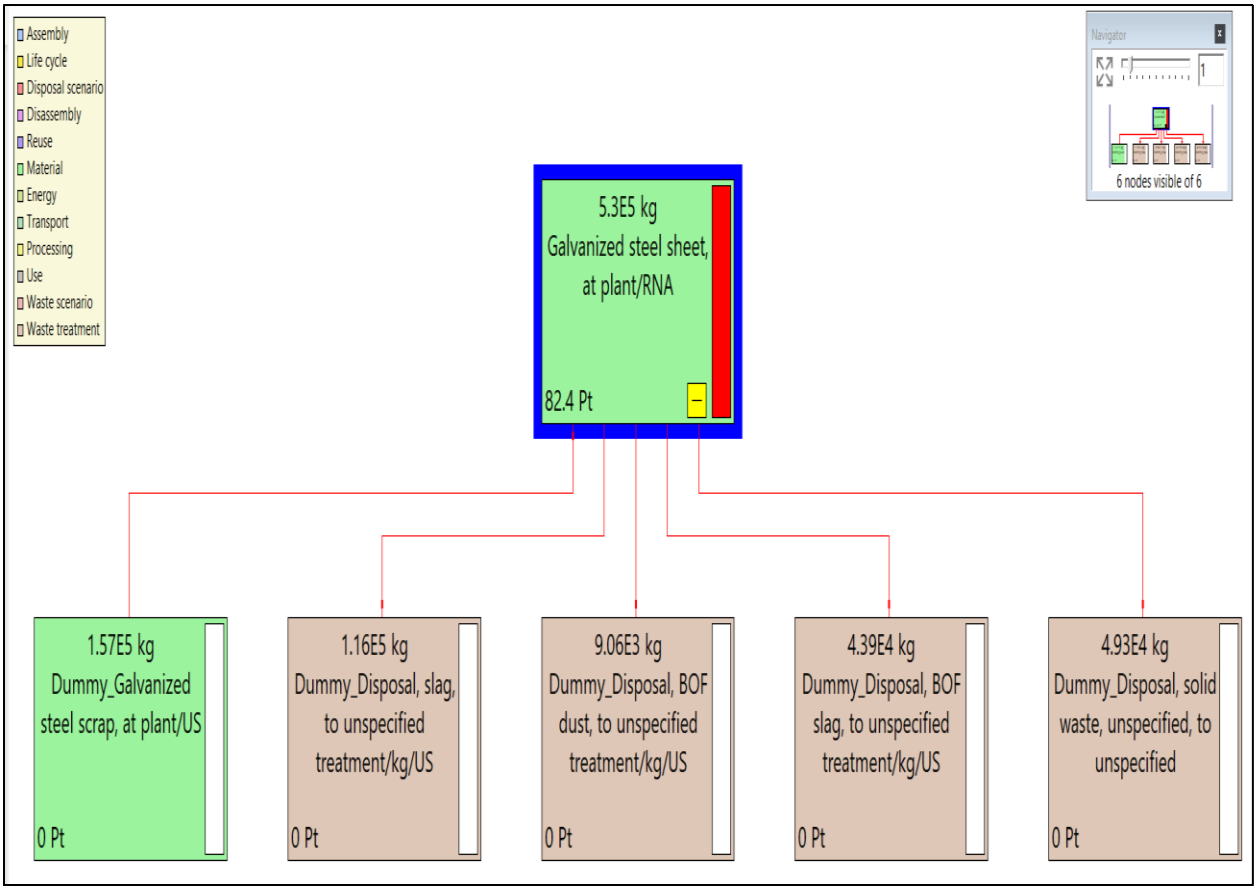
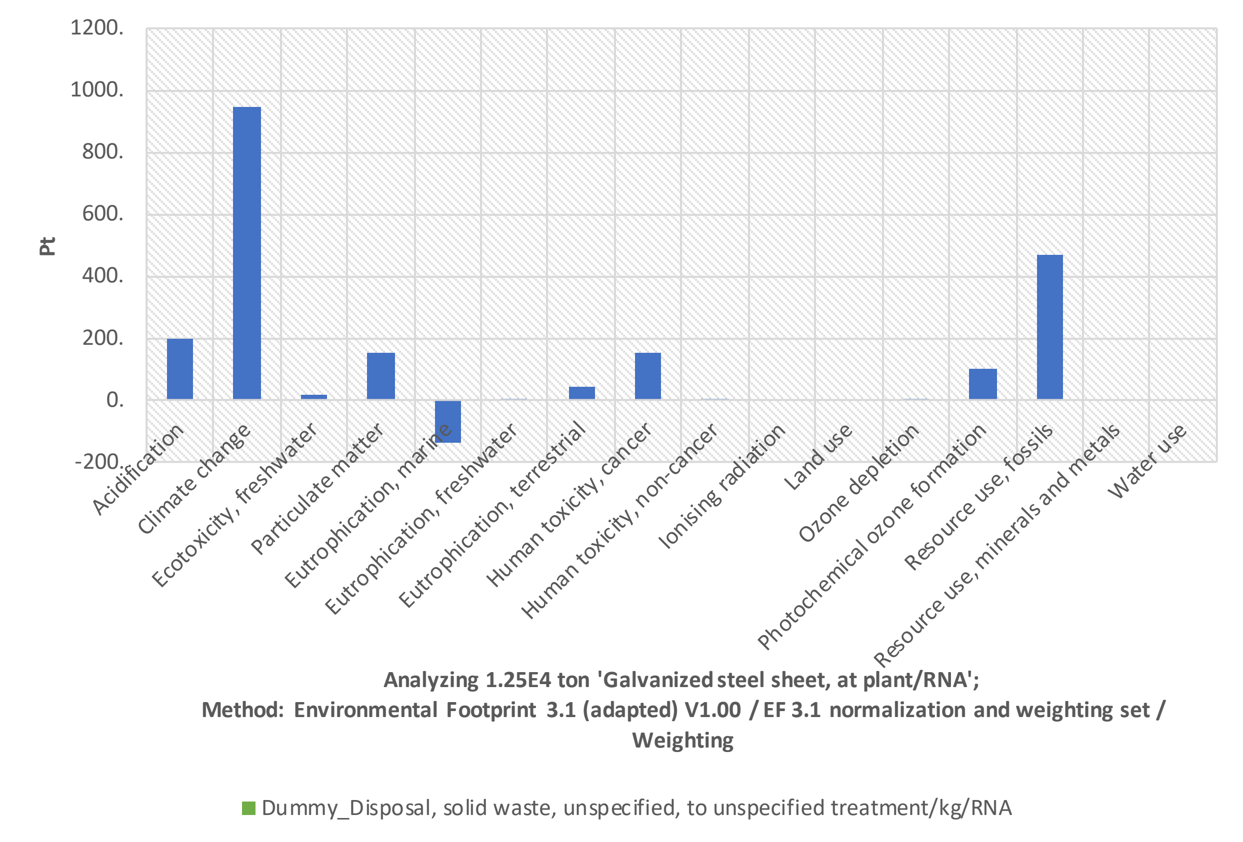


Figure 5-75 Galvanized steel LCA production process

The LCA environmental impacts associated with the galvanized steel used in the Shard project are illustrated in Figure 5-76.



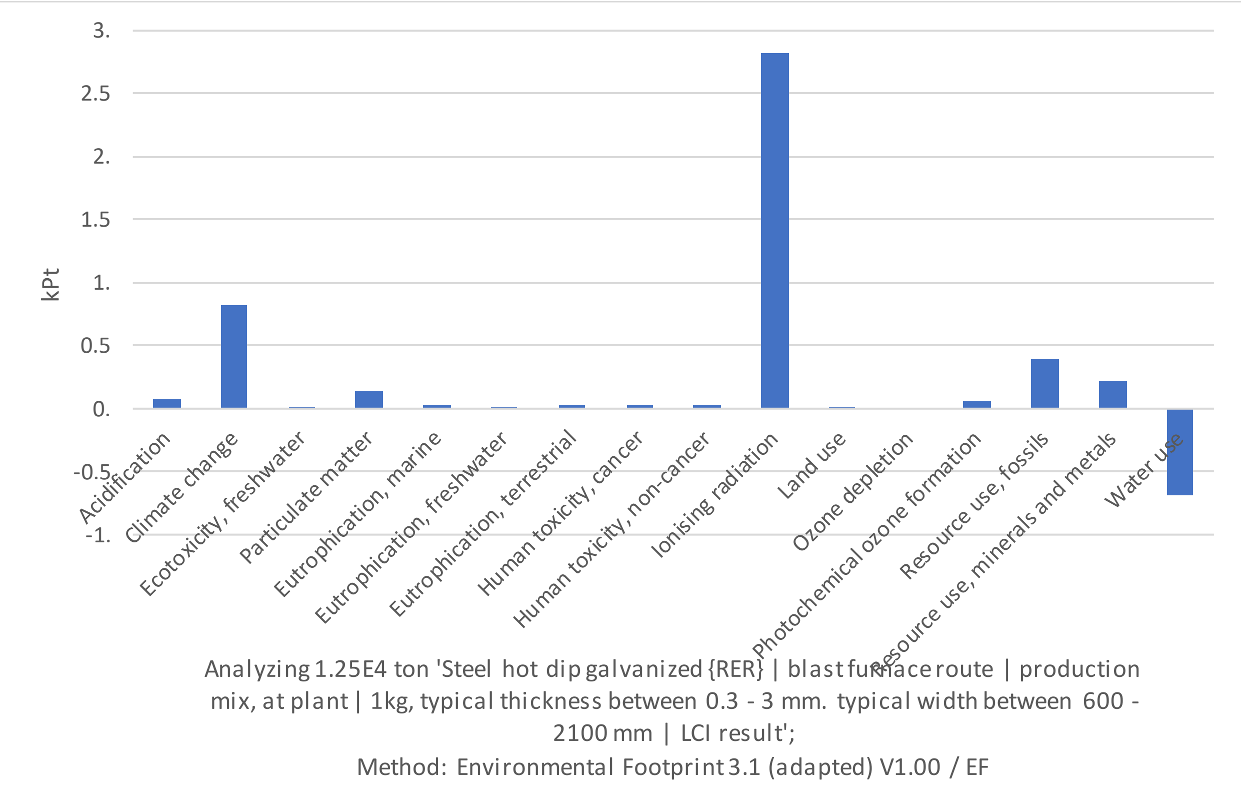


Figure 5-76.a) Galvanized steel LCA environmental impacts, b) Hot-dip Galvanized steel LCA

The data presented in Figure 5-76 introduced substantial findings, which show the project consumption of galvanized steel with the minimum usage of concrete, plus using recycled materials (20% of the steel used in the Shard is from recycled materials (RIBA, 2012)), provided a lower impact on the environment, compared with reinforced concrete designed buildings that were used in Khalifa project for example. However, using a galvanized hot-dip steel rather than normal one, came with the price of increasing the ionising radiation amounts.

Hot dipped galvanized steel showed the similar results concerning climate change and increased the ionising radiation outcome. To analyse this, LCA will not be used to conduct the analysis because it does not contain recycling factors (since recycled materials are used after the demolition of projects which comes at the end of life cycle phases). Also, the normal galvanized steel showed lower fossil resources impacts.

Moreover, Table 5-28 presents the environmental impacts of steel on the project, which are relevant to climate change and airborne emissions, while concrete environmental impacts are demonstrated in Figure 5-77.

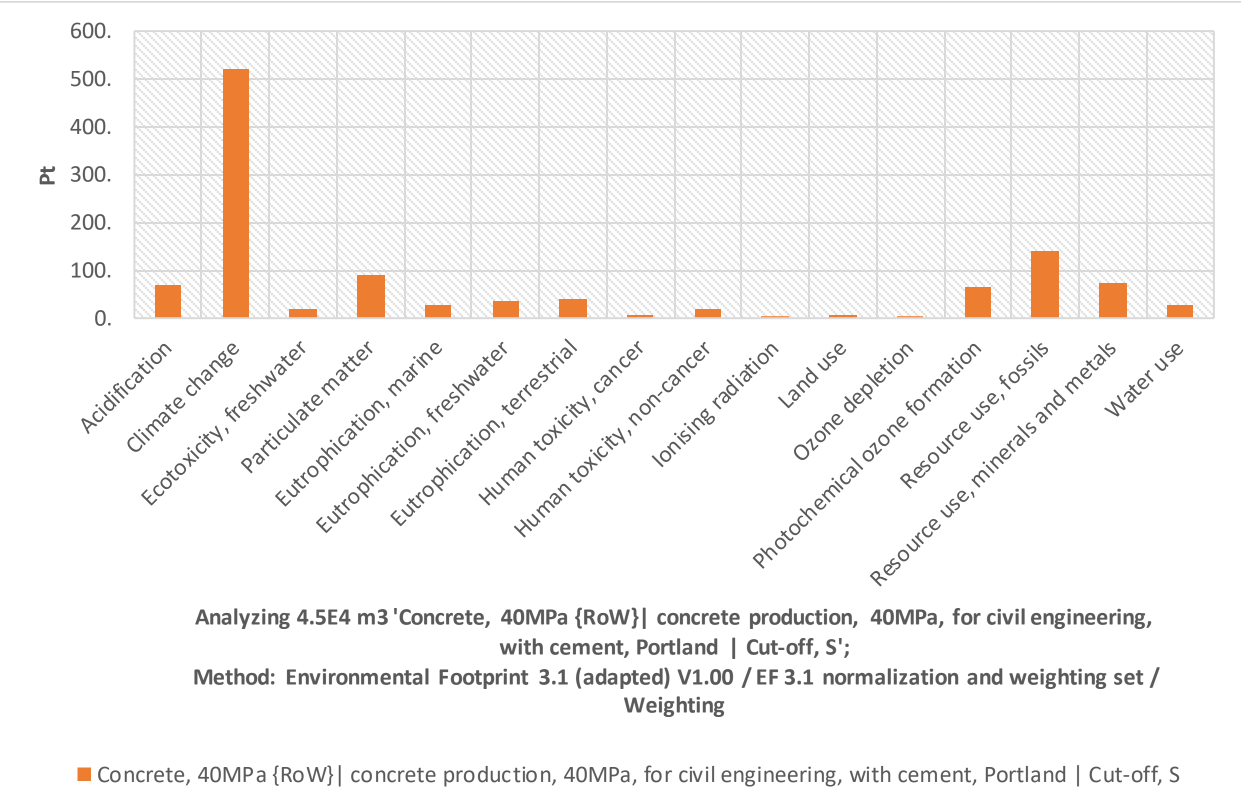


Figure 5-77 Concrete environmental impacts

Table 5-28 Steel climate change airborne emissions

Compartment: Airborne emission
Indicator: Weighting
Cut-off: 0%
☑ Default units
☐ Per sub-compartment
Category: Climate change
◉ Standard
○ Group
☐ Exclude long-term emissions
☑ Skip unused
☐ Per impact category

No	Substance	Compartr	Unit	Total	Steel Electrogalvan
	Total of all compartments		Pt	909	909
	Total of airborne emission		Pt	909	909
1	Carbon dioxide, fossil	Air	Pt	847	847
2	Methane, fossil	Air	Pt	60.6	60.6
3	Dinitrogen monoxide	Air	Pt	1.37	1.37
4	Methane, tetrafluoro-, CFC-14	Air	Pt	0.332	0.332
5	Methane, biogenic	Air	Pt	0.268	0.268
6	Carbon dioxide, land transformation	Air	Pt	0.208	0.208
7	Ethane, hexafluoro-, HFC-116	Air	Pt	0.0325	0.0325
8	Ethane	Air	Pt	0.00454	0.00454
9	Methane, trifluoro-, HFC-23	Air	Pt	0.000536	0.000536
10	Propane	Air	Pt	0.000197	0.000197
11	Propane, 1,1,1,3,3-pentafluoro-, HFC-245fa	Air	Pt	9.14E-5	9.14E-5
12	Nitrogen fluoride	Air	Pt	2.78E-5	2.78E-5
13	Ethane, pentafluoro-, HFC-125	Air	Pt	2E-5	2E-5
14	Butane	Air	Pt	1.55E-5	1.55E-5
15	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	Pt	5.05E-6	5.05E-6
16	Ethane, 1,1,2-trifluoro-, HFC-143	Air	Pt	1.74E-6	1.74E-6
17	Sulfur hexafluoride	Air	Pt	1.27E-6	1.27E-6
18	Methane, difluoro-, HFC-32	Air	Pt	6.2E-7	6.2E-7
19	Methane, monochloro-, R-40	Air	Pt	2.12E-9	2.12E-9
20	Methane, dichloro-, HCC-30	Air	Pt	7.6E-10	7.6E-10
21	Trichloroethylene	Air	Pt	6.04E-10	6.04E-10
22	Chloroform	Air	Pt	1.23E-10	1.23E-10
23	Ethane, 1,2-dichloro-	Air	Pt	1.33E-12	1.33E-12
24	Tetrachloroethylene	Air	Pt	1.21E-12	1.21E-12
25	Ethane, chloro-	Air	Pt	1.64E-15	1.64E-15
26	Bromoform	Air	Pt	7.89E-16	7.89E-16
27	Pentane, perfluoro-	Air	Pt	7.34E-16	7.34E-16
28	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	Pt	3.81E-16	3.81E-16
29	Ethane, 1,1-difluoro-, HFC-152a	Air	Pt	1.29E-16	1.29E-16
30	Ethane, 1,2-dibromo-	Air	Pt	9.92E-17	9.92E-17
31	Methane, dichlorofluoro-, HCFC-21	Air	Pt	1.3E-19	1.3E-19

To calculate the carbon impacts caused by steel per square meter, Table 5-29 Presents the climate change equivalent carbons.

Table 5-29 Galvanized steel environmental impacts

Damage category	Unit	Total	Galvanized steel sheet
Acidification	mol H+ eq	1.75E5	1.75E5
Climate change	kg CO2 eq	3.39E7	3.39E7
Ecotoxicity, freshwater	CTUe	4.4E7	4.4E7
Particulate matter	disease inc.	1	1
Eutrophication, marine	kg N eq	-9.13E4	-9.13E4
Eutrophication, freshwater	kg P eq	148	148
Eutrophication, terrestrial	mol Neq	2.02E5	2.02E5
Human toxicity, cancer	CTUh	0.125	0.125
Human toxicity, non-cance	CTUh	0.0343	0.0343
Iionising radiation	kBq U-235 eq	x	x
Land use	Pt	x	x
Ozone depletion	kg CFC11 eq	0.0923	0.0923
Photochemical ozone form	kg NMVOC eq	8.624	8.624
Resource use, fossils	MJ	3.678	3.67E8
Resource use, minerals and	kg Sb eq	x	x
Water use	m3 depriv.	x	x

$$CE = \frac{cc}{a} = 33900000/398490 = 85.07 \text{ kg } CO_2 / m^2$$

This number is relatively too low compared to the Khalifa project, which has two reasons that played a role: first, the recyclability of steel used and the galvanized type of steel as explained in Figure 5-76. Extended comparison and discussion could be found in the summary of the case studies (Figures 5-99 and 5-100), and in the Discussion Chapter.

8. Summary and Conclusion

The shard project can be considered a successful sustainable high-rise project based on the following observations:

1. The materials aspect was sustainable, as recyclability, and the steel and glass design and usage were sustainable
2. The Shard project encouraged high-density development in London, representing sustainable urban extension in congested cities (RPBW, 2022)
3. The design phase was critical considering the tower's operational energy consumption and usage phase
4. The project's duration (3 years and four months) indicates that it was a fast-track project, considering the large-scale size of the project, giving the chance to produce the minimum embodied carbons during the construction phase (Cradle-to-Site)

Case Study 5: Empire State Building

Project details

Location	New York
Size	208,879m^2
Budget	$40,948,900
Building type	Skyscraper
Building purpose	Office building, observation deck
Number of floors	102
Hight	443.2 m
Date of commencing construction	April 1930
Date of construction completion	May 1931
Architecture	Shreve, Lamb & Harmon
Structural engineer	Homer Gage Balcom
Main contractor	Starrett Bros. & Eken

Figure 5-78 ESB

1. Introduction

The ESB was the fastest erection of a skyscraper ever, according to many resources (Ghosh and Robson, 2015; Jacobsson and Wilson, 2018; Sacks and Bertelsen, 2008) and under the original budget by $23 million and cost only $40 million (Jacobsson and Wilson, 2018), but (Align, 2020) claims that the cost reached $60 million, nevertheless, perhaps there was a difference it was calculating the included items in the building; however, the critical issue is that mega projects are primarily vulnerable to fail or exceeding the budget, just like the AGT case study, where this project did not, plus that this research is not considering the cost as a priority.

The Empire State was, and still an icon of Western civilisation, and it operated in a global environment (Voeltz, 2010) and, according to (Sacks and Bertelsen, 2008), one of the world's most impressive building construction projects.

2. The Rational of the Case Study

The ESB project was chosen as a case study for several reasons; despite its construction more than 90 years ago, it still witnessed several sustainable construction approaches.

It represents the heritage of skyscrapers and how they still represent a sustainable method to meet the rapid demand of urbanisation, development, and human population. Furthermore, ESB construction methods, short time of construction, and optimised use of resources will enrich this research; such practices will be explained later.

3. Project Construction

Gathering data concerning the construction phase of the ESB proved challenging due to the passing of all individuals involved in the project. However, this research managed to access design details and construction processes through research papers, books, and websites. Figure 5-79 presents the parties involved in the ESB project.

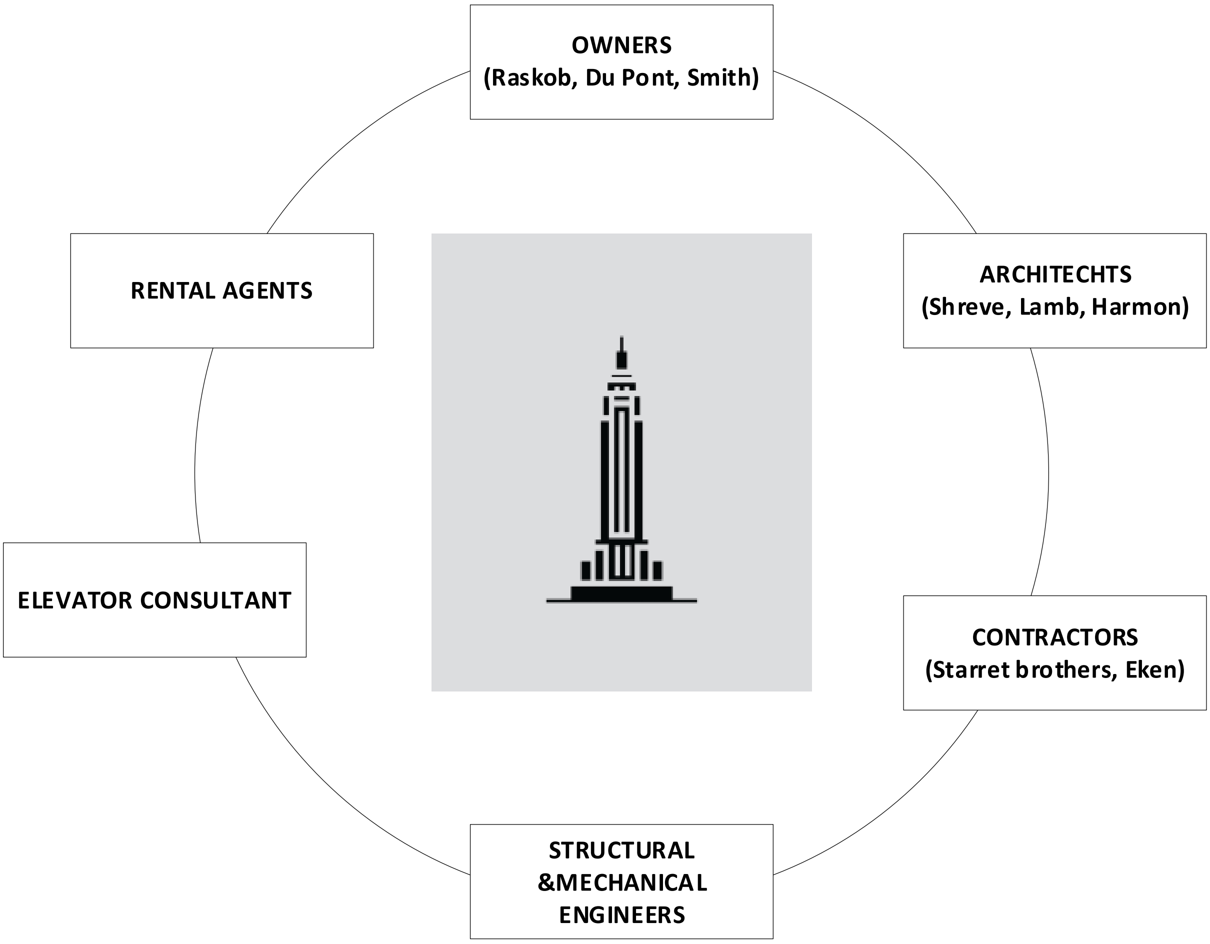


Figure 5-79 Projects parties (Ghosh and Robson 2015)

ESB construction process contains several systems and different materials, and this section will explore and analyse most of them. Starting with construction systems, the ESB project adopted the central systems:

1. Craft Construction
2. Mass Construction
3. Lean Construction
4. Off-site Construction

Craft construction is related to hand made works (Sacks and Bertelsen, 2008), which is still valid to our days, especially with specific jobs on site, while mass construction was adopted in the early 20th century from the car manufacturing industry, especially by Ford's production system or what was called Fordism (Williams et al., 1992).

The mass production system was created to respond to the high demands for goods or services, such as cars, foods, buildings, etc. The building sector, especially dwelling projects, had the advantages of mass production systems until recently. Mass construction systems contained the following characteristics (Sacks and Bertelsen, 2008):

1. Multiple uniform and repeated spaces or modules
2. Industrial supply chain management
3. Monitor and control production rates
4. Carefully designed logistic systems to deliver materials
5. Standardised work
6. Minimal variety of parts
7. Careful control of tolerances between parts
8. Maximising performance

However, this system had some customisation problems, which were solved by adopting lean production systems introduced earlier in this research, a system derived from the car manufacturing industry, but this time from Toyota.

OSC was adopted in several primary materials: steel frames, precast concrete, windows, and glass facades. This adoption proves that OSC was and still is a practical approach to creating a dynamic, sustainable building project, especially when combined with other systems such as craft and mass construction systems.

Such systems are essential to explore to pin down the environmental impacts of these high-rise building projects. (Fluhrer Caroline et al., 2010) Claim that ESB recently has reduced energy consumption and carbon emissions, reducing operational energy and carbon, but what about embodied carbon emissions?

The use phase of the building includes embodied carbons represented in the maintenance, refurbishment, and demolition works, which were introduced earlier in this research. So, when this building is recreated to reduce energy consumption and be more sustainable, it will, by default, reduce the embodied emissions.

On the other hand, in the cradle-to-site phase represented by construction works, we gathered data regarding the materials and systems used; all showed sustainable processes that presumably eventually reduced carbon emissions as much as possible at that time, especially knowing that they had been using construction systems that motivated such environmental impacts, which was introduced earlier.

Table 5-30 presents the detailed construction process of the ESB project.

Table 5-30 Project construction process in the ESB (Sacks and Bertelsen 2008)

Flow aspect		Description
Design & Information		Collaborative Design Team - immediate flow of design information. Regular release of design information in relatively small batches Standardized and simplified design involved a reduction of information flow needed on site Creation of the Empire State Building Club' to encourage open dialogue among every actor of the project
Previous Work		4 TAKT tasks fit to the structural elements of the building; flexibility of the remaining tasks to follow the pace set by the TAKT tasks
Material	Bulk Materials	Pull system to make materials keep moving to workstations Move materials only once Application of "reverse logistics" to remove rubble and packaging Material deliveries to site buffered from deliveries to work locations and weekly inventory of materials Material deliveries outside of the working hours
Prefabricated Components		No storage of prefabricated elements on site - unloading and setting in place as soon as they arrived Offsite staging: steel elements stored at the wharf and "pulled" by truck to the site as required
Crew		Staggered working hours of crews to match elevator capacities Food and other facilities provided on floors Guides at elevator relay stations to direct workers
Equipment		11 derricks, 17 hoists, 2 concrete plants, rail tracks and abundant other equipment in a dedicated logistic system Continuous availability during workdays (extensions performed outside working hours)
Space		Storage areas limited Temporary offices on a sidewalk bridge to avoid interference with the activities on site Ample floor areas organized in generie space
External Conditions		By law, work had to be stopped in case of rain, snow. high winds: enclosed building completely before the advent of severe winter

4. Materials

The ESB project used the conventional materials still in use so far: 57,000 tonnes of reinforced steel, 48,000 m^3 concrete (C30 and C40), 270,000 m^2 reinforced mesh, and 10 million bricks (R. Sacks and Partouche, 2010).

Since it was a fast-track project in a bustling area, excessive inventory was avoided by determining site logistics and using the materials within three days following their arrival (Ghosh and Robson, 2015). According to the same authors, these actions led to minimising the waste of materials (Ghosh and Robson, 2015) and cutting down unnecessary transportation. Figure 5-80 gives an example of how materials were transported throughout the project.

Figure 5-80 Construction works (Jacobsson and Wilson, 2018)

According to (R. Sacks and Partouche, 2010), the material handling and making in the project was done through the following process:

1. Standardising construction elements such as windows, frames, and stones make it possible to reduce installation time
2. Material transportation was used in a mass process to reduce workers' movements on site
3. It enhanced the workflow of contractors by controlling the contractors' pace
4. The work on-site uses off-site prefabrication as much as possible with perfect accuracy
5. Mass construction was used as it is characterised by uniformity, repeated modules, supply chain management, monitoring product rates, carefully designed logistics systems for materials delivery, and a minimum variety of parts

Prefabricated materials were planned and distributed as an assembly line of standard parts moving in flow to reduce the time between arrival and on-site use (R. Sacks and Partouche, 2010). Moreover, the manufacturing industry's influence on the planning and execution of the ESB is due to the driving force of the John Raskob. His connection with General Motors (GM) helped insert car manufacturing systems into construction processes (Ghosh and Robson, 2015).

Figure 5-81 Construction of high floors (Geographic Guide, 2022)

5. Challenges

Constructed during the Great Depression, this large-scale project faced a multifaceted challenge. Moreover, its location within a densely congested urban area further complicates matters. Factors like the availability of materials, skilled labour, efficient transportation, and adherence to health and safety standards may have presented additional obstacles to the project's completion.

6. Data Collection Analysis

Many critical research studies were conducted on the ESB project, obviously due to its importance and the long time since its delivery. See Figures 5-82 and 5-83.

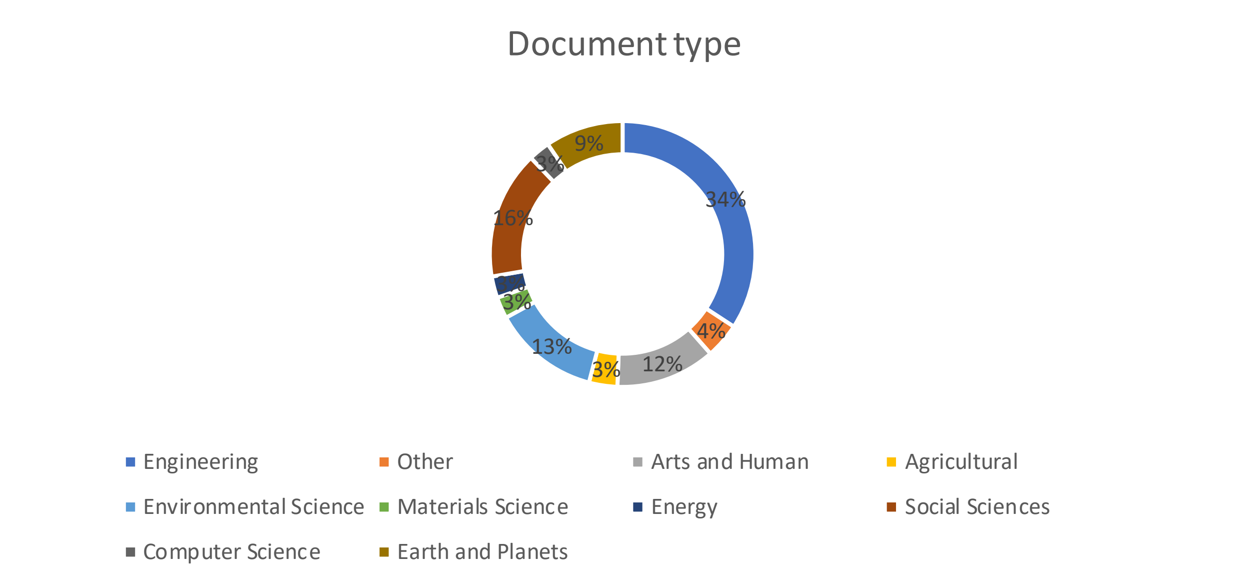


Figure 5-82 ESB research documents by type (Scopus)

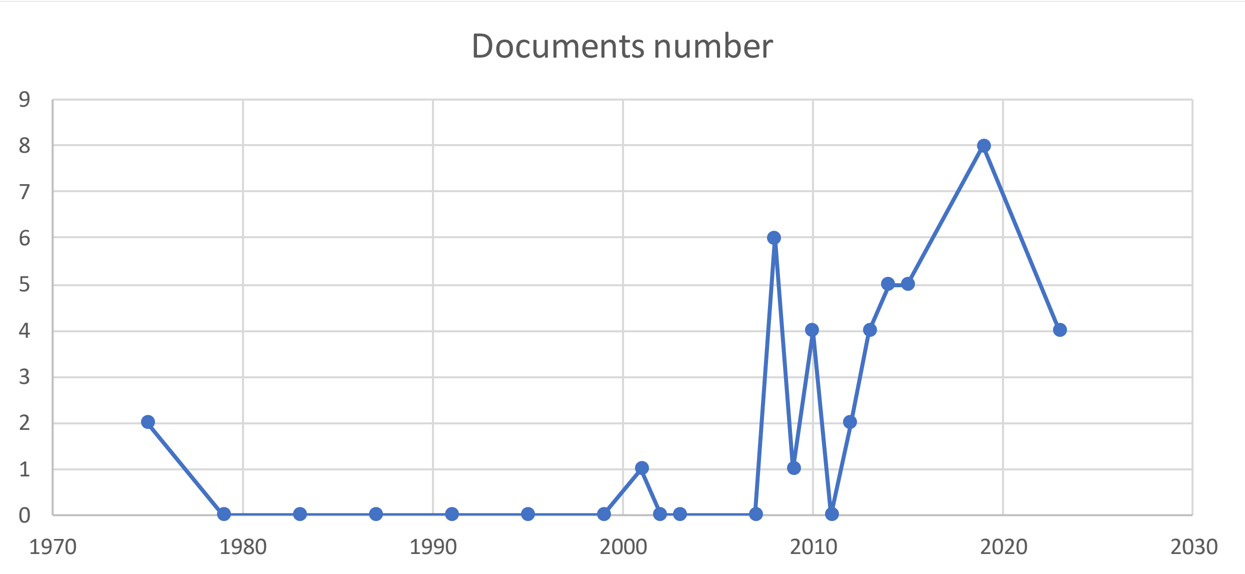


Figure 5-83 Number of ESB research documents by year (Scopus)

Figures 5-82 and 83 demonstrated a notable rise in the number of research studies conducted over the past 15 years, with a particular emphasis on various background topics predominantly within the engineering field. These figures illustrate an increasing interest in engineering disciplines and reflect the growing significance of engineering-related research in addressing contemporary challenges and advancing technological solutions. The inclusion of diverse background topics within the engineering discipline indicates the interdisciplinary nature of modern engineering research and its relevance to a wide range of fields, further underscoring its importance in shaping scientific and technological advancements.

7. Sustainability and Carbon Footprint

The Environmental Footprint method is the impact assessment method adopted in the transition phase of the European Commission. The implementation is based on the Environmental Footprint 3.1 method published during the EF transition phase. It includes the normalisation and weighting factors published in July 2022.

The concrete LCA analysis assumed that all concrete used was grade C40, as presented in Figure 5-84.

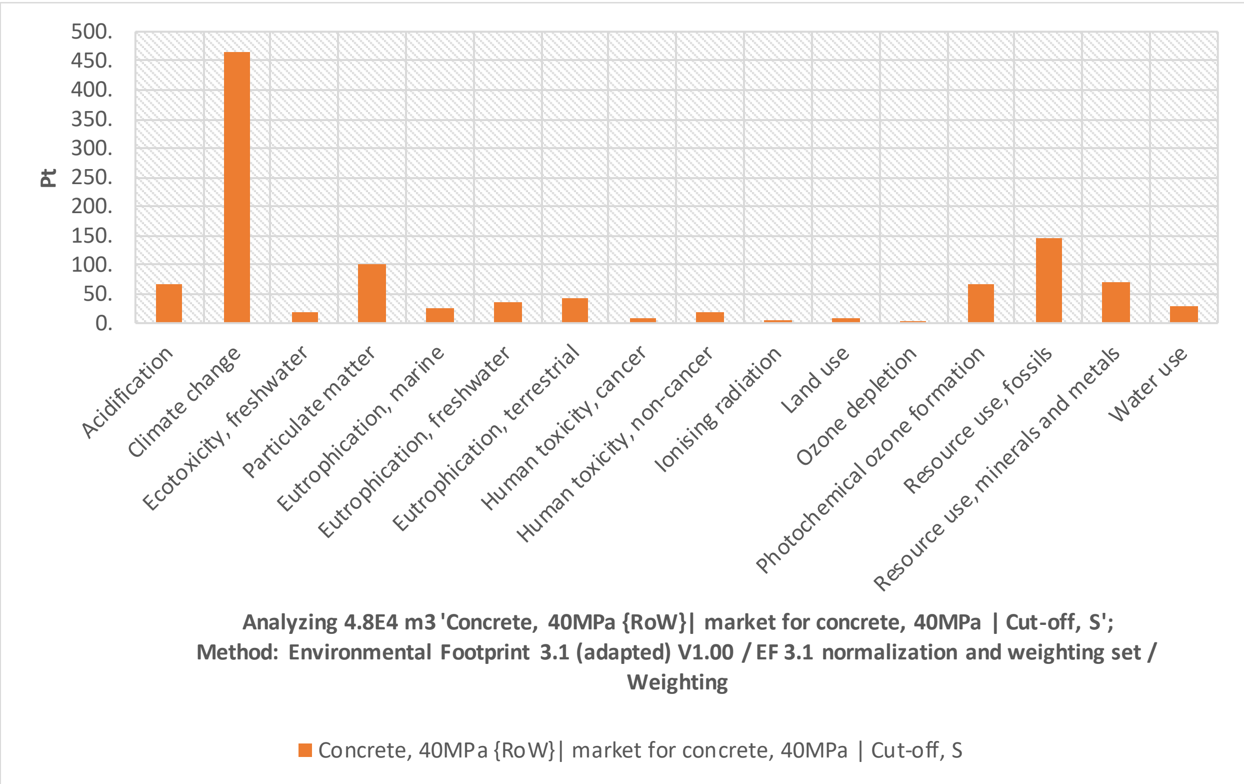


Figure 5-84 Concrete LCA environmental impacts

Climate change was also the highest impact in the ESB project; moreover, the timing of the project, the availability of sustainable methods and materials, and available technologies such as telecommunication explain the high number of environmental impacts of ESB compared to the other case studies projects.

Moreover, climate change was analysed using LCA software according to the associated emissions presented in Table 5-31.

Table 5-31 Concrete LCA climate change emissions

Compartment: All compartments
Indicator: Weighting
Cut-off: 0%
☐ Default units
☐ Per sub-compartment
Category: Climate change
◉ Standard
☐ Exclude long-term emissions
☑ Skip unused
○ Group
☐ Per impact category

No	Substance	Compartr	Unit	Total	Concrete, 40MPa
1	Carbon dioxide, fossil	Air	Pt	437	437
2	Methane, fossil	Air	Pt	24.2	24.2
3	Dinitrogen monoxide	Air	Pt	1.31	1.31
4	Methane, biogenic	Air	Pt	0.394	0.394
5	Sulfur hexafluoride	Air	Pt	0.339	0.339
6	Carbon dioxide, land transformation	Air	Pt	0.204	0.204
7	Methane, tetrafluoro-, CFC-14	Air	Pt	0.0702	0.0702
8	Methane, trifluoro-, HFC-23	Air	Pt	0.0117	0.0117
9	Methane, chlorodifluoro-, HCFC-22	Air	Pt	0.00895	0.00895
10	Ethane, hexafluoro-, HFC-116	Air	Pt	0.00869	0.00869
11	Methane, land transformation	Air	Pt	0.00177	0.00177
12	Methane, tetrachloro-, CFC-10	Air	Pt	0.00152	0.00152
13	Ethane	Air	Pt	0.00141	0.00141
14	Methane, bromotrifluoro-, Halon 1301	Air	Pt	0.00102	0.00102
15	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	Pt	0.000559	0.000559
16	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	Pt	0.000334	0.000334
17	Ethane, 1,1-difluoro-, HFC-152a	Air	Pt	0.000192	0.000192
18	Methane, dichloro-, HCC-30	Air	Pt	0.000183	0.000183
19	Methane, dichlorodifluoro-, CFC-12	Air	Pt	5.65E-5	5.65E-5
20	Propane	Air	Pt	5.11E-5	5.11E-5
21	Butane	Air	Pt	2.74E-5	2.74E-5
22	Ethane, 1,2-dichloro-	Air	Pt	2.15E-5	2.15E-5
23	Chloroform	Air	Pt	1.95E-5	1.95E-5
24	Methane, bromochlorodifluoro-, Halon 1211	Air	Pt	1.53E-5	1.53E-5
25	Ethane, 1,1,1-trichloro-, HCFC-140	Air	Pt	1.06E-5	1.06E-5
26	Methane, monochloro-, R-40	Air	Pt	9.62E-6	9.62E-6
27	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	Pt	3.38E-6	3.38E-6
28	Tetrachloroethylene	Air	Pt	2.86E-6	2.86E-6
29	Methane, trichlorofluoro-, CFC-11	Air	Pt	2.47E-7	2.47E-7
30	Ethane, chloro-	Air	Pt	2.05E-7	2.05E-7
31	Methane, bromo-, Halon 1001	Air	Pt	1.63E-7	1.63E-7
32	Trichloroethylene	Air	Pt	1.49E-8	1.49E-8
33	Methane, dichlorofluoro-, HCFC-21	Air	Pt	5.75E-9	5.75E-9
34	Nitrogen fluoride	Air	Pt	4.18E-10	4.18E-10
35	Ethane, pentafluoro-, HFC-125	Air	Pt	1.41E-29	1.41E-29
36	Ethane, 1,1,1-trifluoro-, HFC-143a	Air	Pt	1.69E-30	1.69E-30

Analyzing 4.8E4 m3 'Concrete, 40MPa {RoW}| market for concrete, 40MPa | Cut-off, S';Method: Environmental Footprint 3.1 (

Table 5-31 highlights that carbon emissions constitute most GHG contributions. This emphasises the reason behind this research's focus on carbon emissions.

Steel analysis using LCA is presented in Figure 5-85 and Table 5-32.

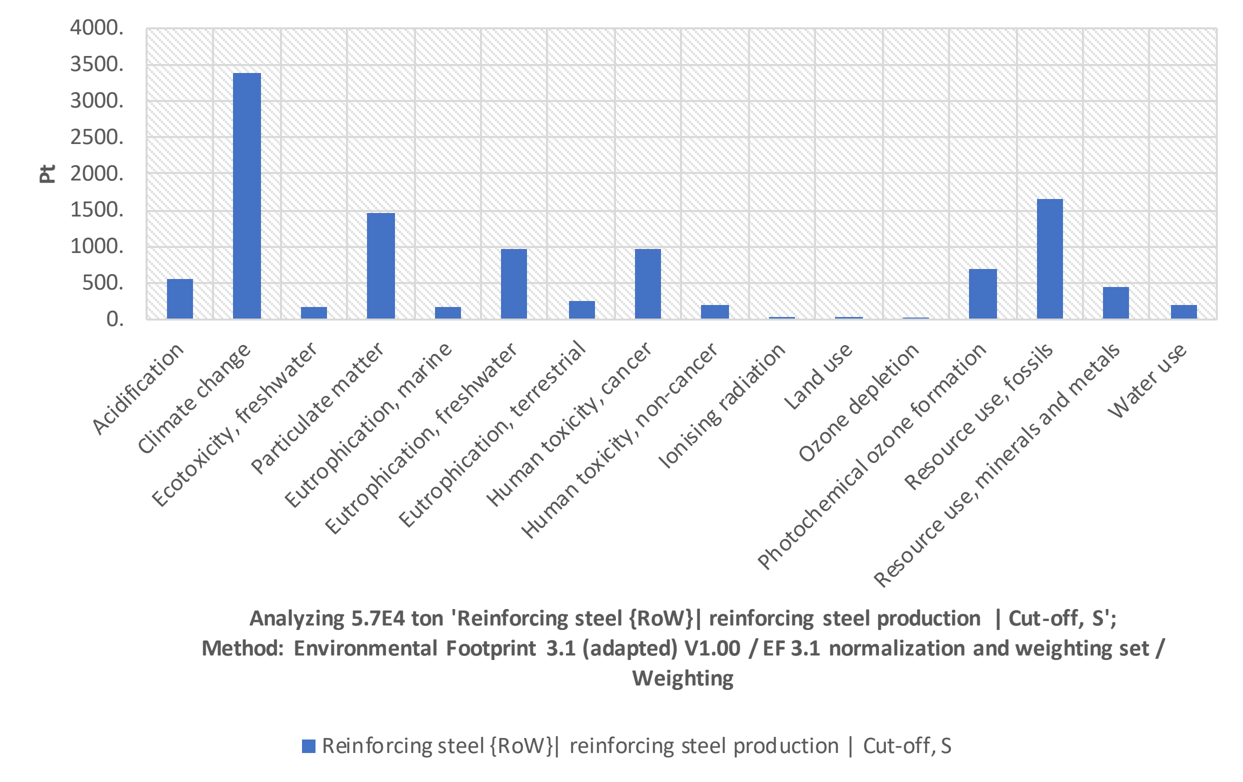


Figure 5-85 Reinforced steel LCA environmental impacts

Analysing the database using LCA, climate change and carbon emissions were the highest.

Table 5-32 Reinforced steel airborne emissions

Compartment: Airborne emission
Indicator: Weighting
Cut-off: 0%
Default units
Per sub-compartment
Category: Climate change
Standard
Exclude long-t
Skip unused
Group
Per impact cate

No	Substance	Compartr	Unit	Reinforcin steel
	Total of all compartments		kPt	3.39
	Total of airborne emission		kPt	3.39
1	Carbon dioxide, fossil	Air	kPt	3.01
2	Methane, fossil	Air	kPt	0.357
3	Dinitrogen monoxide	Air	kPt	0.0122
4	Sulfur hexafluoride	Air	kPt	0.00334
5	Methane, chlorodifluoro-, HCFC-22	Air	kPt	0.00274
6	Carbon dioxide, land transformation	Air	kPt	0.00217
7	Methane, biogenic	Air	kPt	0.00208
8	Methane, tetrafluoro-, CFC-14	Air	kPt	0.000333
9	Methane, trifluoro-, HFC-23	Air	kPt	9.37E-5
10	Ethane	Air	kPt	6.17E-5
11	Ethane, hexafluoro-, HFC-116	Air	kPt	4.19E-5
12	Methane, land transformation	Air	kPt	1.53E-5
13	Methane, tetrachloro-, CFC-10	Air	kPt	7.18E-6
14	Methane, bromotrifluoro-, Halon 1301	Air	kPt	5.64E-6
15	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	kPt	2.69E-6
16	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	kPt	1.17E-6
17	Methane, dichlorodifluoro-, CFC-12	Air	kPt	9.87E-7
18	Ethane, 1,1-difluoro-, HFC-152a	Air	kPt	8.99E-7
19	Propane	Air	kPt	3.07E-7
20	Methane, bromochlorodifluoro-, Halon 1211	Air	kPt	1.93E-7
21	Methane, dichloro-, HCC-30	Air	kPt	1.58E-7
22	Butane	Air	kPt	1.23E-7
23	Chloroform	Air	kPt	1.15E-7
24	Ethane, 1,1,1-trichloro-, HCFC-140	Air	kPt	1.12E-7
25	Methane, monochloro-, R-40	Air	kPt	1.02E-7
26	Tetrachloroethylene	Air	kPt	4.27E-8
27	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	kPt	3.62E-8
28	Ethane, 1,2-dichloro-	Air	kPt	1.58E-8
29	Methane, trichlorofluoro-, CFC-11	Air	kPt	5.74E-9
30	Methane, bromo-, Halon 1001	Air	kPt	1.52E-9

To analyse the LCA in numbers, Table 5-33 presents the climate change impact of the steel used in the project.

Table 5-33 Reinforced steel environmental impacts

Damage category	Unit	Total	Reinforcing steel {GLO)
Acidification	mol H+ eq	5.11E5	5.11E5
Climate change	kg CO2 eq	1.22E8	1.228
Ecotoxicity, freshwater	CTUe	5.45E8	5.45E8
Particulate matter	disease inc.	9.92	9.92
Eutrophication, marine	kg N eq	1.23E5	1.23E5
Eutrophication, freshwater	kg P eq	5.5E4	5.5E4
Eutrophication, terrestrial	mol Neq	1.286	1.286
Human toxicity, cancer	CTUh	0.775	0.775
Human toxicity, non-cance	CTUh	1.46	1.46
Ionising radiation	kBq U-235 eq	3.746	3.74E6
Land use	Pt	3.67E8	3.67E8
Ozone depletion	kg CFC11 eq	2.33	2.33
Photochemical ozone form	kg NMVOC eq	6.18E5	6.18E5
Resource use, fossils	MJ	1.31E9	1.31E9
Resource use, minerals	kg 5b eq	381	381
Water use	m3 depriv.	2.567	2.56E7

Using Equation 7 resulted in very high carbon emissions per square meter for only reinforcing steel.

$$\boldsymbol{CE = \frac{CC}{a} = \frac{1.22E8}{208879} = 584.07\ kgCO2e/m2}$$

The significantly higher number observed in this case study can primarily be attributed to the old date of the project's construction, which necessitated the utilisation of more resource-intensive energy sources and reduced reliance on modular machinery. These numbers even exclude the installation of 270,000 m^2 of steel mesh!

The concrete calculation used the same approach presented in Table 5-34.

Table 5-34 Concrete environmental impacts

Damage category	Unit	Total	Concrete, 40MPa
Acidification	mol H+ eq	6.584	6.58E4
Climate change	kg C02 eq	1.99E7	1.99E7
Ecotoxicity, freshwater	CTUe	5.43E7	5.43E7
Particulate matter	disease inc.	0.652	0.652
Eutrophication, marine	kg N eq	1.94	1.9E4
Eutrophication, freshwater	kg P eq	2.33E3	2.33E3
Eutrophication, terrestrial	mol N eq	2.13E5	2.13E5
Human toxicity, cancer	CTUh	0.00602	0.00602
Human toxicity, non-cance	CTUh	0.151	0.151
Ionising radiation	kBq U-235 eq	2.61E5	2.615
Land use	Pt	7.527	7.527
Ozone depletion	kg CFC11 eq	0.104	0.104
Photochemical ozone form	kg NMVOC eq	6.03E4	6.03E4
Resource use, fossils	MJ	1.198	1.198
Resource use, minerals	kg Sb eq	64.9	64.9
Water use	m3 depriv.	4E6	4E6

$$\boldsymbol{CE = \frac{CC}{a} = \frac{19900000}{208879} = 95.2\ kgCO2e/m2}$$

This number seems rational, considering the project's bulk structure relied on steel. This calculation was subjected to Table 3-2 classification, resulting in an even lower amount, equal to **76.9 kg CO_2 e/m^2**. However, according to LCA, climate change results are usually higher for more life cycle stages concluded and more holistic impacts, as explained previously.

8. Summary and Conclusion

The ESB project was chosen as a case study because it represents sustainable construction approaches and its heritage as a skyscraper. The construction phase was analysed through research papers, books, and websites, and it was found that the ESB adopted several construction systems and materials, including craft, mass, lean, and OSC, as well as conventional materials like steel and concrete.

These systems and materials optimised resource use, reduced construction time, and lowered costs. The ESB has also recently reduced its energy consumption and carbon emissions, contributing to its sustainability. While there is limited information on the embodied carbon emissions of the construction process, the use phase of the building has shown a reduction in carbon emissions through sustainable practices. Overall, the ESB remains an icon of construction projects and an example of successful project management in the construction industry.

Case Study 6: Shanghai Tower

Project details

Location	Lujiazui / China
Floor area	380,000m^2
Budget	2.35 billion USD
Building type	Skyscraper
Building purpose	Hotel, shops, urban amenities
Number of floors	128
Hight	632m (580m structural height)
Date of commencing construction	2008
Date of construction completion	2015
Architecture	GENSLER
Structural engineer	Thornton Tomasetti
Main contractor	The Shanghai Construction and Development CO. LTD

Figure 5-86 The Shanghai Tower

1. Introduction:

The Shanghai Tower, which is in the busy area of Lujiazui, a financial core zone of Shanghai city in China, was built to cope with the increased demand for urbanisation, especially within the most populated country in the world.

The skyscraper, which is 632m high, includes a vertical business district, a hotel, and a shopping mall. It has a unique design and modular construction materials.

2. The Rationale

Selecting China as an economic and human population power to all industries, especially construction and engineering ones, Shanghai Tower represents an excellent example of sustainable development of a significant financial district in China.

Located in the Lujiazui core zone, it is the tallest high-rise building in China (Gong et al., 2017; Wood Anthony and Parker David, 2013; J. Wu et al., 2019), which gives this research a good case study and an advantage to exploring which is perhaps the most important building in their country, just like The Shard in London and Khalifa Burj in Dubai.

3. Design and Planning

The design of Shanghai Tower envisioned a new way of supertall towers rising from the 'sky lobby' at the ground. The upper floors will have hotels, a cultural venue, and an observation deck, while the central floors have office spaces (Wood Anthony and Parker David, 2013).

A mega frame core wall structural system is applied for the main structure of the Shanghai tower. The maximum section size of the super column is 5300 mm by 3700 mm. The central core wall is 30m by 30 m (Sun et al., 2011), and (Xia Jun et al., 2010) stated that the concrete elements were used as shell elements. In contrast, steel elements were used as beam elements, providing the post-elastic behaviour of steel and concrete, as presented in Figure 5-87.

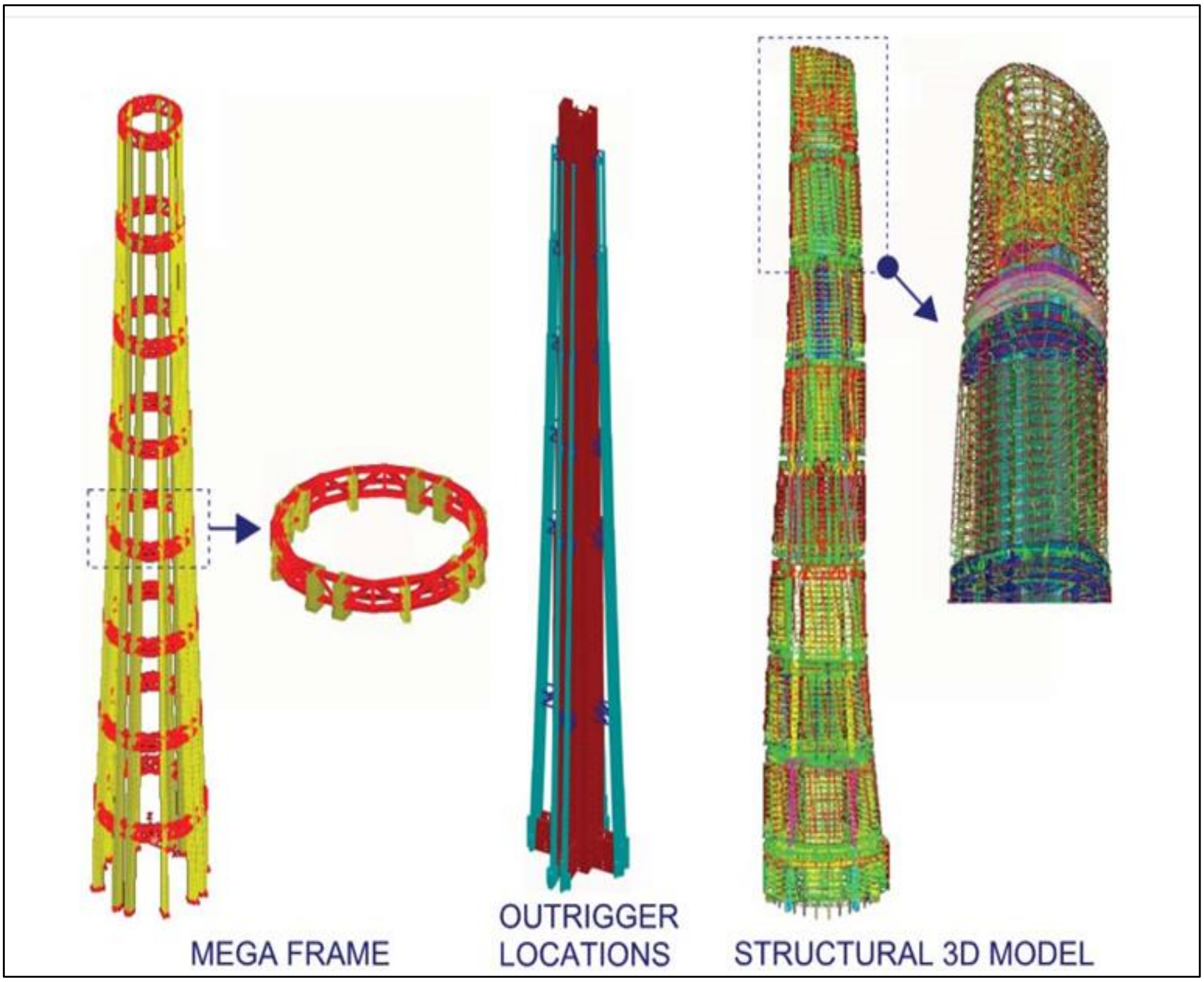


Figure 5-87 Shanghai Tower design concept (Xia Jun et al., 2010)

According to (Jiang et al., 2015), the lateral system consists of three parts: concrete composite core, exterior mega frame, and outrigger trusses. See Figure 5-88.

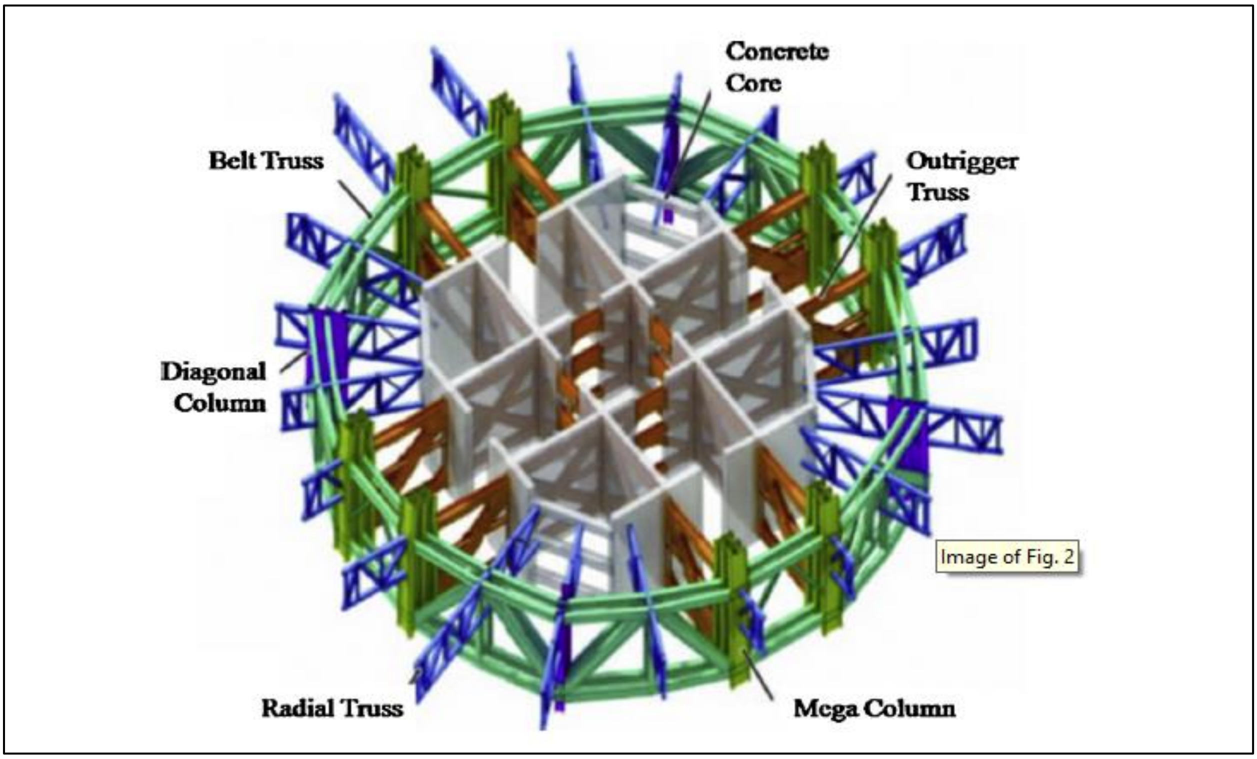


Figure 5-88 Structural design system (Jiang et al., 2015)

4. Construction and Materials

Concrete and steel were essential factors in the building projects, and the large quantity, type, and pouring processes were highly considered at the start of the project. Concrete composite structures combine the advantages of steel and concrete structures that can be best applied to high-rise and super-tall buildings. However, steel structures are not intensely fire-resistant, especially when temperatures reach 600 Celsius (Jiang et al., 2015).

60,000m^3 of concrete was poured into the foundation in a process that guaranteed regular hydration with no joints allowed (Gong et al., 2017), and this required a good mix design of the C50 concrete and a total on and off-site collaborations.

According to (Gong et al., 2017), fly ash and slag powders were added to the grade C50 concrete to decrease the total hydration heat, which KJ/Kg measures. This confirms that the environmental impacts of carbon emissions should be mitigated consequently.

The project had consumed 31,400 metric tonnes of steel rebars (Posco, 2018). Two construction sequences were adopted. The first construction sequence was by the concrete pouring of the beams simultaneously with the concrete pouring of the walls. For the second construction sequence, the concrete pouring of the beams was postponed to the outside of the tower (Sun et al., 2011).

Vertical steel members were installed at the building core to facilitate the outrigger connections (Xia Jun et al., 2010). Furthermore, the wise collaborative installation of concrete and steel elements was critical to the project delivery. See Figure 5-89.

Figure 5-89 Construction stages of Shanghai Tower (Zhang et al., 2016)

5. Data Analysis

The next Figure 5-90 presents the 431 general research documents found on Scopus, confined to 149 specific documents regarding construction within scopes of engineering, materials science, and environmental science.

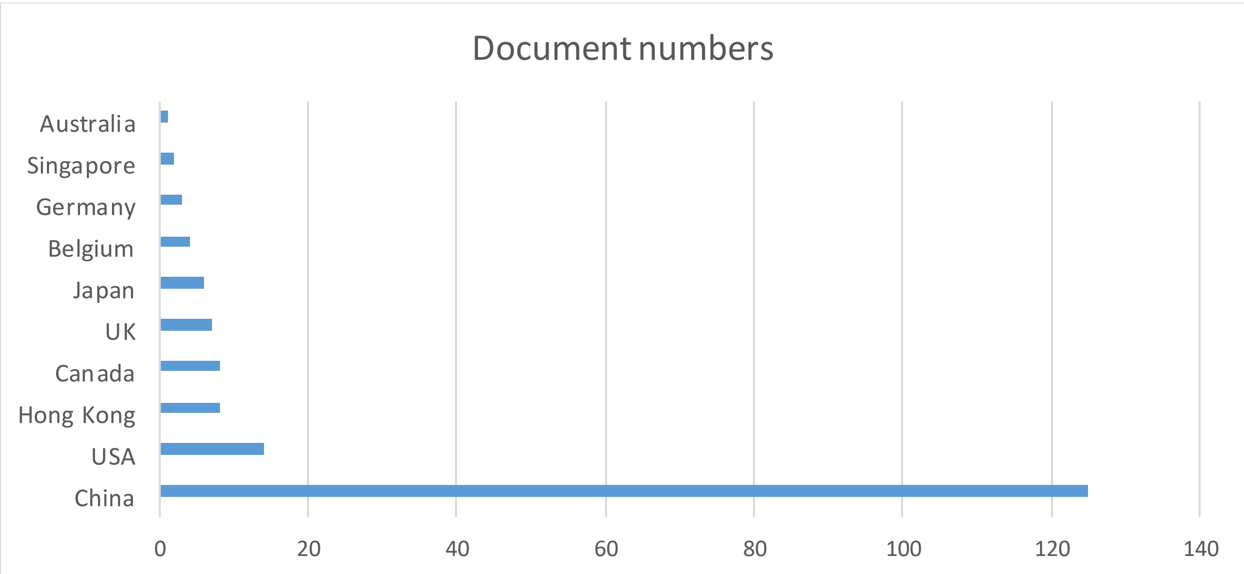


Figure 5-90 Number of research documents for the Shanghai Tower project (Scopus)

A good number of research studies are being conducted in China, where logically because of the location, the Shanghai Tower project was the highest among these research case studies, which also shows evident attention is given to the construction of high-rise buildings. Moreover, according to the same research documents, Figure 5-91 explains the area of interest.

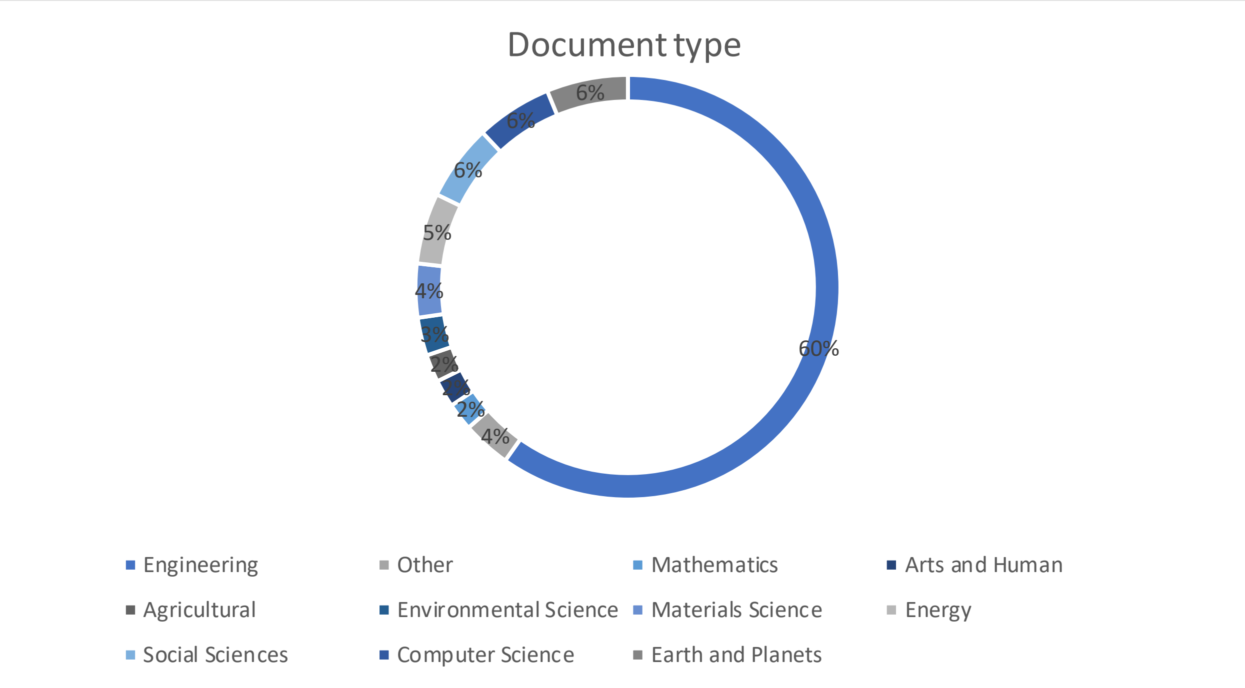


Figure 5-91 Document types for the Shanghai Tower project (Scopus)

Figure 5-91 highlights the engineering background as the primary domain of the documents, which aligns closely with the focus and scope of the study. This finding suggests that the research primarily draws upon engineering literature, expertise, and knowledge to investigate the subject matter. The research aims to provide specialised insights and contribute to the existing body of engineering knowledge within the chosen field by emphasising the engineering background as a prominent domain.

6. Sustainability and Carbon Footprint

The design of the Shanghai Towers aimed to achieve the LEED Gold rating and China Green Building Three Star Rating through the following practices (Sun et al., 2011):

1. Daylighting: The continuous glass skin admits the maximum daylight into the atria
2. Sun-shading: To reduce heating and cooling loads
3. Building controls intelligent building controls that lower energy costs
4. The cogeneration system is the 2,200-kilowatt natural gas–fired cogeneration system

5. Wind turbines will produce an estimated 54,000 kilowatt-hours per year in renewable energy
6. Regional materials: Local sourcing of products is sustainable because it reduces transportation-related environmental impacts and boosts local economies

Most previous points are more considered with operational energy and carbons, except point 6. Using more local materials and reducing transportation are ways to mitigate embodied carbons during the construction phase (cradle-to-site).

To analyse the project environmentally in terms of LCA using the LCA software database, Figure 5-92 presents the LCA of the concrete used in the Shanghai project.

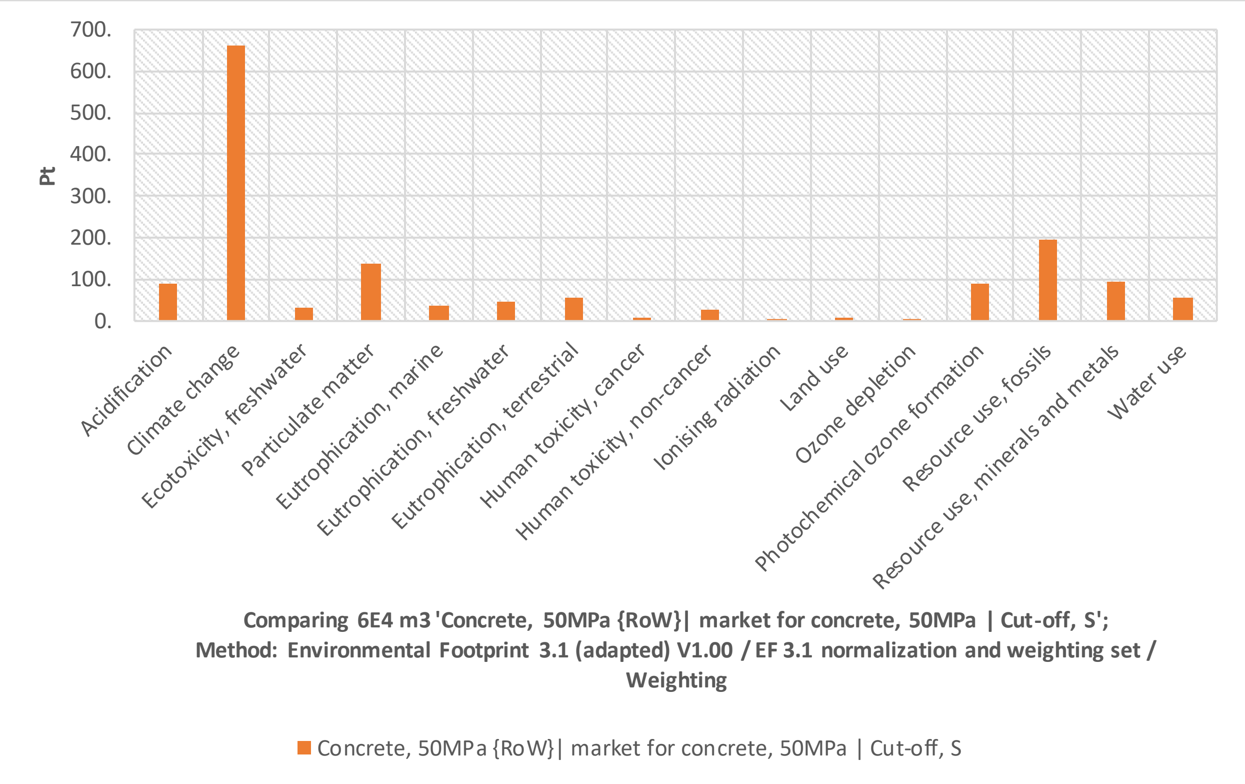


Figure 5-92 Concrete LCA environmental impacts

To understand the LCA of the concrete used in the project, Table 5-35 presents the associated emissions with the impact of climate change in the Shanghai project, according to LCA. It clearly shows the superiority of carbon emissions. Moreover, these indicators show that the higher the materials used, the higher the environmental impacts, explained by carbon emissions and climate change. Nevertheless, it needs to distinguish the practices used in construction or the planning and design differences.

Table 5-35 Concrete airborne emissions

Compartment: Airborne emission
Indicator: Weighting
Cut-off: 0%
☐ Default units
☐ Per sub-compartment
Category: Climate change
◉ Standard
○ Group
☐ Exclude long-term emissions
☑ Skip unused
☐ Per impact category

No	Substance	Compartr	Unit	Total	Concrete, 50MPa
	Total of all compartments		Pt	663	663
	Total of airborne emission		Pt	663	663
1	Carbon dioxide, fossil	Air	Pt	627	627
2	Methane, fossil	Air	Pt	32.5	32.5
3	Dinitrogen monoxide	Air	Pt	1.72	1.72
4	Carbon dioxide, land transformation	Air	Pt	1.02	1.02
5	Methane, biogenic	Air	Pt	0.548	0.548
6	Sulfur hexafluoride	Air	Pt	0.409	0.409
7	Methane, tetrafluoro-, CFC-14	Air	Pt	0.0794	0.0794
8	Methane, land transformation	Air	Pt	0.0195	0.0195
9	Methane, trifluoro-, HFC-23	Air	Pt	0.0166	0.0166
10	Ethane, hexafluoro-, HFC-116	Air	Pt	0.0105	0.0105
11	Methane, chlorodifluoro-, HCFC-22	Air	Pt	0.00896	0.00896
12	Ethane	Air	Pt	0.00193	0.00193
13	Methane, bromotrifluoro-, Halon 1301	Air	Pt	0.00154	0.00154
14	Methane, tetrachloro-, CFC-10	Air	Pt	0.00109	0.00109
15	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Air	Pt	0.000319	0.000319
16	Ethane, 1,1-difluoro-, HFC-152a	Air	Pt	0.000299	0.000299
17	Methane, dichloro-, HCC-30	Air	Pt	0.000288	0.000288
18	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Air	Pt	0.00027	0.00027
19	Methane, dichlorodifluoro-, CFC-12	Air	Pt	7.69E-5	7.69E-5
20	Propane	Air	Pt	6.81E-5	6.81E-5
21	Butane	Air	Pt	3.64E-5	3.64E-5
22	Chloroform	Air	Pt	1.88E-5	1.88E-5
23	Methane, bromochlorodifluoro-, Halon 1211	Air	Pt	1.83E-5	1.83E-5
24	Ethane, 1,1,1-trichloro-, HCFC-140	Air	Pt	1.31E-5	1.31E-5
25	Methane, monochloro-, R-40	Air	Pt	1.2E-5	1.2E-5
26	Ethane, 1,2-dichloro-	Air	Pt	1.01E-5	1.01E-5
27	Tetrachloroethylene	Air	Pt	3.59E-6	3.59E-6
28	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Air	Pt	3.54E-6	3.54E-6
29	Methane, trichlorofluoro-, CFC-11	Air	Pt	2.94E-7	2.94E-7
30	Methane, bromo-, Halon 1001	Air	Pt	1.85E-7	1.85E-7

To analyse steel LCA, Figure 5-93 presents the processes associated with steel rebar production in the Shanghai project, and Figure 5-94 presents the LCA results.

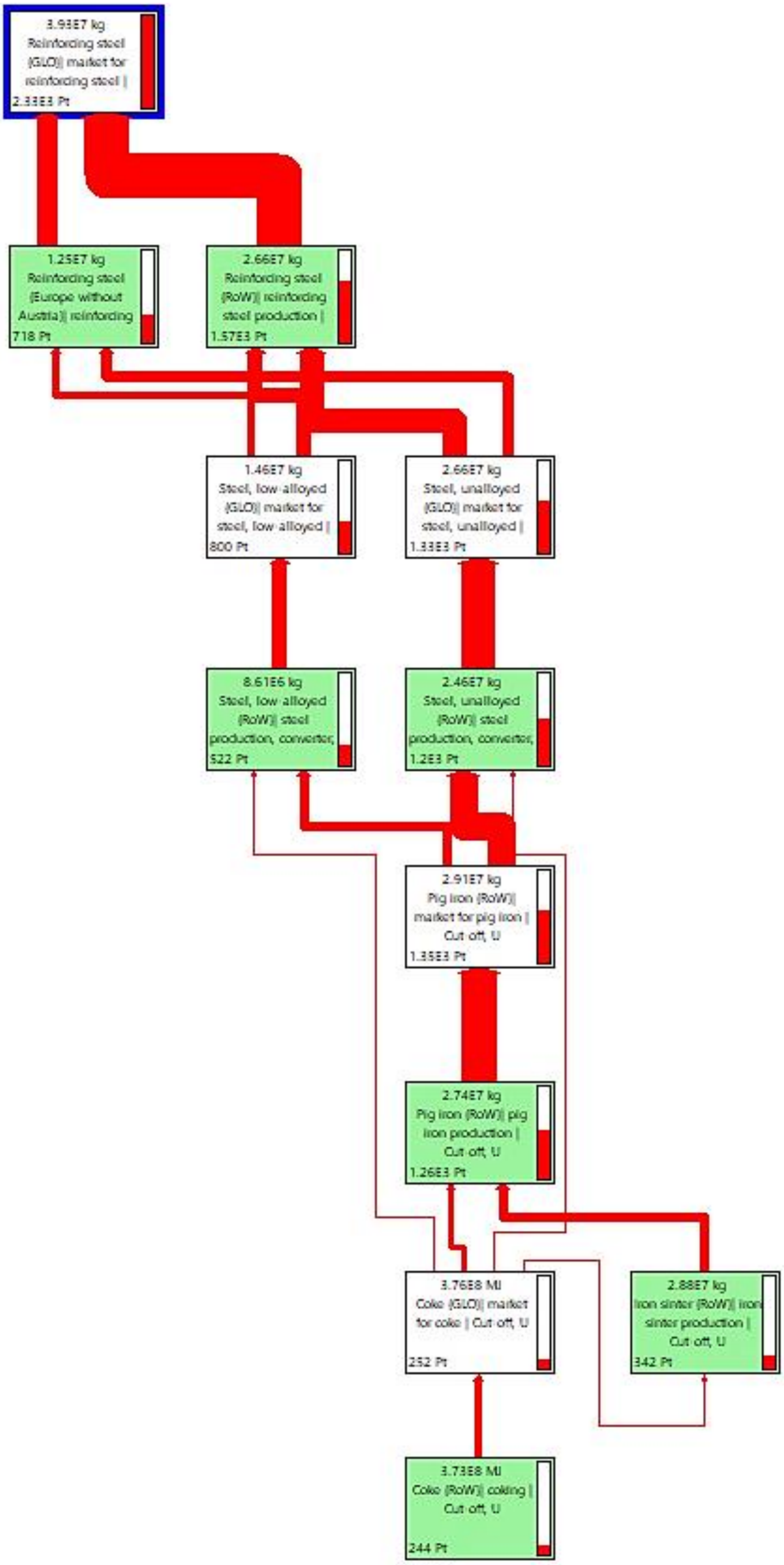


Figure 5-93 Reinforced steel LCA production process

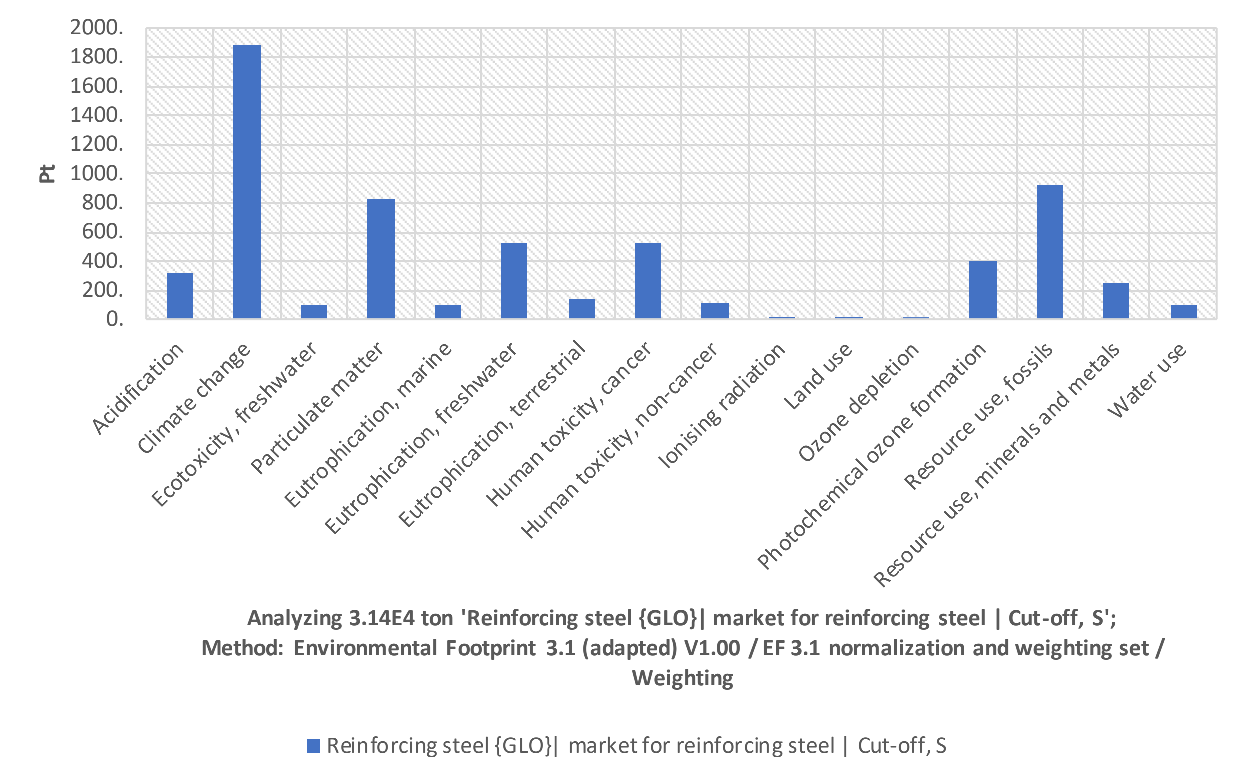


Figure 5-94 Reinforced steel LCA environmental impacts

To validate these results, the amount of climate change emissions is calculated for concrete and steel using Tables 5-36 and 5-37.

Table 5-36 Concrete environmental impacts

Damage category	Unit	Total	Concrete, 50MPa
Acidification	mol H+ eq	8.114	8.114
Climate change	kg CO2 eq	2.38E7	2.38E7
Ecotoxicity, freshwater	CTUe	8.867	8.86E7
Particulate matter	disease inc.	0.901	0.901
Eutrophication, marine	kg N eq	2.444	2.44E4
Eutrophication, freshwater	kg P eq	2.7E3	2.7E3
Eutrophication, terrestrial	mol N eq	2.68E5	2.68E5
Human toxicity, cancer	CTUh	0.00783	0.00783
Human toxicity, non-cance	CTUh	0.188	0.188
Ionising radiation	kBq U-235 eq	3.02E5	3.025
Land use	pt	1.02E8	1.02E8
Ozone depletion	kg CFC11 eq	0.142	0.142
Photochemical ozone form	kg NMVOC eq	7.8E4	7.8E4
Resource use, fossils	MJ	1.53E8	1.53E8
Resource use, minerals and	kg Sb eq	78.7	78.7
Water use	m3 depriv.	7.576	7.576

Table 5-37 Reinforced steel environmental impacts

Damage category	Unit	Total	Reinforcing steel
Acidification	mol H+ eq	2.75E5	275E5
Climate change	kg CO2 eq	6.7E7	6.77
Ecotoxicity, freshwater	CTUe	2.9E8	2.9E8
Particulate matter	disease inc.	5.39	5.39
Eutrophication, marine	kg N eq	6.494	6.494
Eutrophication, freshwater	kg P eq	3.03E4	3.03E4
Eutrophication, terrestrial	mol Nea	6.74E5	6.74E5
Human toxicity, cancer	CTUh	0.428	0.428
Human toxicity, non-cance	CTUn	0.798	0.798
Ionising radiation	kBq U-235 eq	1.826	1.826
Land use	Pt	1.9E8	1.98
Ozone depletion	kg CFC11 eq	1.25	1.25
Photochemical ozone form	kg NMVOC eq	3.32E5	3.32E5
Resource use, fossils	MJ	7.08E8	7.08E8
Resource use, minerals and	kg Sb eq	207	207
Water use	m3 depriv.	1.427	1.427

Using equation 7($\boldsymbol{CE = CC/a}$) has resulted in **62.6** kg CO_2 e/m^2 for the concrete and **176.3 kg CO_2 e/m^2** for the steel.

7. Summary and Conclusion

The case study highlighted the significance of sustainable construction in China, which is driven by its vast population and the potential demand for tall buildings. The Shanghai Tower exemplified a successful sustainable construction endeavour, employing eco-friendly materials and attaining LEED and China Green Building Three Star Ratings. Nevertheless, concerns were raised regarding the project's duration and cost relative to other skyscrapers, emphasising the necessity for faster construction to diminish embodied carbon emissions.

The Shanghai Tower is a remarkable demonstration of sustainable and inventive engineering and construction. Its distinctive design, utilisation of modular construction materials, and incorporation of sustainable elements render it an iconic structure in China's urban scenery. The project's use of concrete, steel, and pioneering structural systems showcases the possibilities of constructing tall and supertall buildings. Additionally, the tower's sustainability features, including renewable energy use and local material resourcing, underscore commendable efforts toward curbing its environmental impact. The tower is an exemplary case study for future global high-rise construction projects.

Data Validation for the Case Studies

First, the author validated all the outsources used in case studies' data collection references by using SCRIBD. An extensive digital library offering over a million full-length titles, including popular bestsellers and niche publications. They also have a vast collection of over a hundred million user-shared documents covering various topics. Additionally, Scribd publishes original and experimental works in text and audio formats (SCRIBD,2023).

The results were as follows:

The sources in the reference list are all valid, and the authors are all credible. The sources are from various reputable publishers, including academic journals, government agencies, and trade magazines. The authors are all experts in their respective fields, and their work is well-cited.

Here is a breakdown of the sources:

- Abdelrazaq, A. (2012). "High-Rise Buildings Validating the Structural Behaviour and Response of Burj Khalifa: Synopsis of the Full-Scale Structural Health Monitoring Programs." Retrieved from the Council on Tall Buildings and Urban Habitat (CTBUH) website. The author, a structural engineer involved in the Burj Khalifa project, offers a detailed overview of the building's structural health monitoring program to ensure safety.

- Abraham O. (2019). "Effective Project Management in Contemporary Developments: Case Study Burj Khalifa Tower." Retrieved from the International Project Management Association (IPMA) website. The author, a project manager experienced in large-scale projects like Burj Khalifa, shares insights into project management challenges and their resolutions.

- Aldred, J. (2010). "Burj Khalifa - A new high for high-performance concrete." Retrieved from the Proceedings of the Institution of Civil Engineers: Civil Engineering. The author, a civil engineer specialising in high-performance concrete, provides a technical overview of the concrete used in constructing Burj Khalifa.

- Align. (2020). "Case Study-The Empire State Building." Retrieved from Align Construction Solutions' website. This article presents a case study of the Empire State Building project, highlighting its early use of lean construction techniques.

- Alotaibi, B.S., Khan, S.A., Abuhussain, M.A., Al-Tamimi, N., Elnaklah, R. and Kamal, M.A. (2022). "Life Cycle Assessment of Embodied Carbon and Strategies for Decarbonization of a

High-Rise Residential Building." Retrieved from the journal Buildings. The University of Nottingham authors conduct a life cycle assessment focused on embodied carbon in a high-rise residential building.

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Results and Analysis

The sustainability of high-rise and large-scale buildings has become critical in advancing urbanisation and environmental challenges. This section analyses the relationship between construction methods, embodied carbon emissions, and sustainability by examining six comprehensive case studies.

The study investigated the environmental impact of different construction approaches, focusing on the utilisation of prefabricated methods, such as steel, recycled materials, fly ash concrete, and

GGBS , as opposed to traditional construction systems that tend to yield higher embodied carbon emissions, particularly with the use of concrete elements.

Additionally, the case studies explored the influence of project duration on sustainability, revealing that, logically, shorter projects tend to have lower embodied carbon emissions than longer ones. This is attributed to the increased material consumption and energy expenditure in prolonged construction timelines.

Consequently, the findings underscore the necessity of a holistic assessment of carbon emissions, incorporating considerations of material types, construction methods, and project duration to accurately evaluate and enhance the environmental impact of large-scale building projects. By shedding light on the interplay between construction techniques and environmental consequences, this study contributes to a more informed and responsible approach to building practices, which is vital for achieving a sustainable future.

The complete analysis of the selected case studies used SimaPro, IBM SPSS, Scopus, Microsoft Visio, and Excel to present and analyse the data, as well as a simple table with resources to summarise the inputs used.

The sustainability analysis was based on climate change and carbon emissions associated with the case study projects.

The first diagram used was to clarify the region and countries of the case studies, presented in Figure 5-95.

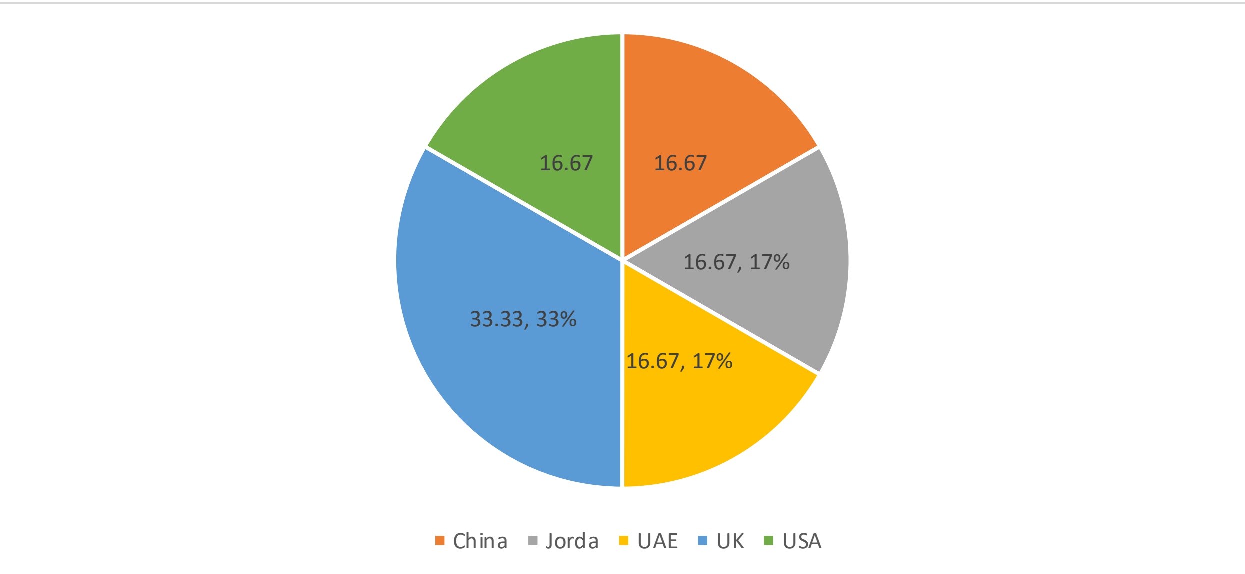


Figure 5-95 Region and countries of the case studies

Figure 5-96 illustrates the connectivity of construction methods with sustainability according to the research analysis of case studies.

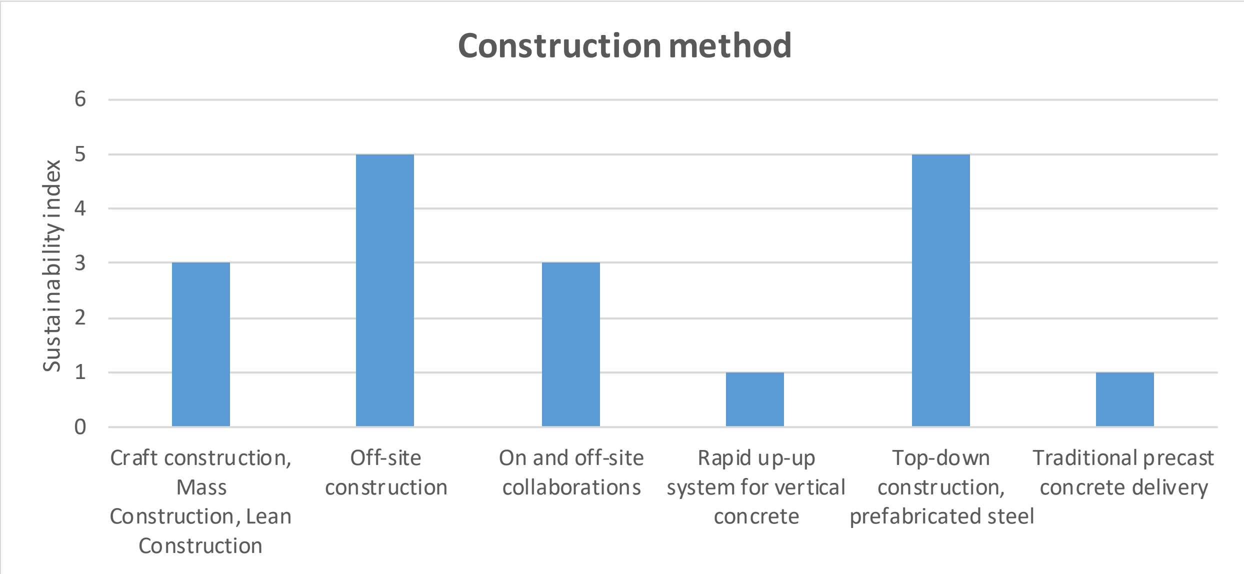


Figure 5-96 Construction method and sustainability

The more materials are used, the more environmental impacts will occur, with a slight contribution to the practices, recyclability, energy resources, means of transportation and others, especially when comparing different construction methods. This finding can criticise the sustainability assessment of large-scale or high-rise construction projects. To define such assumptions, the research will combine the collected data and analyse the findings holistically.

The following summary, Table 5-38, dealt with the relation between the construction method used in the selected projects and the bulk materials, with the sustainability and embodied carbons scale.

Table 5-38 Case summaries

	Construction Method	Bulk Materials	Embodied Carbons	Sustainability
1 SPECS	Off-site construction	Prefabricated concrete, steel structure, reinforced concrete	1	4
2 AGT	Traditional precast concrete delivery	Reinforced concrete	5	1
3 Khalifa	rapid “up-up” system for vertical concrete	Steel, concrete	4	2
4 Shard	Top-down construction, prefabricated steel	Steel	2	4
5 ESB	Craft construction, Mass construction, Lean co	Steel, concrete, wood	4	3
6 Shanghai	On and off-site collaborations	Fly ash and slag powders	4	3
Total N	6	6	6	6

Table 5-38 presented using more prefabricated methods, primarily steel recycled materials. Fly ash concrete and GGBS steel will produce lower embodied carbon emissions, whereas traditional construction systems tend to produce higher embodied carbon, especially when using concrete elements.

Table 5-39 shows the relationship between the selected projects' duration, cost, and sustainability.

Table 5-39 Duration and cost effect

		Project Duration	Cost	Sustainability
SPECS		Two years	89 million GBP	5
AGT		19 years	563 million USD	1
Khalifa		5 years	1.5 billion USD	1
Shard		3 years	425 million GBP	5
ESB		1.08 years	40.9 million USD	3
Shanghai		7 years	2.35 billion USD	3
Total	N	6	6	6

The duration of projects had good environmental and cost impacts; however, high-cost projects had the norm of producing higher embodied carbon emissions, resulting in more environmental impacts, eventually leading to lower sustainability achievements. It was shown clearly in the AGT case study. Nevertheless, it should be emphasised here that the focus is on the construction stage of the projects rather than the usage or operational stage of the building.

(Fregonara et al., 2018) had studied this relation by recommending that achieving environmental sustainability in the construction sector requires a long-term perspective on all actions throughout the building life cycle, as initial design decisions significantly impact a building's longevity. Life-Cycle Cost Analysis (LCCA) is crucial for assessing the technological and economic feasibility of a building project.

Several studies have conducted economic sustainability and proposed the implication of circular economy for the process and success of sustainable projects (Alaloul et al., 2022; Fregonara et al., 2018; Rostamnezhad and Thaheem, 2022). The holistic approach is attached in Appendix 10.

Table 5-40 summarises case studies subjected to carbon emissions calculation of steel and concrete using LCA software, except for the SPECS and AGT case studies, which are excluded due to the minimal impact of the SPECS project and the absence of data for the AGT project.

Table 5-40 Embodied carbons calculations summary

Case Study	Steel Type	Quantity **Metric ton**	CE **kg CO_2 eq/ m^2**	Concrete Type	Quantity Cubic meter	CE **kg CO_2 eq/ m^2**	Sum **kg CO_2 eq/ m^2**
Burj Khalifa	Reinforcing steel rebar	39,000	188.7	C50,60,80	330,000	281.7	470.4
The Shard	Galvanized steel	12,500	85.07	C40	45,000	48.1	133.17
Empire State Building	Structural steel	57,000	584.07	C40	48,000	95.2	679.27
Shanghai Tower	Reinforcing steel rebar	31,400	176.3	C50	200,000	62	373.96

$$\mathbf{EC_{avg} = (\sum a+b+c+d)/ n}$$

Equation 9

Equation 9 was used to calculate the average embodied carbon emissions per square meter (kg CO_2 eq/m^2) across multiple case studies. The resulting average value of **414.2 kg CO_2 e/m^2** might indicate a considerable improvement in addressing environmental concerns related to embodied carbon in high-rise and large-scale buildings. This average aligns with the status of embodied carbon levels in such structures. However, it is essential to note that the overall average is significantly influenced by the exceptionally low carbon emissions observed in the Shard and Shanghai Tower case studies.

The reduced carbon emissions in The Shard project are due to the use of lower quantities of steel and concrete, the application of galvanized steel, and the incorporation of fly ash in the concrete mix, all of which proved to be beneficial.

Figure 5-97 to visualise the table summary.

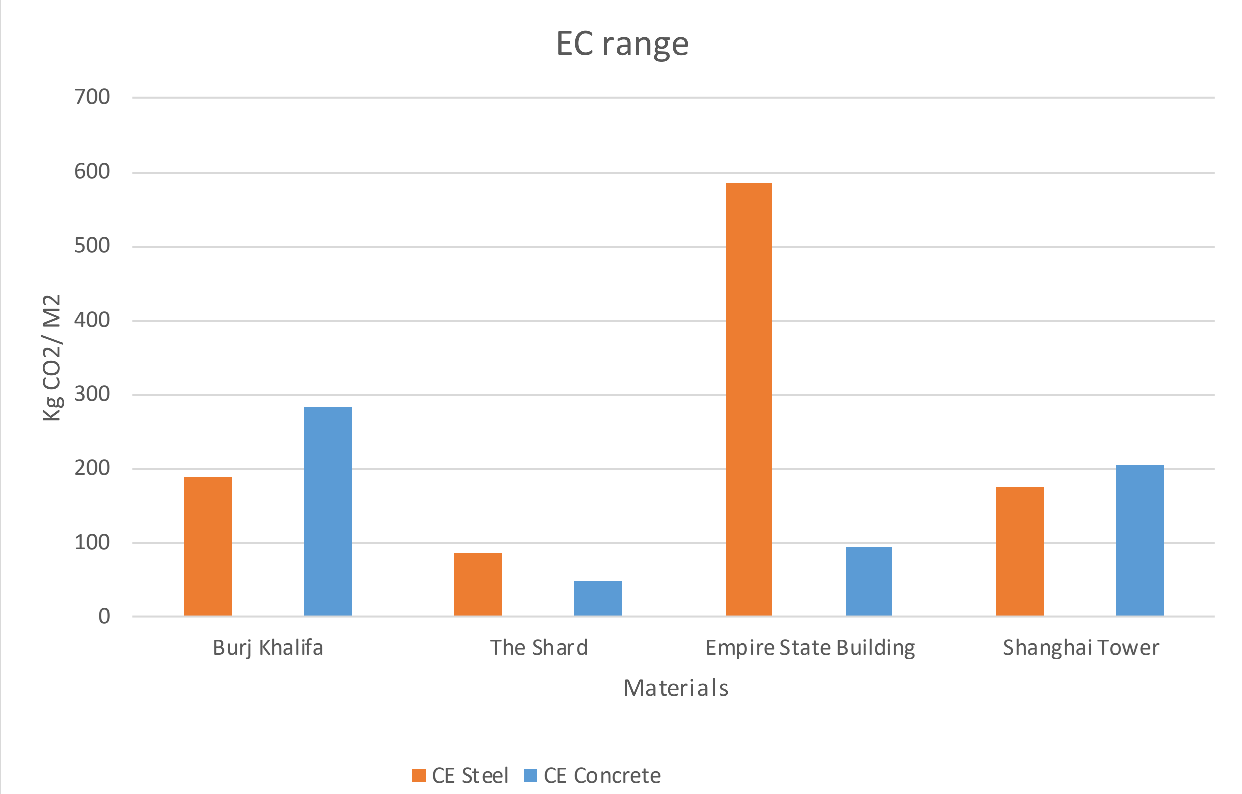


Figure 5-97 Embodied carbons range in the case studies

After reviewing Table 5-40 and Figure 5-97, the higher usage of materials will generally result in more environmental impact. However, the carbon emissions associated with construction cannot be determined solely by the quantity of materials used but rather by the specific materials chosen and the construction methods employed. The project's duration also plays a significant role, as seen in the Empire State Building case study. Similarly, despite the higher quantity of concrete used, the Shanghai project's carbon emissions were comparatively lower. Moreover, the minimum amount of concrete usage in the Shard resulted in minor carbons. Hence, a comprehensive assessment of carbon emissions must consider the material types, construction methods, and project timeline to gauge their environmental impact accurately.

A substantial recent announcement by The Embodied Carbon Review/One Click LCA, the embodied carbon caps are increased by 700kg CO_2e for each above-ground parking place and by 3000kg CO_2e for each underground parking place, where the calculation is based on the value of the 50 years, and divided by total building area (Globally, 2018). This is significant in differentiating construction project types, especially high-rise buildings, which mostly come with underground parking lots to serve the building's purposes. More focus should be on reducing the embodied carbons of such projects.

During this research, the author attended the carbon summit in November 2023, held in London and organised by One Click LCA. Before construction, the summit introduced a new stage for the embodied carbon emissions (A0) nonphysical process. This new stage might add accuracy to carbon emissions, especially the indirect ones introduced previously in Equation 5 in section 3.7.

Table 5-41 Case studies summary with sources

Scope	SPECS Project	Amman Gate Tower	Burj Khalifa	The Shard	Empire State Building	Shanghai Tower
Location	UK	Jordan	UAE	UK	USA	China
Project duration	2022-2024	2005-2024	5 years	3 years	13 months	7 years
Construction Method	Off-site construction	Traditional precast concrete delivery	rapid “up-up” system for vertical concrete	Top-down construction, prefabricated steel	Craft construction, Mass construction, Lean construction, Off-site construction	On and off-site collaborations
Cost	89 million GBP	563 million USD	1.5 billion USD	425 million GBP	40.9 million USD	2.35 billion USD
Bulk Materials	Prefabricated concrete, steel structure, reinforced concrete	Reinforced concrete	Steel, concrete	Steel	Steel, concrete, wood	Fly ash and slag powders
Project Construction Sustainability (LCA)	Highly sustainable	Low sustainable	Low sustainable	High sustainable	Sustainable	Sustainable
Embodied Carbons	Very low	Very high and still occurring	High	Low	High	High
Sources	Interviewing, site visit, (Morgan Sindall, 2022), (University of Hertfordshire, 2022)	Interviewing, site visit, (Abu-Hamdi, 2017b; Abu-Hamdi et al., 2018)(Abu-Hamdi, 2017; Hourani, 2014; Jordan Green Building Council and Friedrich-Ebert-Stiftung Amman Office, 2016)	Interviewing, (Abdelrazaq, 2012; Abraham O, 2019; Aldred, 2010; Baker and Pawlikowski, 2015; Barreiro-Gomez et al., 2021; Bogomil, 2020; Ponzini and Alawadi, 2022; Sotoudehnia and Rose-Redwood, 2019)	(Bogomil, 2020; RPBW, 2022; STEEL FOCUS: THE SHARD-Some pointers on reaching the top, 2022; Sungur et al., 2021; The Guardian, 2012)	(Align, 2020; Ghosh and Robson, 2015; Jacobsson and Wilson, 2018; Sacks and Bertelsen, 2008; R Sacks and Partouche, 2010)	(Gong et al., 2017; Jiang et al., 2015; Sun et al., 2011; J. Wu et al., 2019; Xia Jun et al., 2010; Zhang et al., 2016)

5.3.2 Discussion

The case studies showed that the quantities and type of materials dominate the environmental impacts, leaving a small space for the construction practices, project date, project duration, and location to control such impacts. The increase in environmental impacts is logical when using more construction materials. However, it was observed that when using the LCA method for calculating the environmental impacts, only some solid progress was made when comparing old high-rise construction projects like ESB with new projects such as Shanghai Tower, Burj Khalifa, and The Shard.

The Shard project showed a superior reduction in water use, resource use, eutrophication, and land use. However, it is more relevant to the type of steel adopted in the construction (Galvanized steel sheets) than the project contribution. Moreover, there needs to be more contribution to reducing the impacts of climate change, which is the focus of this research.

While steel and concrete are the heaviest used materials in construction projects, it is essential to note that other materials like glass, tiles, gypsum boards, and electric fixtures were not included in the LCA analysis because they are typically manufactured and processed off-site. This off-site manufacturing process contributes to lower energy consumption and reduced carbon emissions.

To illustrate this, Figure 5-98 was created to present LCA of Glass used in the Shard case study as an example, which was containing 56000 m^2 of double-glazed glass. The full projects analysis is produced in **Appendix 9**.

The glass LCA results showed the superiority of climate change impacts among other environmental impacts, such as the rest of materials. However, the amount of points or equivalent carbon emissions is very minimal compared to steel and concrete materials. See Figure 5-98.

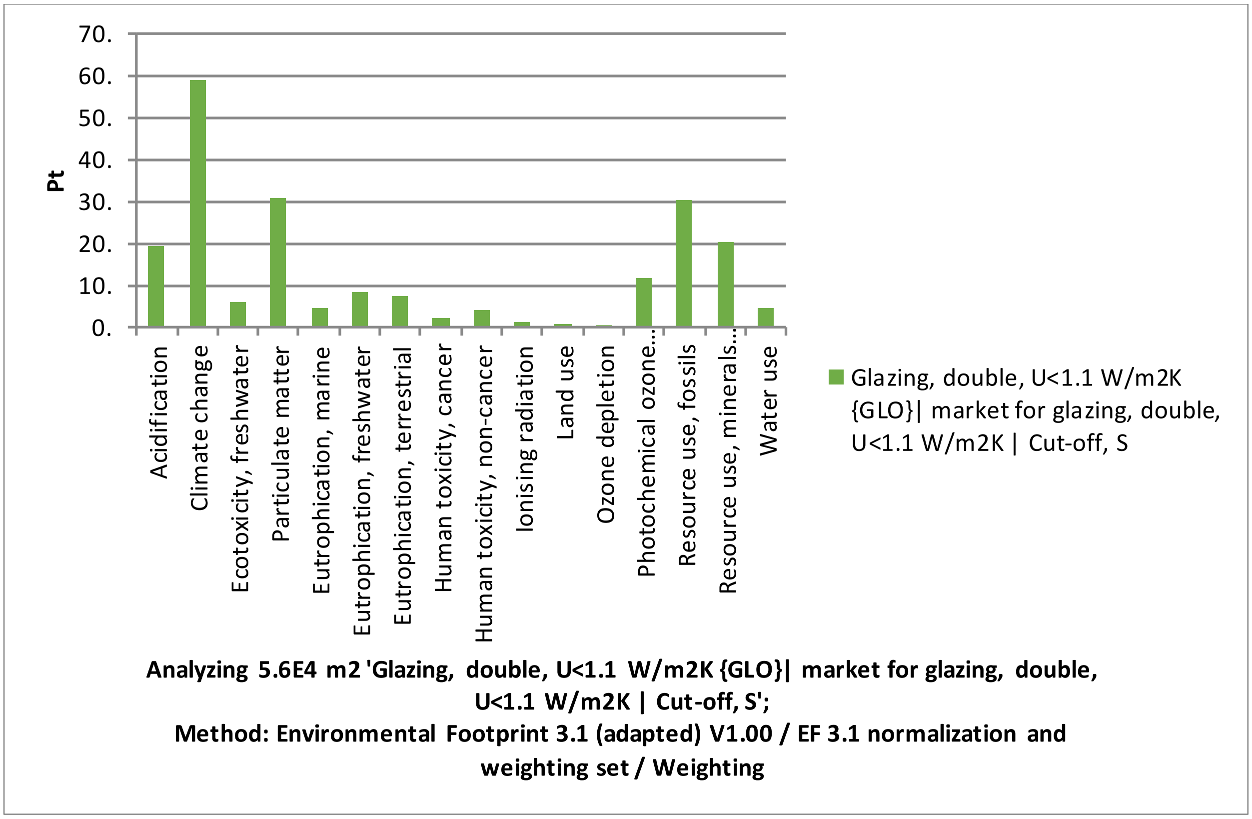


Figure 5-98 Glass LCA environmental impacts in the Shard case study

The glass LCA showed a clear lower amount of environmental impacts especially climate change with less climate change points than 60, compared to steel impacts in the same project resulted in more than 900 points.

The benchmark in these case studies can be used to compare the results of LCA studies to each other. This can help practitioners rank their results and identify areas that can be improved (Raqqad, 2023).

The duration and location of the project were crucial factors in determining the overall sustainability status of the project, alongside other factors such as economic and social conditions.

Some research gaps were found while using the LCA software database. For example, some uncertain data should be reconsidered, where the software does not specify the date of the project being analysed because the time factor could heavily influence the energy and emissions rates according to available technologies and transportation means.

Similar gaps were identified by (Minunno et al., 2021) due to the absence of a comprehensive benchmark formed by aggregating LCA results and the absence of guidelines enabling LCA practitioners to compare their findings regarding the environmental impact of buildings.

Moreover, the LCA database provided by LCA software does not conclude the project duration, which should contribute significantly to the quantification process of environmental impact. AGT and ESB case studies explored the importance of project duration, especially in embodied carbon emissions evaluation. However, most studies, such as (Araújo et al., 2020) and (Teng and Pan, 2020), estimated that the operational lifetime of buildings when using LCA software is equal to 50-70 years.

Also, some concrete grade classes above C 60 were unavailable in the LCA software database. (green ncap, 2023) addressed this by stating that LCA cannot be as precise as emissions testing, where the outcome must always be considered an estimate based on generally available data and assumptions. Moreover, it can also fail to reveal the assessment if the question is not precisely and appropriately formatted (Horne et al., 2009). (Säynäjoki et al., 2017) discussed that despite an International Organization for Standardization (ISO) standard guiding LCA practice, the ways of conducting an LCA are not standardised. The results can vary significantly due to the choice of method, especially with the lack of guidance in selecting a functional unit for reporting and comparing LCA results (Minunno et al., 2021).

Another notable gap in existing research is the need for more consideration given to the specific locations of projects in LCA. Typically, the location is associated only with the general region of the construction material under assessment. For example, steel regions are categorised as Global (GLO), North Africa (NA), Europe (Euro), Rest of the World (ROW), and so forth. This approach is commonly applied to various materials.

However, it is essential to recognise that specifying each country and territory separately would require significant effort. This level of granularity is crucial because natural resources, means of transportation, policies, and other factors can vary significantly among neighbouring countries. These variations can provide more accurate and context-specific data for conducting comprehensive LCAs. Although it may be challenging, including specific country-level data would lead to a more precise understanding of the environmental impacts associated with construction materials and practices.

Furthermore, updating material status in the software typically requires one to two years. Consequently, when evaluating a recently completed construction project, it is wise to wait for the updates to be completed. This precautionary measure helps avoid potential inaccuracies or falsified information from premature assessments. The difficulty in replicating LCA results can undermine their perceived reliability and trustworthiness.

According to (McLeod and O'Connor, 2020), When finishing a project, it is advisable to archive it carefully to preserve its data, as library changes can affect the project's results over time. Exporting the project in LCA software format, including related library data and impact assessment methods, is a recommended approach for archiving. Note that some SimaPro versions may not support data export, and you can compare different versions on the PRé website at www.pre-sustainability.com/content/the-simapro-family.

Steel diameters (Reinforced Steel) were also not considered when using the software, as it is assuming that the type and weight of steel rebars are enough to determine the impacts; however, the size and weight of steel rebars can influentially be decisive and affect the transportation process, site inventory, methods used to format the rebar.

The contribution of embodied carbon emissions was not explicitly identified, as the focus was primarily on general carbon emissions and their impact on climate change. However, relative estimates of embodied carbon emissions were determined based on the available database and software used for analysis.

To fill such gaps, the further data collected through interviews and questionnaires shall address and explain these gaps.

5.3.3 Case Studies Summary and Conclusion

The intensive cases present a comprehensive analysis of these construction projects' environmental impacts and sustainability.

Some practices included optimisation practices in materials and resources; however, one of the drawbacks of optimisation in construction is that it can lead to inefficient use of resources, lack of creativity, and decreased safety.

This can be a problem unless the optimisation process is managed appropriately. Where the process of achieving the optimisation goals in construction was discussed by (Mei and Wang, 2021), and can be achieved through the following structural optimisation encompasses:

1. Size optimisation, focusing on cross-sectional areas as design variables
2. Shape optimisation, adjusting nodal coordinates
3. Topology optimisation, optimising node connections to eliminate unnecessary structural members
4. Multi-objective optimisation, which integrates size, shape, and topology for enhanced design outcomes, also referred to as layout optimisation

Moreover, the calculations and numbers of environmental impacts, specifically carbon emissions, are vulnerable and subjected to several uncertainties due to the diversity and complexity of construction projects, in addition to the region and location.

LCA can extensively present a holistic demonstration and assessment for construction projects; however, there are some uncertainties surrounding its adoption.

Land depletion was minimised in all high-rise buildings because they used smaller areas compared to other construction projects such as roads, flat buildings, multi-dwellings, etc.

The conclusion is that sustainable practices should be considered throughout the construction process of supertall buildings to ensure that the designated output is achieved. The case studies of the Shanghai Tower and the Burj Khalifa illustrate the importance of sustainable practices in constructing supertall buildings. More comprehensive analysis is represented in Table 5-42 with adding the Shard and ESB.

Moreover, Figure 5-99 is combining the Steel LCA data to easily illustrate the undertaken case studies. While Figure 5-100 presents the concrete environmental impacts.

Table 5-42 Sustainable practices comparison

Aspect	Burj Khalifa	The Shard London	Shanghai Tower	Empire State Building (ESB)
Construction Methods	Self-climbing formwork, rapid vertical concrete delivery	Top-down construction method, modular assembly of spire	Mega frame core wall system, outrigger trusses	Craft construction, mass construction, off-site construction
Design Practices	Advanced techniques like GPS monitoring ensured verticality. Circular steel forms for nose columns and panel formwork for floor slabs were employed	Wind engineering principles applied for the Buttressed-core system, optimising materials usage and wind resistance. Modular assembly of spire segments enhanced efficiency and safety	Concrete composite structure combined steel and concrete advantages, supported by an integrated lateral system for structural integrity and seismic performance	Utilized craft and mass construction systems, with off-site prefabrication to enhance efficiency and reduce waste
Materials	High-performance concrete (C50, C60) with fly ash for sustainability. Reflective glazing and aluminium used for exterior	Hot-dip galvanized steel and triple glazed blue panel systems. Focus on using recycled materials in construction	C50 concrete with fly ash and slag powders to reduce carbon emissions. Extensive use of steel rebars for structural reinforcement	Structural steel (57,000 tonnes), concrete (C30, C40), reinforced mesh, and bricks. Emphasized mass production methods and logistical efficiency to minimize waste
Cranes	Three main tower cranes strategically positioned. Self-climbing capability reduced crane dependency during construction	Modular assembly of steel segments for spire minimized crane lifts	Installation of vertical steel members facilitated outrigger connections, optimising crane usage	Derricks, hoists, and dedicated logistics system ensured continuous availability during workdays
Techniques	Efficient use of self-climbing formwork and prefabricated reinforcement accelerated construction pace	Modular assembly and pre-assembly of spire segments reduced onsite assembly time and enhanced safety	Integrated approach with concrete and steel elements for structural strength and seismic resilience	Standardization of construction elements and off-site prefabrication streamlined workflow and reduced installation time
Sustainability	Use of fly ash in concrete reduced environmental impact. Sustainable materials like reflective glazing used in exterior	Utilization of hot-dip galvanized steel and recycled materials contributed to sustainable construction practices	Incorporation of fly ash and slag to reduce carbon emissions during construction	Implemented mass construction and off-site prefabrication to minimize material waste and environmental impact
Environmental Impact	Implemented sustainable construction systems and materials to mitigate environmental footprint	Focus on reducing material usage and waste through modular construction and sustainable materials	Reduced carbon emissions through innovative concrete mix design and efficient construction processes	Emphasis on reducing operational and embodied carbon emissions through efficient design and construction practices
Challenges	Addressed extreme climate conditions in the Middle East, ensuring materials' durability and construction efficiency	Overcame height and wind challenges in London, optimising design for wind resistance and construction safety	Managed fire resistance of steel structures at high temperatures, ensuring structural integrity and safety	Managed logistical challenges and site constraints in a fast-paced urban environment, minimizing material handling and waste

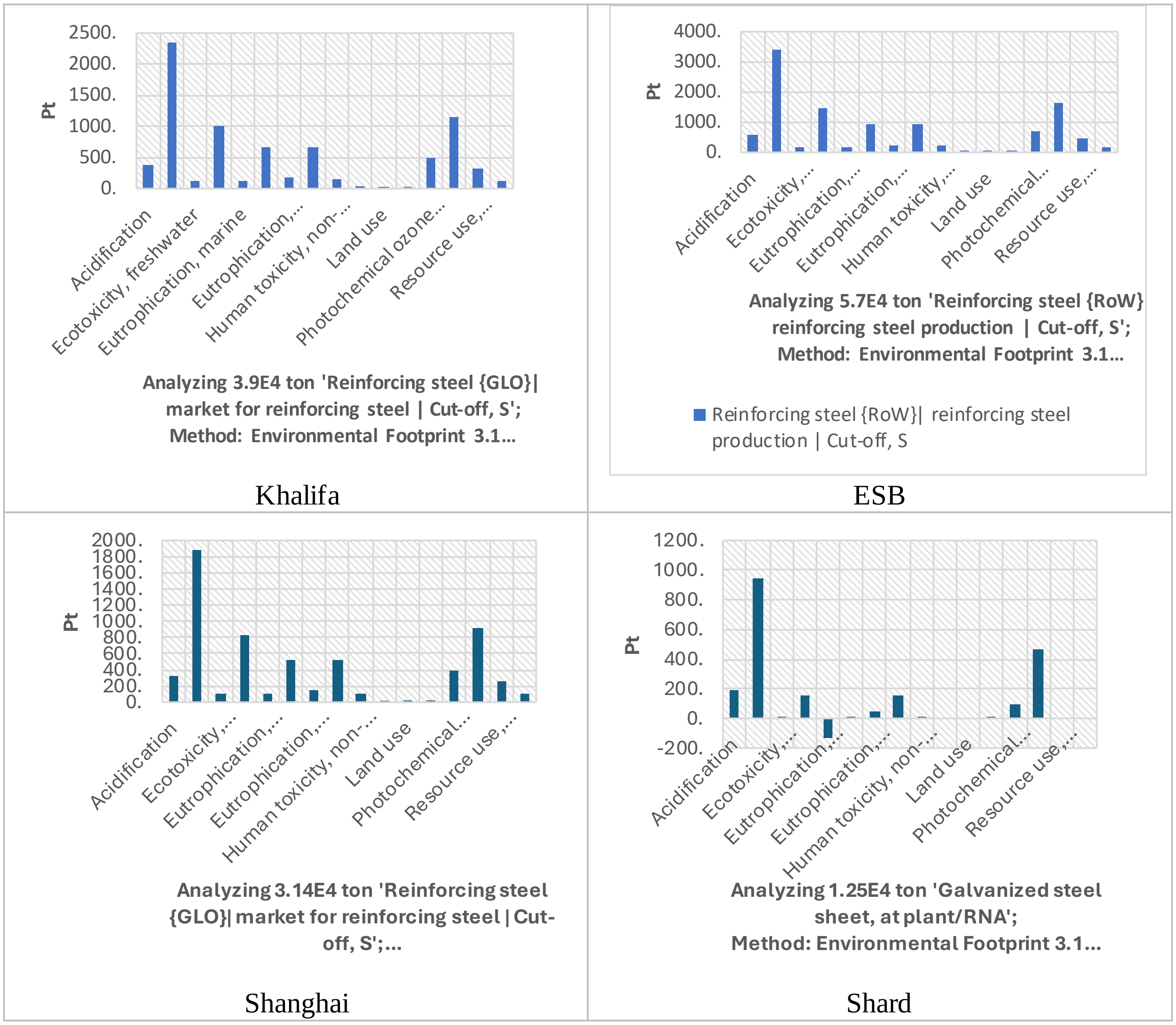


Figure 5-99 Steel LCA comparison

As previously mentioned, climate change impacts were a significant concern across all projects, influenced by differences in material quantities and construction methods. Notably, the Shard project successfully minimised Eutrophication impacts.

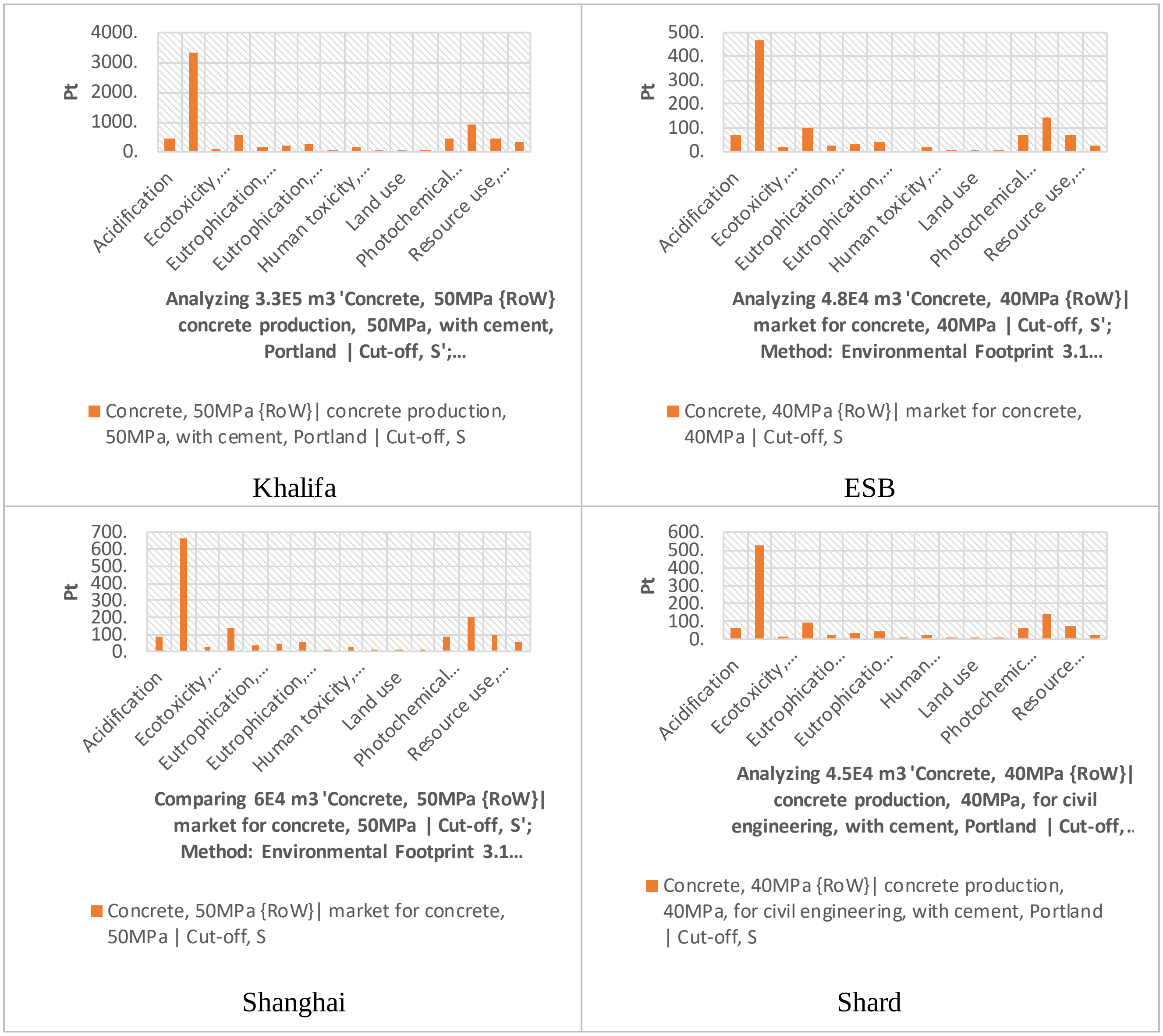


Figure 5-100 Concrete LCA comparison

The Empire State Building was an old but valuable case study that examined environmental concerns in constructing supertall buildings. The study highlights the conventional materials used in the construction of the ESB even with agile construction methods duration of the construction process as potential obstacles to reducing embodied carbon emissions. The study highlighted the importance of considering sustainability from the design phase to the construction phase of a building project.

The geographical location of the projects significantly influenced their sustainable construction status. Figure 5-101 presents a global climate zone map, clearly demonstrating that projects in

Amman and Dubai (AGT and the Burj Khalifa) are situated in much warmer climate zones compared to those in London or New York. This difference in climate likely impacts the sustainability practices and challenges faced by these projects.

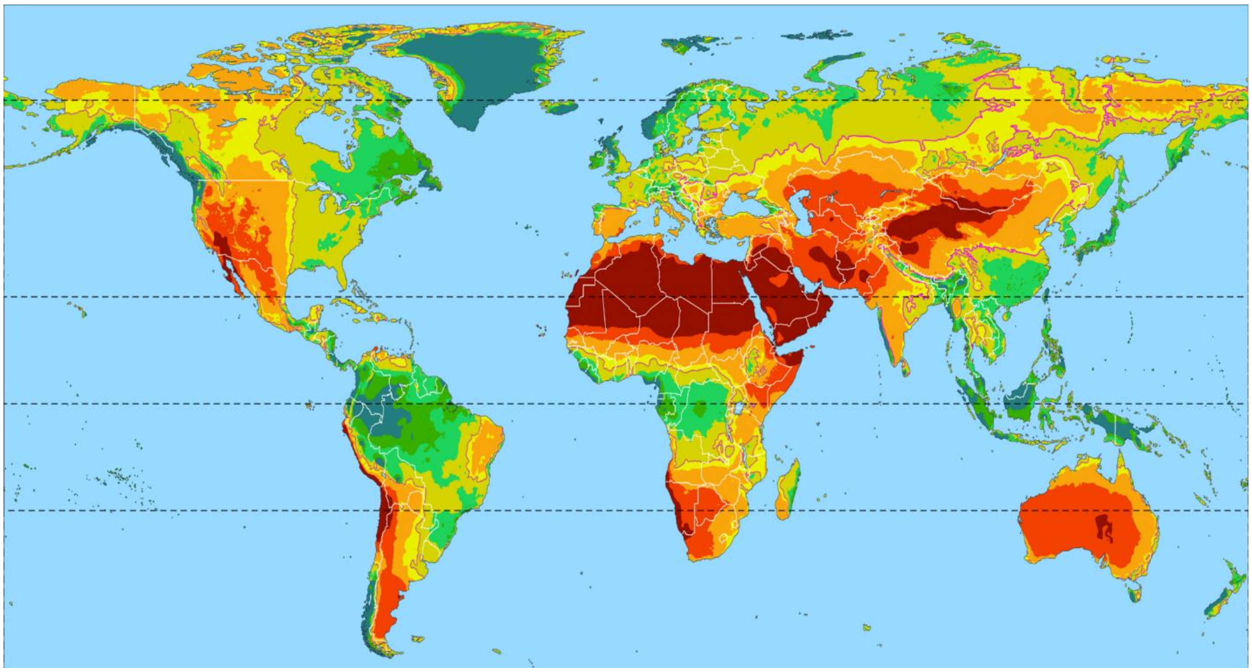


Figure 5-101 World's climate zones (Köppen, 2023)

According to the latest update, Figure 5-101 represents different climate zones or regions (Köppen, 2023). Various climate classifications can influence the choice of environmentally sustainable construction methods, considering the distinctive conditions and attributes of the project's location. For instance, regions often present individual climate-related challenges and prospects that impact decisions regarding building materials, construction techniques, energy systems, and other sustainable design elements. Grounded in the climate zone of a specific location, grasping the climate zone of a specific location aids in pinpointing the most suitable sustainable strategies tailored to that area.

The research can suggest several future works related to sustainable construction practices, including:

1. Conducting a more detailed analysis of the embodied carbon emissions of the construction process, including transportation and other indirect emissions

The analysis should encompass all activities from cradle-to-gate stages, as directed by the data collection highlighting prioritisation mainly during the production phase and usage stage. Which are usually out of the executing contractor's role. The research posits that contractors, often perceived as the least trusty and weakest link in construction projects (Alzahrani and Emsley, 2013; Wong et al., 2008) , receive less scrutiny from shareholders. Consequently, this neglect might allow contractors to prioritise activities that maximise their profits without objections, potentially affecting overall project sustainability goals.

2. Investigating the economic feasibility of sustainable construction practices, including the costs and benefits of different construction systems and materials

The economic aspect of sustainable construction is integral to the implementation of environmental sustainability, as extensively investigated in this research (Futas et al., 2019b; Górecki et al., 2019; Jeong et al., 2019).

3. Examining high-rise buildings' social and cultural impacts on the surrounding communities, including urbanisation, gentrification, and displacement issues

Examining the social and cultural impacts of high-rise buildings on communities involves studying urbanisation, gentrification, and displacement. High-rises symbolise urban development, attracting investment and reshaping neighbourhoods. They accelerate urbanisation, altering demographics and cultural landscapes. Gentrification brings benefits like better amenities but raises property prices, displacing residents. Addressing these impacts requires urban planning and policies promoting equitable development to mitigate negative consequences on communities. Such issue was exposed in the case study of AGT project, also discussed explicitly by (Hourani, 2014; Moncaster and Malmqvist, 2020; Saha, 2022).

4. Exploring new and innovative sustainable construction technologies and materials, such as 3D printing and renewable energy systems

The research explored the limitation of such technologies in building large-scale projects, also renewable systems are mostly involved in the usage stage of buildings. However, many recent studies have explored the potential of such technologies, and the link to the UNSGs, such the study done by (Singh et al., 2021) and (Tabassum and Ahmad Mir, 2023).

Based on this work, an implementation as a large-scale fabrication method was demonstrated with an autonomous on-site robot featuring a large hydraulic system. The technique of spraying, which distributes an atomized medium with compressed air in small droplets over an area, has many conventional applications in the construction sector. This includes the spraying of paint and coatings, concrete, and PU insulation foam, making it highly useful for future sustainable large-scale buildings.

(Bedarf et al., 2021) had explained the process of using 3D printing in larger projects shown in Figure 5-102, by using drones to reach out higher places. (Tabassum and Ahmad Mir, 2023) confirmed that 3D printing allows for the creation of complex and intricate designs that were previously difficult to achieve using traditional methods. To address sustainability concerns, they explore eco-friendly alternatives such as high-volume fly ash, geopolymers, and recycled glass aggregates for use in 3D printing. These materials not only reduce environmental impact but also improve the long-term strength and performance of building components.

Figure 5-102 Steps of using 3D printing using drones (Bedarf et al., 2021)

(Singh et al., 2021) introduced Cloud manufacturing which is characterised by the extensive accumulation and exchange of manufacturing resources and tools. Modern manufacturing methods require comprehensive process design, encompassing everything from initial design to final machining. Unlike traditional approaches, cloud manufacturing does not necessitate standardisation or multiple iterations between design and machining teams. However, complex computing in conventional manufacturing poses significant challenges for in-depth research and application within the cloud manufacturing framework.

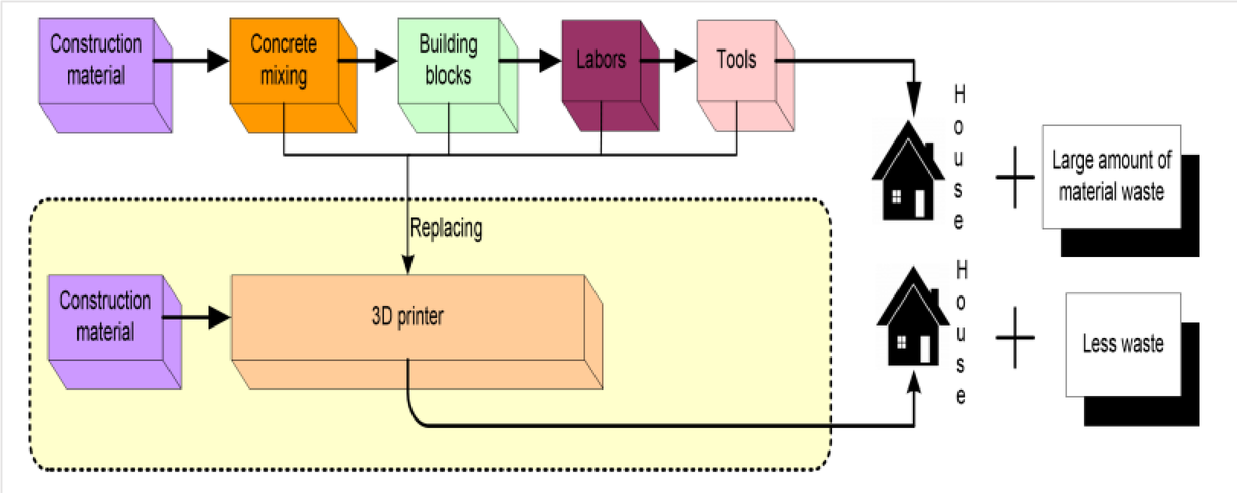


Figure 5-103 Process of cloud manufacturing for construction (Singh et al., 2021)

Figure 5-103 illustrates how 3D printing can replace traditional construction processes. Conventional methods involve multiple stages including concrete mixing, building block production, labour, and tools, leading to substantial material waste. In contrast, 3D printing streamlines these stages, significantly reducing material waste and enhancing overall efficiency.

5. Despite the research does not depend on numbers as explained because they are vulnerable and subjected to changes, however a rough amount below 400 kg.CO_2.eq/m^2 shall be considered sustainable project target in the case of the examined large scale and high-rise projects complied with lower climate change impacts

But the priority target is lowering climate change impacts as they are the most impacts among case studies results. Moreover, conducting case studies of sustainable construction practices in other regions and contexts to identify best practices and lessons learned.

6. Making better uniformed and consistent databases in software such as LCA software

5.3.4 Qualitative Interviews Data

Introduction

Interviews are a common, worthwhile technique for collecting data and can be applied in many research projects. They consist of highly structured questions, which are predetermined and unstructured (Kara et al., 2015). However, this research adopted the semi-structured interviews, justified by the specifications explained by (Kallio et al., 2016). A critical benefit of the semi-structured interview method is its ability to foster reciprocity between the interviewer and the participant. This enables the interviewer to spontaneously generate follow-up questions based on the participants' responses while allowing participants to express their thoughts and perspectives verbally.

The interviews were chosen carefully to fill the needs of this research project. Interviewees were selected based on multi-criteria, which are (sampling system):

1. High experience in civil engineering projects
2. Appreciated academic contributions to construction projects and sustainability
3. Regions are distributed relatively to cover much-needed world locations to present the associated perspectives and influences

Several experts' backgrounds were interviewed, including civil engineers, construction managers, and academics.

Data Analysis

The qualitative research data was collected from different individuals involved in the construction industry, including site managers, civil engineers, project managers, and civil engineering professors. The data includes responses to questions related to sustainability, environmental impacts of construction, environmentally sustainable practices, embodied carbon emissions, measurement units, and mitigation measures.

According to (LeCompte, 2000), these points should be considered when analysing qualitative data:

To analyse qualitative data effectively. Here are some key points to keep in mind:

- Analysis should be based on clearly articulated theories and responsive to research questions
- A good analysis should yield meaningful results to the people for whom they are intended and described in the language they understand
- Creating meaningful results involves validity or whether research findings seem accurate or reasonable to the people being studied

- Analysis involves transforming big piles of data into succinct statements that describe, explain, or predict something about what the researcher has studied
- The first step in analysis is identifying sources of bias and selectivity in data collection and analysis
- The analysis involves tidying up the data and arranging it neat and organised
- Analysis should be done meticulously and with attention to detail
- Emphasises the importance of being aware of the effects of both tacit and formative theory in guiding data collection and analysis

The qualitative research method used was a questionnaire-based approach. Participants were asked a series of questions related to their opinions, definitions, and perspectives on sustainability and environmental impacts in construction (know-how). The responses were then recorded and analysed for patterns, trends, and common themes.

The data collected from the respondents provides insights into their understanding of sustainability. They emphasize reducing operational and embodied carbon emissions, using renewable and recyclable resources, and balancing resource use to preserve ecosystems and natural resources for the future. The respondents also highlight the importance of material selection or modification, depletion of natural resources (fossil fuels), waste reduction, and energy efficiency in construction projects' design, construction, and maintenance stages for achieving environmental sustainability.

The data collected indicates a growing awareness of environmental impacts in construction, specifically focusing on embodied carbon emissions during the project's construction phase. Respondents discussed various units of measurement, including Kg CO_2 /m^2 and metric tonnes, to quantify these emissions. They emphasised the significance of construction practices such as off-site and on-site technologies in reducing carbon emissions. Furthermore, they recommended prioritising environmentally conscious practices during the design phase of construction projects.

The respondents also mention challenges in achieving environmental sustainability in the construction industry, including the increased demand for construction materials, the need for practicality and compromise between different approaches, and significant changes in construction methods over time despite the increasing construction activity.

Interview protocol approval is in **Appendix 2.**

The list comprises professionals from various locations and roles presented in Table 5-43 and Figure 5-104.

Table 5-43 Occupation of interviewees

Occupation					
		Frequency	Percent	Valid Percent	Cumulative Percent
	Chartered Civil Engineer specialising in Strategic Land and Sustainable Infrastructure Development	1	2.6	2.6	69.2
	Civil and Structural Engineer	1	2.6	2.6	71.8
	Civil Engineer	2	5.1	5.1	76.9
	PhD Research Candidate	1	2.6	2.6	79.5
	Professor Civil Engineering	1	2.6	2.6	82.1
	Project Manager/ Civil Engineer	1	2.6	2.6	84.6
	Researcher	1	2.6	2.6	87.2
	Senior Lecturer	1	2.6	2.6	89.7
	Senior Lecturer / Programme Leader	1	2.6	2.6	92.3
	Senior Teaching Fellow & Construction Professional	1	2.6	2.6	94.9
	Site Manager	1	2.6	2.6	97.4
	Urban Planner	1	2.6	2.6	100.0
	Total	13	100.0	100.0	

Location

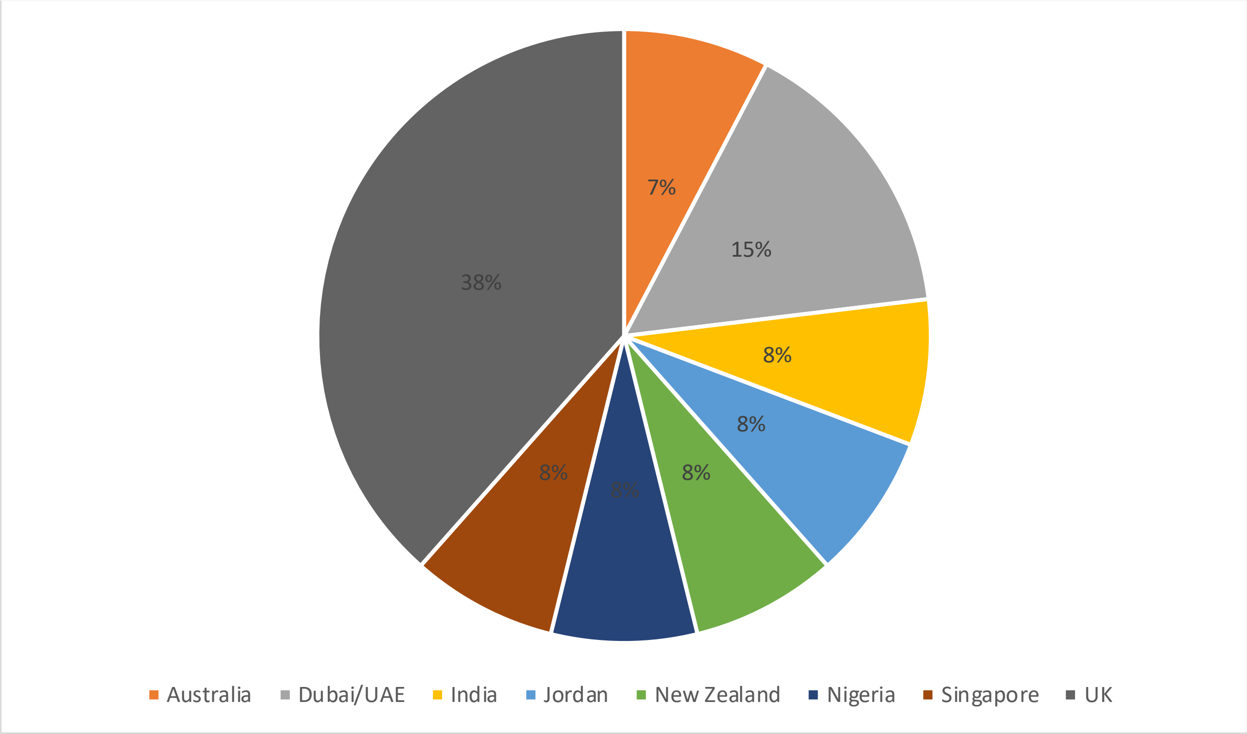


Figure 5-104 Location distribution

The list of locations provided likely pertains to selected interviewees' origins or current locations. Here is an analysis based on the repeated entries:

1. UK (United Kingdom): The UK is a prominent hub for civil engineering and academic pursuits. It boasts a highly developed construction sector known for its world-class universities
2. Amman/Jordan: Amman, the capital of Jordan, might be where an interviewee is based. Jordan's construction sector has seen significant growth, and Amman serves as a crucial centre for engineering activities in the region
3. Dubai/UAE (United Arab Emirates): Dubai is renowned globally for its ambitious construction projects and urban development. Its thriving engineering and construction sector attracts professionals from various parts of the world
4. Hatfield/UK: Hatfield, a town in the UK, likely serves as a specific location for an interviewee at the University of Hertfordshire. It is part of the broader UK context

5. London/UK: London, the UK's capital, is a major global city. It hosts a diverse range of professionals, including those in engineering and academia. It is a central hub for research, education, and engineering projects
6. Nigeria: In West Africa, Nigeria is experiencing substantial growth in its construction and engineering sectors. It is a crucial location for professionals involved in development and infrastructure projects
7. India: India's construction industry is rapidly expanding, and professionals here often engage in research and development activities. It is an essential location for academic and industry-related work
8. Australia: Australia boasts a well-established construction and engineering sector. Professionals here contribute significantly to academia and industry, making it a prime location for research and practice
9. New Zealand: has a robust construction sector that contributes significantly to its economy. The country focuses on sustainable and resilient building practices, emphasising energy efficiency and environmental conservation. The construction industry in New Zealand adheres to stringent building codes and regulations to ensure safety and quality standards in infrastructure development
10. Singapore: possesses a highly advanced construction industry known for its innovation and efficiency. The country implements cutting-edge technologies like BIM and PPVC to streamline construction processes. Sustainability is a key focus, with initiatives promoting green buildings and environmentally friendly practices throughout the construction sector. Moreover, Singapore prioritises urban planning and infrastructure development, aiming for intelligent, interconnected, and resilient cities while ensuring compliance with stringent building standards and regulations

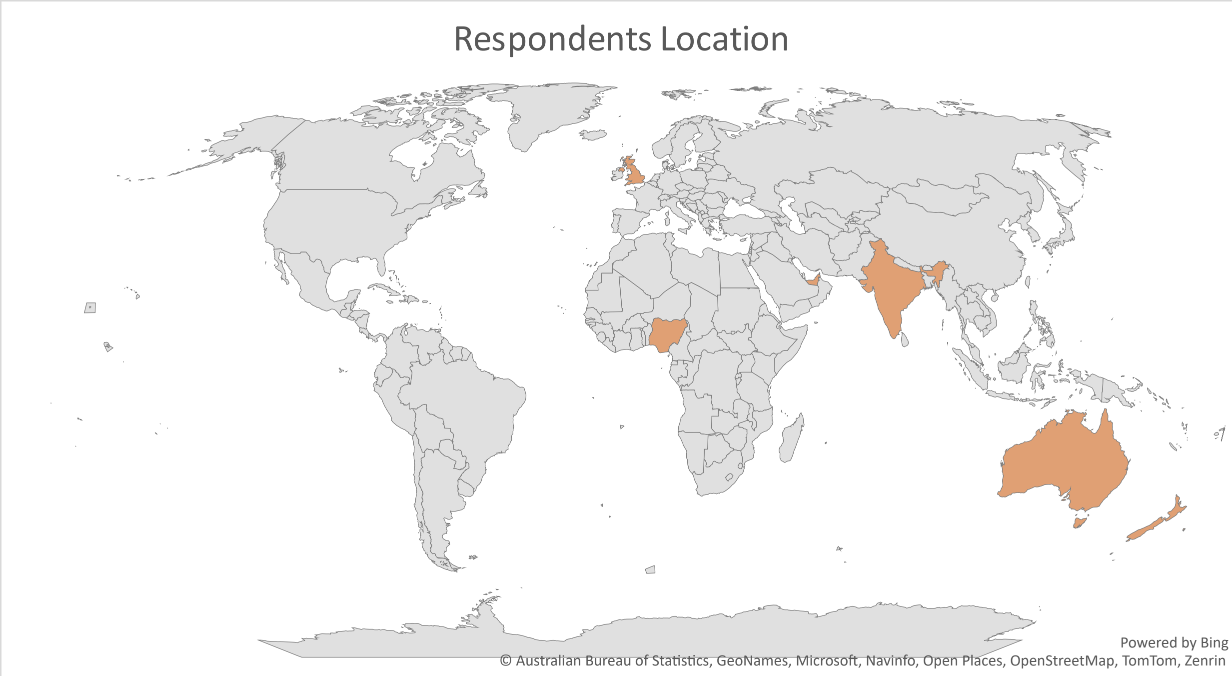


Figure 5-105 Map of interviewees regions

This analysis, also shown in Figure 5-105, suggests that the selected interviewees have diverse geographic origins or current locations, each contributing to the fields of construction, engineering, and academia in different ways. The various locations may offer insights into a global perspective on these industries.

Q.1 Sustainability definition:

Most of the respondent's definitions were according to the UN definition of sustainability. According to the United Nations, sustainability is characterised as achieving a harmonious equilibrium among society's economic, social, and environmental aspects (Ogunmakinde et al., 2022).

This balance aims to fulfil the current needs while maintaining the ability of future generations to meet their own needs. In the context of a project, sustainability entails implementing various measures to decrease energy consumption, natural resources, and manufactured resources. It also involves enhancing waste management practices, creating employment and training opportunities for disadvantaged groups, and safeguarding or enhancing the environment's state and individuals' well-being. The environment encompasses all land, water, and air within any naturally occurring or human-made structure above or below ground.

It was observed that most recent high-rise projects, especially the ones located in the UK and Europe, do not include lower or basement floors. The investigation with interviewees explored the following reasons:

1. Safety and security
2. High cost of construction
3. Higher operational and maintenance expenses
4. Less sustainable method compared to upper floors

Q.2 How can you define environmental sustainability in construction in one sentence?

Environmental sustainability in construction involves carefully choosing resources and implementing practices that minimise operational and embodied carbon emissions. This commitment spans all construction phases, from conception to operation, emphasising long-term ecological health and a diminished environmental footprint.

The interviewees highlighted several crucial aspects central to sustainable construction:

1. Emission Reduction through Resource Selection: Addressing carbon emissions in construction by choosing materials and methods that decrease operational and embodied carbon throughout a building's life. This includes using recycled materials, integrating passive solar design, and employing energy-efficient appliances

2. Reduction of Environmental Impact: Focusing on minimising waste, adopting sustainable practices, and preserving natural ecosystems. This encompasses recycling materials, conserving water, and avoiding deforestation

3. Holistic Environmental Considerations: Advocating for a life cycle approach to minimise environmental impact, considering materials and operational energy use. Architects play a crucial role in designing energy-efficient buildings and incorporating recycled materials

4. Ethical Resource Utilisation: Prioritising sustainable materials and practices to prevent environmental harm, such as using bamboo and avoiding harmful chemicals

5. Preservation of Natural Ecosystems: Protecting natural habitats and ecosystems by refraining from practices like deforestation and collaborating with local communities.

6. Designing for Carbon Reduction: Creating energy-efficient buildings and cities that employ sustainable materials to reduce energy consumption and waste generation

These varied perspectives underscore the importance of a comprehensive, environmentally conscious approach at every construction stage. This approach aims to mitigate environmental impact and promote sustainability within the industry.

Q.3 Which are the most critical environmental impacts caused by human activities?

Global warming, resulting from human activities, stands out as the primary environmental impact. It is the underlying factor for various consequential effects, including elevated sea levels, ice melting, droughts, extreme weather events, and worldwide environmental disruptions.

Q.4 Which are mostly considered environmentally sustainable practices (the significant long-term benefits):

The environmentally sustainable practices primarily considered for their significant long-term benefits include:

1. Material selection or modification:

Focuses on responsible sourcing, reuse, and modification of materials, aiming to reduce embodied carbon and overall environmental impact.

2. Off-site construction:

Aim to minimise waste and time on site, potentially improving build quality and efficiency, albeit with considerations about additional materials and potential inefficiencies.

3. On-site practices (such as 3D printing and additive manufacturing):

Offers potential benefits in innovation, efficiency, and optimisation of construction activities, although the significant uptake might take time, particularly regarding electric plant usage and efficiency measures.

4. Software utilisation (e.g., BIM, PMP, LCA):

Provides tools for more sustainable selection, efficient estimation of resources, and improved efficiency across sign and construction phases.

While each practice reduces emissions and waste, material selection or modification is essential due to its potential for responsible sourcing, reuse, and lower embodied carbon. Off-site construction and advanced software tools also significantly reduce waste and optimise construction activities for long-term environmental benefits.

Q.5 What are the most critical environmental impacts during the construction stage of projects?

Based on the interviews, it was found that the construction phase of projects gives rise to critical environmental concerns:

1. Generation of waste:

Construction activities result in substantial waste, leading to increased landfill disposal, resource wastage, and higher levels of embodied carbon emissions.

2. Depletion of natural resources:

This is mainly linked to the consumption of fossil fuels and raw materials, impacting both material production and construction processes.

3. Greenhouse gas emissions:

Emissions such as CO,CH_4,N_2O, HFCs, SO_2, and PFCs play a significant role in contributing to global warming and environmental degradation.

4. Water wastage:

Inefficient water usage during construction contributes to resource depletion and strains the environment.

5. Threat to natural resources (flora and fauna):

Construction activities threaten local ecosystems, affecting flora and fauna through habitat disruption or destruction.

While each impact is noteworthy, waste generation, depletion of natural resources, greenhouse gas emissions, water wastage, and the threat to natural resources emerge as crucial environmental concerns during the construction phase of projects. Addressing these issues requires proactive measures for mitigation and reduction.

Q.6 What priority should be given nowadays to construction projects?

Nowadays, construction projects should primarily address embodied and operational carbon emissions. This emphasis on both aspects is crucial as it encompasses considerations across the project's life cycle, from material selection and construction practices (embodied carbon) to energy efficiency and renewable options during the operational phase (operational carbon). Prioritising both allows for a comprehensive approach to reducing greenhouse gas emissions, fostering sustainability throughout the project's lifespan.

However, respondents' answers related explicitly to embodied carbon emissions were as follows:

1. Respondents mentioned that embodied carbon emissions were a crucial environmental impact during construction
2. The increased embodied carbon emissions could be attributed to increased demand for construction materials
3. Some respondents preferred off-site construction technologies to mitigate embodied carbon emissions
4. According to the respondents, the priority stage for applying environmentally mitigating practices was the whole life cycle, with more focus on the design stage

Q.7 A study on embodied carbon over the last decade revealed a mean value of 510.91 $KgCO_2/m^2$, contrasting with recent studies citing 600 $KgCO_2/m^2$ during construction. Why might this value have increased?

The answers were summarised in the following points:

1. Responsibility in design

2. Project specifications and building details

3. Advancements in architecture

4. Increased demand for construction materials

5. Material selection and on-site construction practices

6. Incorporating carbon equivalents (eq)

7. Consistency issues in carbon measurement

8. Variations across building types (e.g., residential, office, retail)

9. Uncertainty in including fit-outs

10. Evolving baseline standards for carbon measurement

11. Advancements in materials, construction, operations, and technology

12. Changes in environmental regulations and sustainability standards

13. Location-based construction variations

14. Impact of poor workmanship on delays and rework

Q.8 The best unit to measure embodied carbon emissions in construction projects varies based on considerations related to specific aspects and ease of visualisation. However, the commonly suggested units include:

1. $KgCO_2/m^2$: Reflects kilograms of carbon per square meter, considering production, delivery, and disposal of materials

2. Kg/m^2: Dependent on construction methods and materials used

3. Metric tons (tonnes): Useful for representing large quantities typically used in construction

4. m^3: Handy for measuring solids, liquids, and gases, providing easy visualisation

5. kg: Simplicity in measurement

6. $kgCO_2e$ per m^2: Useful for an initial overview of a building's impact and further analysis into subsystems

Ultimately, the choice of the unit depends on the specific purpose of data collection and reporting, with Kg CO_2/m^2 often considered a practical starting point due to its ability to represent the impact per unit area in construction projects.

Q.9 What is better to apply to mitigate carbon emissions: off-site construction technologies, on-site construction technologies, or both? Why?

The effectiveness of mitigating carbon emissions depends on the context, but both off-site and on-site construction technologies offer distinct advantages in reducing environmental impact:

Off-site construction:

- Allows for precise planning and controlled environments, enhancing energy efficiency and reducing emissions during construction

- Minimises transportation emissions by centralising production and potentially using locally sourced materials

- Offers efficiency, quality, safety, and cost benefits due to controlled conditions and standardised processes

On-site construction:

- Provides adaptability and customisation, crucial for complex or unique projects, potentially reducing additional material and energy needs

- Incorporates locally sourced materials, cutting transportation emissions and supporting sustainability

- May be more efficient in urban areas with limited space for transportation and logistics

Considering the unique advantages of each method, a combination of off-site and on-site construction technologies could offer a comprehensive approach to carbon emission mitigation, primarily when evaluated case-by-case, to optimise transportation quality control and minimise construction delays.

Q.10 If not combined throughout the whole lifecycle of the project, at which stage of the construction project priority should be given to applying environmentally mitigating practices?

It is evident that opinions vary, but there is a strong emphasis on multiple stages within the construction project lifecycle for prioritising environmentally mitigating practices:

1. Design stage:

This stage involves critical decisions regarding materials and methods, influencing the project's environmental impact from its inception.

2. Whole life cycle (WLC):

Emphasises the importance of considering sustainability across the entire project lifespan, ensuring a comprehensive approach to environmental mitigation from start to finish.

3. Early stages:

Early implementation allows for more significant and lasting effects, making this phase crucial for embedding sustainable practices.

4. Procurement:

How the industry purchases materials can significantly impact sustainability outcomes and should be considered alongside design and lifecycle stages.

The consensus suggests that the integration of environmentally friendly practices should span the entire lifecycle of a construction project, starting from the design phase and continuing throughout the project's lifespan WLC. Each stage—design, early phases, procurement—plays a crucial role in achieving overall sustainability, and it is crucial not to fragment the process to ensure accurate and comprehensive sustainability.

Q.11 Which material would you recommend between steel, concrete, and timber, to deliver an environmentally sustainable high-rise building project (from cradle to grave)?

The opinions on the most environmentally sustainable material for a high-rise building project vary, considering factors such as recyclability, carbon emissions, sourcing, and manufacturing processes:

1. Steel:

It is considered for its recyclability and potential sustainability if sourced from recycled materials and manufactured using energy-efficient processes.

2. Concrete:

Acknowledged for its structural capacity but criticised for significant carbon emissions during production. Suggested ways to enhance sustainability include utilising lower-carbon cementitious materials.

3. Timber:

Some believe timber is not the most sustainable option due to challenges related to accurate carbon calculations, early harvesting impacting carbon sequestration, and insufficiently accounting for processing and transportation costs. However, others support timber for its potential carbon negativity and lower energy-intensive manufacturing processes.

Overall, while steel's recyclability is often highlighted as a sustainable feature, the environmental impact of concrete and timber relies heavily on various considerations such as sourcing, processing, and efficient manufacturing techniques. Some suggest a hybrid approach combining materials for more sustainable outcomes. Ultimately, a comprehensive study evaluating the embodied carbon of each material, considering sourcing, amount, and usage specifics, would help determine the most environmentally sustainable choice for high-rise construction projects.

Q.12 The best type of project needing environmentally sustainable solutions varies, with different perspectives favouring:

1. High-rise buildings:

Due to their substantial footprint and potential for significant energy and resource efficiency improvements, sustainable practices in these structures can notably reduce their environmental impact.

2. Infrastructure:

It emphasised its broad scope, essential role in growth, and potential impact due to the diverse range of materials and opportunities for sustainability improvements.

3. Pavement:

It is highlighted for its expansive surface area and consequent influence across regions; it has an environmental impact spread widely using:

In urban areas, housing projects offer opportunities to enhance energy efficiency, resource conservation, and resident quality of life through sustainable practices.

Different views highlight the interconnectedness of these projects and the need for sustainability across the board. High-rise buildings, infrastructure, housing, and even mid-rise buildings all present opportunities for implementing environmentally sustainable solutions, whether through energy efficiency, material choices, or improved construction practices.

Q.13 Are high-rise buildings considered a sustainable method of construction from cradle to grave? Why?

High-rise buildings are not universally considered sustainable from cradle to grave due to various factors:

1. Material Use: The materials used significantly impact sustainability. Some argue that low-rise buildings are more sustainable due to better insulation, while high-rises may rely on materials with higher embodied carbon.

2. Energy Efficiency: While high-rises can accommodate more people in a smaller area, enhancing energy efficiency in land use, transportation, and infrastructure, challenges such as vertical transportation inefficiencies and limited natural ventilation could detract from their sustainability.

3. Embodied Carbon: High-rises tend to have higher embodied carbon due to their larger structures and reliance on certain construction materials, impacting their overall sustainability.

4. Construction Practices: Construction methods such as pre-cast cement blocks in some regions might reduce material waste, but the cement-based process could still pose sustainability concerns.

5. Design and Operations: The sustainability of high-rises depends on considerations like energy and water efficiency, waste reduction, choice of construction materials, indoor air quality, social impacts, and ongoing operational practices.

6. Challenges of Modification: The difficulty in modifying or disassembling high-rise structures adds to concerns about sustainability.

While high-rise buildings can be designed and operated sustainably, it requires meticulous planning, eco-friendly practices, and careful consideration of various factors across the building's life cycle to mitigate environmental impacts and enhance sustainability.

Q.14 Are environmentally sustainable construction practices responsible for low innovation uptake in the construction industry?

The opinions are varied on whether environmentally sustainable construction practices contribute to low innovation uptake in the construction industry:

1. Yes: Some believe sustainable practices contribute to low innovation uptake, often citing factors like the cost and size of contracting companies as influencing this situation

2. No: Others disagree, stating that sustainable practices are essential but do not necessarily hinder innovation. They argue that environmental sustainability can be one of the parameters driving innovation without necessarily causing a low uptake in innovation

3. Mixed Views: Opinions also indicate a need for more innovation in the construction industry independent of sustainable practices. Some highlight that the construction sector needs to adopt innovations faster than other industries, regardless of sustainability initiatives

4. Environmental Drive for Innovation: Contrary views suggest that sustainable practices drive innovation in the industry. They propose that past practices were environmentally detrimental, and the shift towards sustainability catalyses innovation despite challenges in the construction sector's general resistance to change

5. Uncertain/Unsure: Some respondents express uncertainty or need for clarity regarding the relationship between environmentally sustainable practices and innovation uptake in construction

Overall, opinions range from seeing sustainability as a potential barrier to innovation due to cost and company size to viewing it as a driving force that necessitates innovation in an industry historically resistant to change.

Q.15 Awareness and Reasonability:

The respondents' awareness level of the construction industry's role in protecting the environment and climate change varies. The awareness scale ranges from very limited (1) to fully aware (10). Some respondents rated it as a 10, indicating a high level of awareness. Other interviewees rated 3, 6, and 7, which suggest a moderate awareness level. One respondent, for example, mentioned that the level of awareness depends on the country, with some regions having more legislation and focusing on decarbonisation plans, leading to a rating of 8. Another respondent mentioned that while there is a strong awareness overall, some parts of the industry still need in-depth analysis of the impact of environmental and climate change on a project level.

Additionally, it was noted that senior teams tend to be more aware, but workers on the ground may have lower awareness levels. In the UK market, respondents rated the awareness level as 7 or 8, with leadership and professionals being more informed but implementation facing challenges due to commercial pressures. Overall, respondents acknowledged increasing awareness of sustainability, but practical steps still needed for effective implementation, resulting in ratings from 1 to 10 on the awareness scale.

Q.16 Can you name (generally) three main challenges in building high-rise projects?

The main challenges in building high-rise projects often encompass various aspects:

1. Structural Engineering: Creating robust structural solutions to withstand gravitational, wind, and seismic forces is a significant challenge in high-rise construction

2. Elevator Systems: Designing and implementing efficient and energy-conscious elevator systems poses challenges in speed, capacity, waiting times, and energy consumption, which are crucial for tall buildings

3. Sustainability and Urban Planning: Balancing the desire for tall, dense structures with sustainability considerations involves addressing energy efficiency, materials usage, and urban planning, which are complex tasks requiring innovative and eco-friendly design and construction practices

Additional challenges include logistics and planning, infrastructure considerations, safety concerns, materials selection and availability, workforce availability, waste management, energy consumption, achieving net-zero objectives, and social impact. These challenges highlight the multifaceted nature of high-rise projects and the need for comprehensive solutions across different domains to ensure successful construction and operation. Moreover, it can be outlined in detail as follows:

As per respondent feedback on challenges linked to sustainable construction, the following aspects were highlighted:

1. Logistics and Planning: The intricacies of high-rise projects demand meticulous planning involving logistics coordination like material transport, stakeholder management, and compliance with local regulations

2. Design Complexity: Designing high-rise structures involves addressing structural demands, aesthetics, and safety standards, which can pose intricate challenges

3. Quality Control and Precision: Ensuring construction quality across subcontractors and materials is vital for structural reliability, demanding meticulous attention to detail

4. Sustainability Integration: Incorporating sustainable elements like energy-efficient systems and waste management presents challenges regarding material availability, cost, and meeting environmental norms

5. Infrastructure and Geotechnical Factors: Extensive planning for utilities and considering soil stability during construction adds complexity to high-rise projects

6. Safety Measures: Inherent safety concerns such as fire safety and compliance with safety codes require thorough planning and adherence throughout construction

7. Financial Management Managing costs for large-scale high-rise projects, including budgeting and material choices, poses challenges to ensuring financial viability

8. Regulatory Compliance: Negotiating diverse local regulations and obtaining approvals present hurdles in high-rise construction, varying significantly based on location

Q.17 Net zero greenhouse gas emissions by 2050:

Based on the responses provided, there were mixed views on the ambitious objectives for climate change of achieving zero greenhouse gas emissions by 2050 through low-carbon high-rise buildings.

Some reasons for believing in these objectives include meeting client demands, implementing stricter regulations and follow-up by governments, and the potential for collaboration and cooperation among various stakeholders, including politicians, scientists, and society. Some also believe that it is achievable but may require efforts in multiple areas of construction and development.

On the other hand, concerns were raised about limited construction budgets, lack of demand for high-rise buildings in certain regions, challenges with governmental buy-in and changes in government, and the need for a holistic approach to sustainability beyond just high-rise buildings.

It is important to note that achieving net zero greenhouse gas emissions by 2050 is a complex and challenging goal requiring concerted efforts at various levels, including policy, technology, and behavioural changes. Low-carbon high-rise buildings can be one of the potential solutions, but it may also require other strategies and approaches to achieve the target.

Overall, there is belief in the ambitious objectives for climate change and achieving net zero greenhouse gas emissions by 2050. However, there are concerns about the feasibility of achieving this goal solely through low-carbon, high-rise buildings and the need for collaboration and regulation from governments and organisations. Other factors, such as planning legislation and infrastructure, may need to be addressed to achieve this goal effectively. Ultimately, achieving net zero emissions by 2050 will require a holistic approach and the collective efforts of society.

5.4 Convergent Analysis

The pragmatic approach to data collection uses a combination of methods to answer research questions. This approach combines quantitative and qualitative methods, allowing researchers to use the most appropriate method for each component. This approach helps get a broad overview of the research topic and gather detailed information. Using quantitative and qualitative methods, researchers can gain an in-depth understanding of the topic and develop strategies to address the problem.

Results and Discussion

This research avoided depending on only numerical data for several purposes, such as being changeable and needing more consistency, especially with several uncertainties discussed intensively in the literature and data collected in this research. Such as the inconsistency associated with embodied carbon coefficients according to the processor materials adopted. This was discussed by (Gauch et al., 2023).

It becomes evident that there was a distinct difference in the order of the questions. In the qualitative interview, the initial inquiry pertained to determining project priority, followed by introducing the question regarding high-rise projects. In contrast, the quantitative survey placed the high-rise project question ahead of the broader project categorisation, potentially resulting in a skewed perception and inadvertent encouragement for respondents to prioritise high-rise projects over other project types.

It is important to note that both survey approaches share a common objective: exploring strategies to enhance the sustainability of large-scale projects despite their existing challenges. This objective is underscored by the rationale articulated in this research.

To validate these answers, the high-rise building database created through literature and quantitative data prioritises high-rise building projects. Even when it is not a sustainable way of clean or green construction, it is still a sustainable solution for urbanisation issues, as addressed previously. At the same time, it is noticed that in the qualitative interviews, infrastructure projects were prioritised over high-rise projects. Several reasons might cause this: Infrastructural projects, such as pavement works and water fixings, are high-volume projects and are being done for necessity rather than development or investing reasons.

More convergent exploration among different data collection sources can be found in Chapter 6 in the research's objectives analysis, and in Chapter 7 Discussion and Results.

Summary

This research has explored quantitative and qualitative methodologies to assess the significance of embodied carbon emissions in large-scale, high-rise, off-site, and modular construction projects. The quantitative approach involved bibliometric analysis, a questionnaire survey, and summarisation of statistical data. On the qualitative side, case studies and interviews were conducted.

The findings indicate that although off-site construction methods can potentially decrease embodied carbon emissions, they may not consistently emerge as the most effective strategies for emission reduction. Assessing project-specific factors such as location, climate, size, and type becomes crucial in determining the optimal approach to minimise embodied carbon emissions.

Moreover, the adoption of sustainable construction practices, including the use of eco-friendly materials and efficient energy systems, has the potential to reduce a project's carbon footprint significantly. Ultimately, a comprehensive understanding of the role of embodied carbon emissions in construction is essential for devising strategies to decarbonise the construction industry.

Chapter 6 Analysis of Research Objectives

In this chapter, a comprehensive analysis of the research objectives will be undertaken, relying on robust data collected during the research process. This examination will involve a meticulous and systematic comparison of the information gathered from the literature review and data collected. Figure 6-1 is provided to depict the objective analysis process visually. The figure utilizes thick black arrows to denote direct correlations between various elements, emphasizing the interconnectedness of these components. Additionally, dotted lines are employed to signify secondary relationships, indicating nuanced connections within the analytical framework.

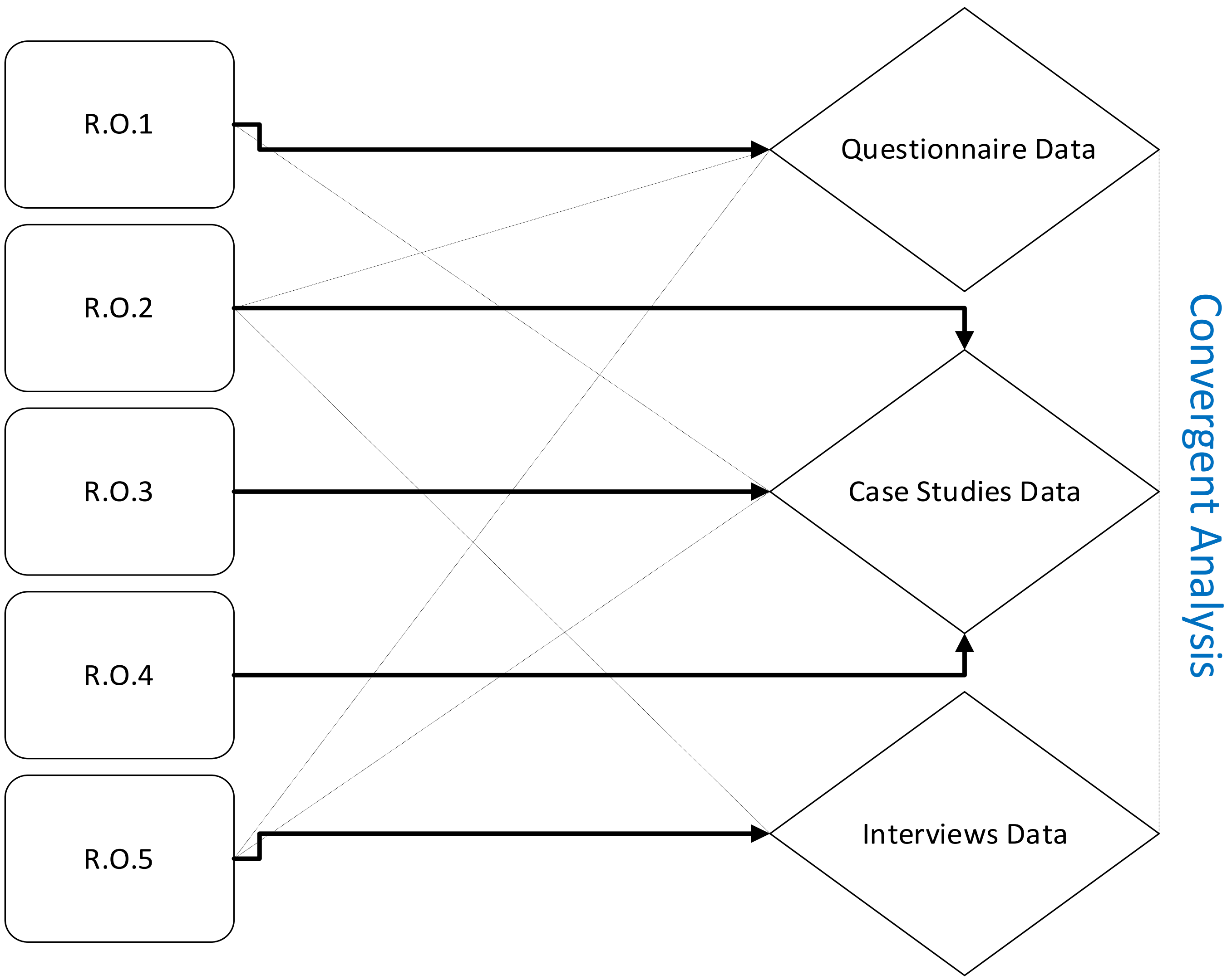


Figure 6-1 Research objectives analysis process

RESEARCH OBJECTIVE NO. 1	QUANTIFY AND IDENTIFY THE ENVIRONMENTAL AND CARBON IMPACT CAUSED BY THE CONSTRUCTION PROJECTS
LITERATURE REVIEW	Climate change, fossil carbon emissions, and methane are the most noticeable impacts caused by construction projects, especially the large ones. There was a norm in percentages of environmental impacts among different types of construction methods or projects; however, there was some linear relationship between concrete and steel construction in contribution to environmental impacts, but steel was introduced as a better material in terms of climate change and air carbon emissions, for the reasons addressed and explained previously, such as prefabrication level, waste generation, recyclability, and others.
QUANTITATIVE DATA	Greenhouse gases (GHG) held the highest influence, accounting for 80%, with CO_2 representing 90% of the selections among the various GHGs.
CASE STUDIES DATA	Conducting selected projects for LCA software showed the superiority of climate change associated with carbon emissions as environmental impact outcomes. However, the results varied depending on each project's size, date, materials, and construction methods.
INTERVIEWS DATA	This objective primarily concerned question number 5 in the interview, where most interviews revealed comparable identification of issues seen in the survey and literature review, like greenhouse gas emissions, water pollution, natural resource depletion, and waste generation. The emphasis was on understanding how these impacts connect and their hierarchical relationship.

RESEARCH OBJECTIVE NO. 2	REVIEWING OFF-SITE PRACTICES, ON-SITE METHODS, AND CARBON MITIGATING STRATEGIES IN THE CONSTRUCTION INDUSTRY BY CREATING A DATABASE
LITERATURE REVIEW	OSC is a viable option for the construction industry in terms of reducing carbon emissions, and further research is needed to explore how to reduce the barriers of OSC and increase its sustainability performance.
QUANTITATIVE DATA	Optimised selection of materials was preferred on off-site or on-site technologies to mitigate carbon emissions.
CASE STUDIES DATA	When adopted, OSC or prefabricated components, especially steel, have created less impact on climate change.
INTERVIEWS DATA	Materials selection was preferred over OSC and on-site practices. Choosing resources that efficiently minimise operational and embodied carbon emissions involves selecting materials and construction methods with reduced environmental impact over the building's life cycle. This encompasses using recycled materials, employing passive solar design, and installing energy-efficient appliances to alleviate carbon emissions.

RESEARCH OBJECTIVE NO. 3	EVALUATING THE ROLE OF EMBODIED CARBON EMISSIONS AND LIFE CYCLE ASSESSMENTS IN CONSTRUCTION PROJECTS
LITERATURE REVIEW	LCA is important for evaluating and measuring carbon footprints in all stages of construction projects, which also developed a more specific LCCA (Life Carbon Cycle assessment) method.
QUANTITATIVE DATA	The respondents showed a good understanding of the importance of both operational and embodied carbons through the life cycle of projects and specified the material production and transportation as the most critical stages of the construction process, with 90% and 50% of respondents, respectively.
CASE STUDIES DATA	There needed to be more focus on the entire LCA of the project, where more focus was developed on the operational stage of the building.
INTERVIEWS DATA	A good understanding and awareness of the importance of focusing on all project stages, especially today, to cope with the aims of decarbonising the construction industry.

RESEARCH OBJECTIVE NO. 4	EXAMINING CONSTRUCTION PROJECTS OF MODERN HIGH-RISE BUILDINGS IN TERMS OF ENVIRONMENTAL SUSTAINABILITY
LITERATURE REVIEW	High-rise building developments offer the advantage of meeting the requirements of modern urban planning by accommodating the increasing population demands and consolidating necessary services and infrastructure within the project site, thus addressing the issue of land depletion. Nevertheless, these projects entail significant material consumption, resulting in higher embodied carbon emissions and increased operational energy usage for the building.
QUANTITATIVE DATA	There was a widespread belief in the potential of high-rise projects to be environmentally sustainable, as evidenced by the responses to questions 18 and 19 in the survey. These questions indicated a preference for high-rise projects over other types regarding their environmental sustainability.
CASE STUDIES DATA	Land depletion was minimised in all high-rise buildings because of the usage of smaller areas compared to other types of construction projects such as roads, flat buildings, multi dwellings and so on. Sustainable practices should be considered throughout the construction process of supertall buildings to ensure that the designated output is achieved.
INTERVIEWS DATA	Participants highlighted the significance of acknowledging all project types in sustainable practices, emphasising their interconnectivity and mutual influence. Moreover, respondents generally agreed that adopting environmentally sustainable approaches across various options—from infrastructure and pavements to housing, mid-rise, and high-rise buildings—is crucial for ensuring a more sustainable future.

RESEARCH OBJECTIVE NO. 5	STANDARDISING THE ASSESSMENT CRITERIA FOR DECARBONISING THE CONSTRUCTION INDUSTRY
LITERATURE REVIEW	Numerous global institutions and organisations in the UK and internationally are dedicated to combatting carbon emissions and striving for net-zero carbon levels. They employ various methods to achieve these goals, such as monitoring and implementing regulations. These entities work tirelessly to mitigate climate change impacts through their advocacy, research, and collaborative efforts across industries and countries.
QUANTITATIVE DATA	(32%) of the survey respondents demonstrated familiarity with all the organisations. However, it was evident that BREEAM is more popular, particularly in the UK and Europe. The profession's location highly dominates the institution's influence and popularity.
CASE STUDIES DATA	As other databases were collected, multiple organisations and entities were involved, but there was more supremacy to green building councils with the selected case study projects.
INTERVIEWS DATA	While this question was not posed directly, most interviews highlighted the necessity for collaboration and alignment between environmental and private institutions. This alignment is crucial to establishing uniform and robust methodologies to attain net-zero objectives.

Chapter 7 Discussion and Results

7.1 Introduction

This thesis answered the research's main questions by reflecting the most important headlines of the research, in which it explored and illustrated the construction industry in terms of environment and sustainability, especially the embodied carbons, which are highly related to the construction process and had proved that it is beside design and production is a significant phase of any large-scale construction projects, especially high-rise ones.

The research was keen to maintain consistency and narrowed as much as possible. Construction projects have many uncertainties and dimensions, so the researcher focused on the construction process and practice as much as possible within similar projects.

Despite the consensus on carbon emissions and the construction industry's role in sustainability on a global scale, most of the studies and tests in this field were conducted more in operational carbons or in the whole life cycle assessment of the project, especially the cradle-to-gate and use stages. However, they gave little focus to embodied carbons and construction process assessment (gate-to-use).

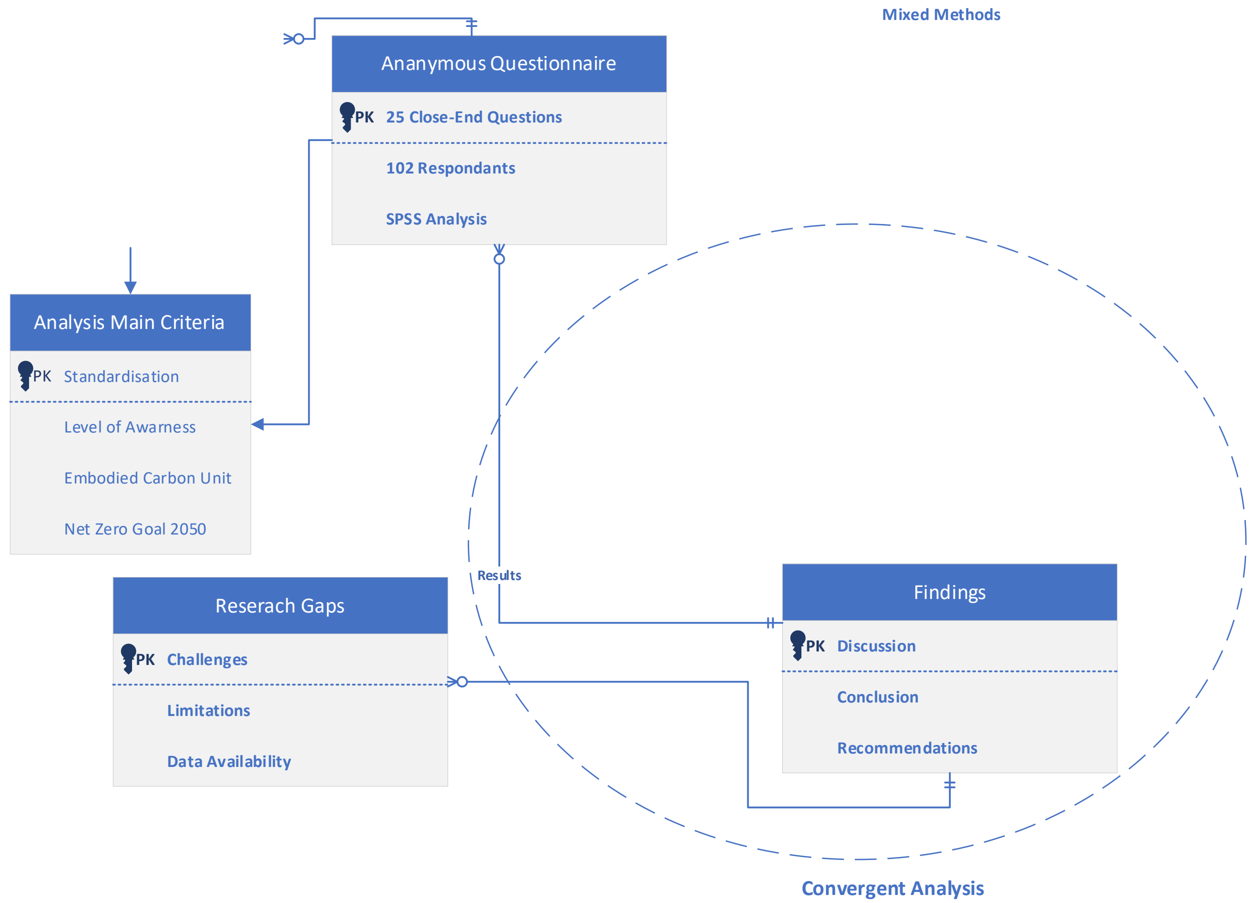
More clarity is needed in defining the best way to mitigate carbon emissions' environmental impacts. Also, the unit of measuring embodied carbons is only sometimes consistent.

The bibliometric study and case studies collected have achieved remarkable results in evaluating the embodied carbons compared to other recent studies and showing the status of environmental sustainability in high-rise buildings.

7.2 Quantitative Questionnaire

The quantitative survey questionnaire results are structured around a research framework focusing on three key criteria: level of awareness, optimism, and standardised procedures in environmentally sustainable construction. This framework provides a lens through which to interpret stakeholders' perspectives and readiness for sustainable practices in the construction industry.

Here is a reminder of the research framework cropped to the quantitative questionnaire framework.



The survey on environmentally sustainable construction captured insights from a broad spectrum of professionals, primarily academics and engineers, providing a comprehensive view of the industry's current state and future outlook. This discussion interprets the survey results through the lenses of awareness, optimism, and the adoption of standardised procedures.

7.2.1 Level of Awareness

The survey results demonstrate a high level of awareness regarding the environmental impacts of construction activities. A significant portion of respondents (55%) identified Greenhouse Gas (GHG) emissions as the primary environmental impact, with carbon dioxide (39.4% solo response) and methane (CH_4, identified by over 45% of respondents) being the most recognised contributors. This awareness aligns with extensive literature, such as the studies by Elshaboury and Marzouk (2021) and Röck et al. (2020), which highlight the critical role of GHGs in the environmental footprint of construction projects.

Moreover, the acknowledgment of operational and embodied carbon emissions across a project’s lifecycle, as emphasised by the survey, indicates a sophisticated understanding of the different sources of emissions. Respondents’ recognition of these emissions suggests a comprehensive awareness of how construction activities impact climate change, supporting the need for mitigation strategies at all stages of a project’s life cycle.

The high level of education among respondents (over 79% holding higher education degrees) correlates with a heightened awareness of sustainable practices. Higher education has been linked to increased innovation and progress in environmentally sustainable approaches (Johnson et al., 2016), which is reflected in the responses.

The geographic distribution of respondents also underscores a global awareness of sustainability issues. With substantial representation from regions like the UK (58.42%) and Jordan (14.85%), the survey highlights how regional experience and the headquarters’ location influence understanding and prioritization of sustainable practices. The UK's leading role in sustainable construction, coupled with the experience from diverse climates and regulatory environments, enriches the awareness and responses captured in the survey.

The survey indicated a strong awareness of the importance of design and material selection in minimising environmental impacts. The majority (81%) pointed to the design and planning phase as crucial, and 42% favoured optimised material selection as the primary method for achieving sustainability. This recognition aligns with research by Orr John, Gibbons, and Orlando (2020), underscoring the role of early-stage decisions in shaping a project’s environmental footprint.

7.2.2 Level of Optimism

The survey results reveal a mixed but generally optimistic view of the construction industry's ability to address carbon emissions. While respondents understand the critical importance of both operational and embodied carbon emissions, there is an implied optimism in the belief that comprehensive sustainability can be achieved by addressing 100% of both carbon types.

The focus on operational and embodied carbon emissions suggests confidence in the industry's ability to mitigate its environmental impact through targeted actions. However, the survey also highlights areas where more effort is needed, such as the moderate preference for a particular measurement unit for embodied carbon emissions, indicating a need for further standardisation and clarity.

Regional differences in optimism are evident, with respondents from the UK showing a strong commitment to sustainable practices, likely driven by the region's regulatory and innovation leadership in this field. The UK's prominence in sustainable construction, as noted in the survey, reflects a positive outlook on achieving environmental goals, bolstered by advanced policies and technologies.

In contrast, respondents from other regions, like Jordan, reflect optimism tempered by practical challenges in implementing sustainable practices within their local contexts. This nuanced view points to the need for localized strategies and support to foster optimism across different regions.

Despite the challenges identified, such as the relatively low endorsement of 2050 objectives (fewer than 45% across age brackets), there is a general optimism about the industry's capacity to meet environmental targets. Despite having economical and technical difficulties, the progress in 2050 goal is promising so far (Wiseman, 2018).

The survey suggests a belief in the effectiveness of current measures and a commitment to advancing sustainable practices, even as it acknowledges the need for further efforts to build confidence in achieving long-term goals.

7.2.3 Standardised Procedures

The survey results highlight a critical issue: the lack of a standardised unit for measuring embodied carbon. With only 52% showing a strong preference for a specific unit ($kgCO_2/m^2$), which is preferred by (De Wolf et al., 2017), where others such as (Ekundayo et al., 2019) prefer that the measurement depends on the need and stage of the project life cycle. The research has shown that there is significant variation in how embodied carbon is measured, influenced by factors such as project type, material variations, and adopted methodologies, beside the project phase factor.

This lack of standardisation can lead to calculation errors and communication challenges among stakeholders. The respondents' insights underscore the need for developing and adopting standardised procedures for measuring and reporting embodied carbon to enhance consistency and accuracy in sustainability assessments.

Material production and transportation were identified as crucial stages in the construction process by 94% and 50% of respondents, respectively. This consensus highlights the importance of standardising practices in these areas to reduce environmental impacts effectively.

Standardised guidelines and best practices for sustainable material production and selection can help streamline efforts to minimise the carbon footprint of construction activities. This approach aligns with the survey’s findings and supports the need for uniform procedures to achieve greater sustainability in material use.

The survey results also point to the importance of a holistic, cradle-to-grave approach in evaluating environmental impacts, as chosen by many respondents. Despite that the production stage of building materials, including building systems and installations, accounts for around 55% of the total emissions (Felicioni et al., 2023). This comprehensive view supports the adoption of standardised procedures that address sustainability across all stages of a project’s lifecycle, from design and material production to construction and end-of-life disposal.

Implementing standardised procedures for assessing and mitigating environmental impacts throughout the project lifecycle can ensure consistent and effective sustainability practices across the industry. This standardisation is critical for addressing the diverse challenges and opportunities presented by different project types and stages.

7.2.4 Research Gaps

During data collection for the anonymous questionnaire on sustainability in construction, a significant gap became evident: the respondents' low understanding of the differences between embodied and operational carbon. This lack of clarity impacts the accuracy of their responses to questions about prioritising project types and choosing the best methods to mitigate carbon emissions.

Many respondents struggled to differentiate these concepts and the distinct stages of a project's lifecycle, leading to potential misinterpretations when evaluating the most carbon-efficient practices. For example, without a clear understanding, a participant might incorrectly prioritise projects that seemingly have lower operational emissions but higher embodied carbon, such as those using traditional construction methods with energy-intensive materials.

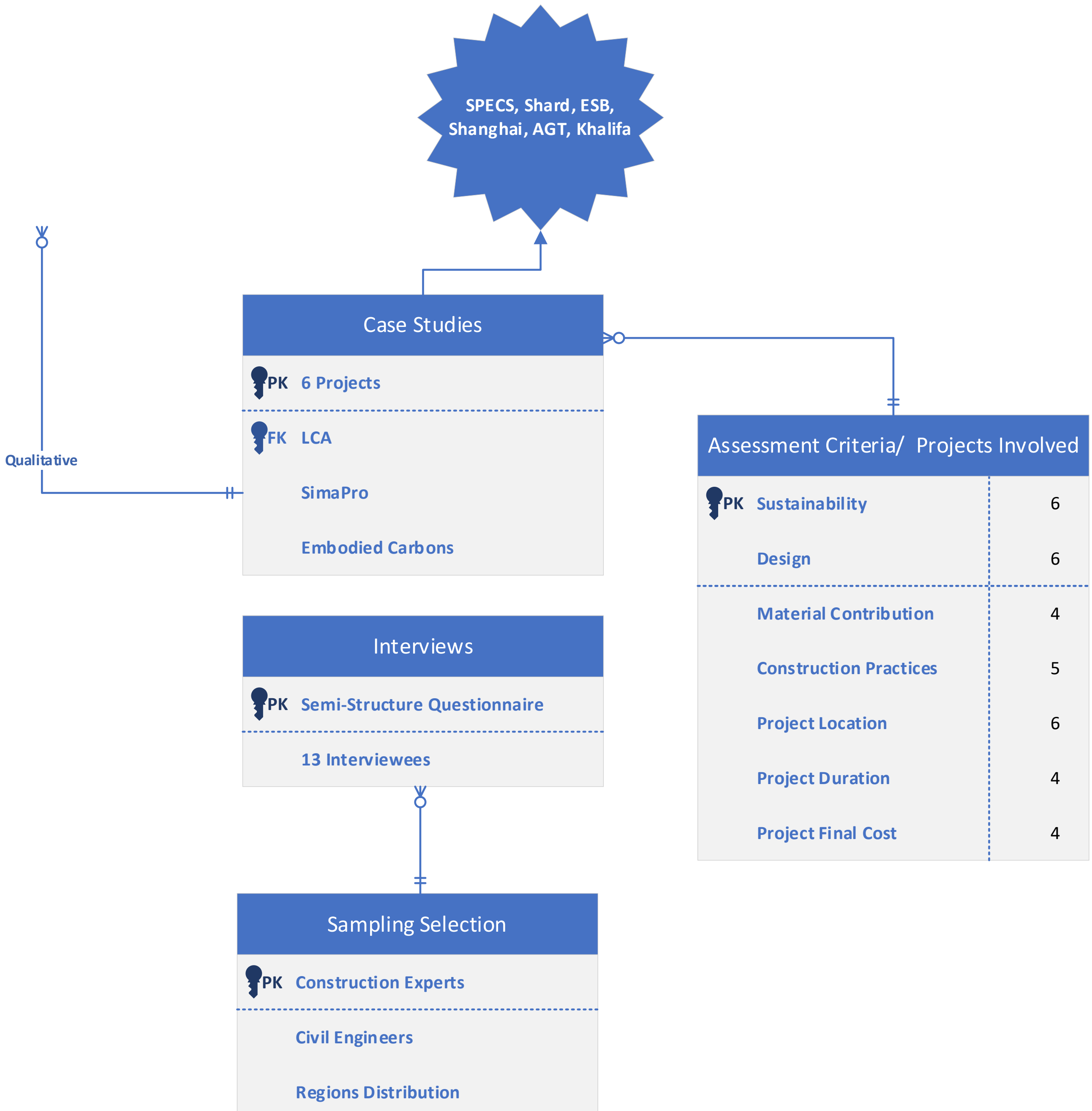
This confusion also complicates assessing the most effective strategies to reduce carbon emissions. Methods like using low-carbon materials or optimising construction techniques (e.g., off-site construction) are primarily targeted at reducing embodied carbon, while improving energy efficiency and utilising renewable energy sources are strategies focused on operational carbon.

Therefore, to enhance the accuracy and reliability of responses, it is crucial to provide clear educational resources that elucidate these concepts and their implications. This will ensure that participants can offer well-informed opinions, leading to more effective and targeted sustainability measures in the construction industry.

7.3 Case Studies

The evaluation of environmentally sustainable construction practices in the Burj Khalifa, Shanghai Tower, The Shard, ESB, SPECS, and ATG case studies reveals several critical insights into the intersection of design, materials, and their environmental impacts. Each project serves as a valuable reference point to understand the roles of design choices, material selection, and construction practices in achieving sustainability, mainly focusing on embodied carbon, life cycle assessment, and overall project sustainability.

Here is a reminder for the case studies part of the research framework.



7.3.1 Materials and Design Contribution

The analysis underscores the substantial influence of material quantities and types on environmental impacts. High-rise buildings predominantly use steel and concrete, significant contributors to embodied carbon. The case of The Shard, which utilised galvanized steel sheets, highlights a reduction in various environmental impacts such as water use and eutrophication. This suggests that material selection, particularly in the choice of construction steel, is pivotal in mitigating specific environmental effects.

However, the comparative analysis of newer projects like the Shanghai Tower and Burj Khalifa against older ones such as the ESB indicates that despite advancements in materials and construction techniques, significant progress in reducing climate change impacts remains limited. This finding aligns with the broader literature, emphasising the need for continual innovation and adoption of more sustainable materials and practices in construction, especially in production stage of materials, which was emphasised by (Cabeza et al., 2021; De Wolf et al., 2017).

The integration of aerodynamic shaping and wind engineering in the design of the Burj Khalifa represented a pioneering approach that has significantly enhanced the tower's resilience against lateral winds, a critical consideration in skyscraper construction. By employing advanced wind tunnel testing and computational fluid dynamics, engineers optimised the tower's form to minimize wind loads and mitigate the effects of turbulent air currents.

This meticulous design not only contributes to the building's structural stability but also reduces the risk of damage to its glass façade and other vulnerable components. Such resilience is crucial for sustainability as it minimises the frequency and extent of maintenance and repair interventions, thereby reducing the associated carbon footprint over the building's lifespan. The integration of aerodynamic principles not only underscores the Burj Khalifa's architectural achievement but also sets a precedent for future high-rise developments seeking to balance aesthetic appeal with environmental durability and operational efficiency.

7.3.2 Embodied Carbon and Life Cycle Assessment

The LCA method, used to evaluate the environmental impacts of construction projects, demonstrated clear advantages in identifying areas where improvements could be made. For example, the LCA of glass used in The Shard revealed lower environmental impacts than steel, emphasising the importance of including diverse materials in LCA studies. However, traditional construction materials like concrete and steel still dominate the environmental impact due to their extensive use in structural elements.

The case studies highlight the necessity of incorporating detailed and specific LCA data, including operational and embodied carbon emissions, to provide a comprehensive sustainability assessment

(Chau et al., 2015; Prado et al., 2020; Rosenbaum et al., 2017). The absence of specific material grades (e.g., concrete classes above C60) and specific project details in LCA databases suggests a gap that could lead to inaccuracies. This underscores the need for more refined and up to date LCA tools and databases to support accurate environmental impact assessments.

7.3.3 Project Duration, Location, and Sustainability

Project duration and location were critical factors in determining sustainability outcomes. This was presented in the literature review especially by (Feng et al., 2018a; Wilberforce et al., 2021; Zavadskas et al., 2017). However, The ESB, constructed over a less extended period (13 months) with traditional methods and materials, showcased higher embodied carbon emissions due to the extensive use of materials and energy. In contrast, more recent projects have benefited from longer construction timelines (Khalifa and Shanghai) and advanced technologies, leading to lower environmental impacts.

Geographical location also plays a significant role in sustainability practices. Projects in warmer climates, such as the Burj Khalifa in Dubai and AGT in Amman, face unique energy consumption and resource use challenges, necessitating tailored sustainability strategies. This regional variation highlights the importance of context-specific solutions in sustainable construction practices.

Determining sustainability targets involves several factors identified in this research, making it challenging to set a specific target number. However, based on data collected from case studies and bibliometric studies, the research suggests that for large-scale projects, a roughly amount of any embodied carbon below 400 kg CO_2e/m^2 should be considered sustainable, given the significant amount of materials used. This threshold was recently studied by (Zhang et al., 2023).

7.3.4 Sustainable Construction Practices and Final Cost

The comparison of construction methods across the case studies reveals that sustainable practices, including advanced construction techniques and prefabrication, contribute significantly to reducing environmental impacts. For instance, the modular assembly in The Shard and prefabricated components in the Burj Khalifa enhanced construction efficiency and reduced waste. However, achieving such efficiencies requires careful management to avoid potential downsides such as reduced creativity and resource use inefficiencies.

The case studies of the Burj Khalifa, The Shard, Shanghai Tower, and the Empire State Building (ESB) illustrate advanced sustainable practices and efficient crane usage in their construction. The Burj Khalifa utilized self-climbing formwork and high-performance concrete with fly ash, strategically employing self-climbing tower cranes to reduce dependency. The Shard's top-down construction and modular spire assembly minimized crane lifts, optimizing material usage and wind resistance. Shanghai Tower's mega frame core wall system, with concrete and steel composites, utilized cranes efficiently for vertical steel installations. The ESB emphasized off-site prefabrication and mass production methods, employing derricks and hoists to ensure continuous crane availability.

These projects demonstrate the integration of sustainable materials, innovative construction techniques, and strategic crane management to enhance efficiency and reduce environmental impact in large-scale building projects.

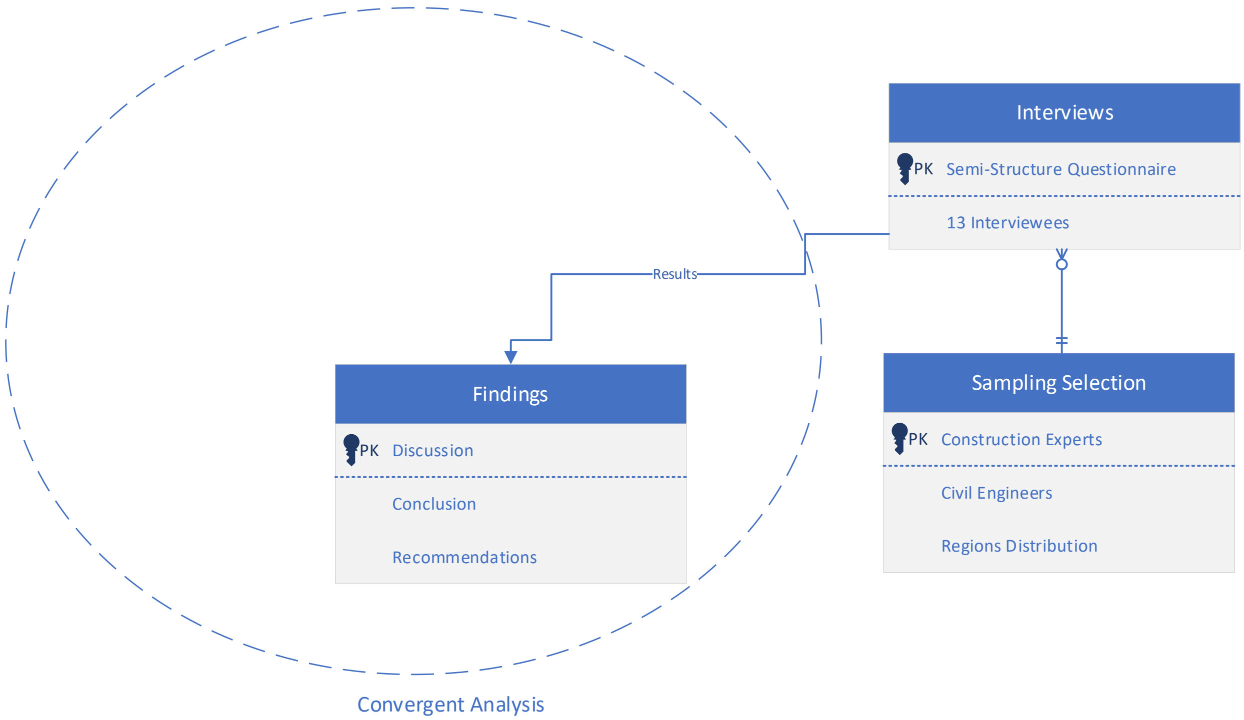
The financial aspect of sustainable construction is also crucial. While initial costs for implementing sustainable practices and materials may be higher (Feng et al., 2018), the long-term benefits include lower operational costs and reduced environmental impacts. This economic consideration is essential for stakeholders to balance sustainability goals with financial viability.

7.3.5 Research Gaps and Future Directions

The case studies identified several research gaps, particularly in using LCA software databases. The lack of precise temporal data and the limited availability of specific material grades highlight the need for more comprehensive and current LCA tools. Additionally, the need for standardised benchmarks for comparing LCA results across different projects poses challenges for practitioners aiming to evaluate and improve their sustainability performance.

Future research should focus on developing more detailed LCA databases with specific country-level data and updated material specifications. This granularity would provide a more accurate and context-specific understanding of the environmental impacts associated with construction materials and practices. Furthermore, integrating comprehensive benchmarks and guidelines into LCA methodologies would enhance their reliability and comparability.

7.4 Semi-Structured Interviews



Based on the qualitative interviews focused on environmentally sustainable construction and embodied carbon, several key discussions emerged, offering insights into the research topic:

Firstly, the interviews indicated a strong consensus among respondents regarding the definition of sustainability, aligning closely with the UN framework. This definition emphasises the need for a balanced approach that integrates economic, social, and environmental factors. Understanding sustainability in this holistic manner is crucial for guiding construction practices that not only minimize environmental impact but also contribute positively to society and economic development.

The interviews also shed light on the challenges specific to high-rise construction projects, particularly in the UK and Europe. Respondents highlighted reasons why recent projects often exclude lower or basement floors, citing concerns such as safety, high construction costs, operational expenses, and sustainability considerations. These findings suggest a trend towards designs that prioritize efficiency and sustainability metrics, potentially aiming to reduce embodied carbon through optimised material use and energy-efficient construction methods.

During discussions on environmental impacts, the interviews identified several critical concerns associated with the construction phase. These include significant waste generation, depletion of natural resources, greenhouse gas emissions, water wastage, and threats to natural ecosystems. These findings underscore the urgent need for adopting sustainable construction practices that address these impacts through efficient resource management and the integration of eco-friendly technologies.

Respondents emphasised the crucial role of material selection in reducing both operational and embodied carbon emissions over a building's lifecycle. This was agreed by the survey questionnaire and case studies conducted. Choices such as using recycled materials and implementing advanced construction techniques like off-site construction were highlighted as effective strategies to minimise environmental footprints while maintaining structural integrity and functionality.

Debates on whether to prioritise off-site or on-site construction methods for mitigating carbon emissions revealed that each approach offers distinct advantages. Off-site construction provides controlled environments that enhance efficiency and reduce waste, whereas on-site construction allows for adaptability and customization, critical for addressing complex project requirements and local conditions.

In terms of measuring embodied carbon, the interviews highlighted $KgCO_2/m^2$ as a commonly suggested unit due to its practicality in quantifying environmental impact per unit area. This metric's popularity underscores its utility in assessing sustainability performance across various construction projects and facilitating informed decision-making regarding material choices and construction methods.

Regarding the impact of sustainable practices on innovation within the construction industry, perspectives were divided. While some viewed sustainability as potentially hindering innovation due to perceived costs and industry inertia, others saw it as a catalyst for driving technological advancements and new practices aimed at achieving environmental goals. This contrast reflects ongoing debates within the sector regarding the balance between sustainability objectives and innovation agendas.

The varying levels of awareness among stakeholders regarding environmental impacts and climate change were also evident in the interviews. While senior leadership generally exhibited higher awareness levels, frontline workers showed knowledge gaps, indicating a need for comprehensive training and awareness campaigns to promote sustainability practices uniformly across the construction workforce.

Discussions on achieving net-zero greenhouse gas emissions by 2050 through low-carbon high-rise buildings highlighted both optimism and scepticism. While such buildings hold promises for reducing environmental impacts, achieving ambitious emission reduction goals requires coordinated efforts across regulatory, technological, and societal dimensions, which was emphasised by (Government Commercial Function, 2022; Pan, 2014; UK Green Building Council, 2021; Wiseman, 2018).

Overall, the research methodology combining qualitative interviews with quantitative methods like surveys and bibliometric analysis provided a nuanced understanding of the complexities surrounding embodied carbon in construction. This hybrid approach underscores the importance of tailored strategies that account for project-specific factors in advancing sustainability goals within the construction industry.

7.5 Research Question

The direct answer for the **research question 1** was that the construction process of high-rise buildings can mitigate embodied carbons through the following strategies:

1. Prefabricated structural elements
2. Material selection
3. Waste management, e.g., Water, sewage, formwork, and equipment
4. LCCA application
5. Reduced transportation distances

Research question 2 is partially answered among question 1, whereas the short answer is yes; however, there are some conditions and compromised solutions to reach the NetZero carbon goal. Using technologies and prefabricated construction methods such as automated construction and prefabrication can reduce embodied carbon and deliver sustainable projects. **Research question 3** was addressed by ensuring uniformity and standardisation in measuring units and focusing on institutional alignment.

<u>The following points summarise the results:</u>

1. There are many ways to achieve environmentally sustainable construction projects. However, the issue is which way to choose as it is only possible to adopt some, especially on one project
2. Many institutions and organisations in each country, specifically the UK, are dealing with carbon emissions and sustainability in the built environment, which is considered an obstacle to sustainable construction
3. Carbon emissions, specifically embodied ones, are the most critical impacts associated with the environmental sustainability of construction projects
4. Embodied carbons have increased recently
5. Large-scale projects, especially high-rise buildings, are required types of projects to adopt modular, sustainable methods, for reasons discussed in chapters 3 and 5. Moreover, these methods apply to other project types discussed in the database of case studies
6. Very few studies implicitly studied reducing embodied carbon in the construction process of projects or construction practices such as off-site construction or on-site activities
7. There needs to be more consistency in measuring CO_2 emissions by a standard unit of analysis such as kg.CO_2/annual, kg.CO_2/m^2, kg.CO_2/kg, kg.CO_2/m^3 and others, due to the complexity of projects and several uncertainties discussed earlier, like location and transportation factors and gaps between the given numbers
8. Practices on the site within construction process activities and works can reduce the uncertainties and variables mentioned in point e. In the research literature, these practices are OSC and on-site technologies, systematically reviewed in Chapter 2
9. Transportation is indispensable in all life cycle assessments, even site processes
10. For embodied energy and carbon assessments, all activities should be traced back to the cradle as much as possible to obtain accurate measures
11. The research discovered new classifications of construction practices, such as "wet" and "dry" concepts. Also, the new LCA stage is "A 0"

In the materials selection category, timber always gave the best results in reducing EC regardless of the project's circumstances, such as location, weather, and size, whereas steel had better durability and recyclability.

Some research gaps were identified while using the LCA software database. Uncertain data and the absence of project-specific dates were notable limitations. Additionally, the database included concrete grade classes beyond C60. Understanding the difference between operational and embodied carbons among some participants is also considered a gap of knowledge that should be addressed.

Chapter 8 Conclusions and Recommendations

The main conclusions can be summarised by the specified vital problems within the construction projects in terms of environmental sustainability, and carbon emissions, especially the embodied are the most to concern, especially in the life cycle of the construction process and works stage, or can be interpreted by "on-site activities", because even when considering off-site construction technologies, they have given excellent results especially when excluding the transportation and production stages.

Formwork plays a crucial role in sustainable construction by promoting efficiency, minimising waste, and reducing the environmental impact of building processes. Modern formwork technologies use reusable or recycled materials to conserve resources and decrease carbon emissions. Additionally, formwork's ability to streamline construction operations leads to shorter project timelines and reduced energy consumption. By adopting sustainable formwork practices, construction industries can move towards more eco-friendly and responsible building methods.

Recommendations are the following points.

1. Making a standard unit for measuring the EC emissions, this research nominated the best available $Kg.CO_2/m^2$, especially when assessing large-scale buildings

Creating a standardised unit for measuring embodied carbon (EC) emissions, such as $Kg.CO_2/m^2$, is crucial for accurate assessment and comparison, especially for large-scale buildings. This unit allows for a consistent metric to evaluate the environmental impact of different construction projects, enabling better regulatory compliance and sustainability benchmarking.

2. Unify the organisations and institutions oriented with sustainability in the UK and abroad with one centralised entity and give the rest a more concentrated specified role

This central body would oversee sustainability initiatives, while specialised roles can be delegated to other entities, ensuring a cohesive and focused approach to environmental goals.

3. Distributing the LCCA stages by involved teams and specialists

Assigning specific stages of the Life Cycle Cost Analysis (LCCA) to involved teams and specialists ensures detailed and accurate assessments. Each team would focus on their expertise area, enhancing the precision of sustainability evaluations and enabling targeted interventions for reducing carbon emissions.

4. Provide each large-scale or high-rise building project with carbon sensors to measure the emissions during construction

Equipping large-scale or high-rise building projects with carbon sensors to monitor emissions during construction provides real-time data. This practice helps in identifying high-emission activities and implementing immediate corrective measures, contributing to better carbon management throughout the construction phase.

5. Adopt a certain level of prefabrication when constructing high-rise buildings, especially non-bearing concrete walls, small RC slabs, stairs, and terraces, because they have minimal risks and reduce environmental impacts caused by site work

Prefabrication, especially for non-bearing concrete walls, small, reinforced concrete (RC) slabs, stairs, and terraces, can significantly reduce environmental impacts. Prefabricated elements are produced in controlled environments, reducing waste and on-site emissions, and can streamline construction processes, leading to shorter project timelines.

6. Using on-site technologies is not very useful for large-scale projects, even though they can highly contribute to mass house construction; for example, renewable and electrical machinery or equipment are better to consider, while technologies such as carbon capture technologies must be explored more

While on-site technologies can contribute to mass housing construction, they may not be as effective for large-scale projects. Renewable and electrical machinery should be prioritized for their lower environmental footprint, while carbon capture technologies warrant further exploration to enhance their feasibility and effectiveness in large-scale applications.

7. Materials selection is crucial to reducing EC and achieving sustainable construction. However, they should be considered based on the conditions and location of the project

Material selection is pivotal in reducing EC and achieving sustainable construction. Choices should be made considering the specific conditions and location of the project, balancing sustainability with practicality. Local materials might reduce transportation emissions, while innovative materials could offer lower embodied carbon.

8. More focus should be on practices done on the site of construction projects, especially high-rise buildings, as there is a colossal inventory of materials and types of machinery

High-rise buildings involve substantial inventories of materials and machinery. Emphasizing sustainable practices on-site can lead to significant reductions in carbon emissions. Efficient material management, waste reduction, and the use of eco-friendly machinery are critical strategies to enhance the sustainability of on-site activities.

9. LCCA can be executed, but it is better to be distributed critically to project parties in more detail:

    1. Cradle to design: for designers and architects
    2. Design to the gate: Civil engineers and contractors
    3. Gate to site: contractors
    4. Gate to use: stakeholders and clients
    5. Cradle to grave: designers and civil engineers
    6. Cradle to cradle: all parties

Eliminating using natural materials, such as fossil fuel, cement, timber, or steel, will never be a solution, but managing how to use them efficiently is what matters.

Appendix 1: Quantitative Data Questionnaire

Ethical approval/Protocol number: **SPECS/PGR/UH/05135**

Please check the link:

https://forms.office.com/Pages/ResponsePage.aspx?id=ur7mk6rEMUevXdc1sJfq2-PxL8NqevlJgAEswZFQUUFURDBDVU8zMDdGR0M4VUtIS1lXNkUwOEFGQi4u

The questionnaire:

1.Occupation and area of expertise (*Choose all what apply*)

Designer / Planner

Consultant

Contractor

Entrepreneur

Engineer(any)

Academic/ Lecturer

Project Manager

2.Please specify your type or branch of occupation

3.Level of education

Bachelor

Master

Doctorate

4.Your age group

25-35

35-45

45-55

55-65

65-75

Over 75

5.Country or region of profession

6.What is the most important type of sustainability in construction projects?

Economic

Environmental

Social

7. What are the most influential environmental impacts of construction projects?

Greenhouse gases (GHG)

Waste generation

Land depletion

Water wastage

Do not know

8. Which gases of GHG have the most environmental impact? *(choose all what apply)*

Carbon dioxide CO_2

Methan CH_4

Nitrous oxide N_2O

Sulfur dioxide SO_2

Sulfur hexafluoride (SF_6)

Do not know

9. What are the most severe consequences of environmental impacts? *(choose all what apply)*

Global warming

Ice melting

Ozone depletion

Drought

Blizzards

Hurricanes

10. Considering all life cycles of construction projects is important, what is the most important phase in the life cycle of a construction project in terms of environmental sustainability?*(choose all what apply)*

Design and Planning

Production and manufacturing

Construction

Use and operation

Maintenance and refurbishment

Demolition

11. Through the whole life cycle of construction projects, which carbon emissions are most important?

Embodied Carbons

Operational Carbons

Both

None

12. In the construction phase of projects, which carbon emissions that should be considered more?

Embodied carbons

Operational carbons

Both

None

13.In which unit it is best to measure carbon emissions in construction projects

Kg. CO2/M2 (carbons per square meter of constructed buildings)

Kg. CO2/Capita (carbons per individual for all mankind)

Kg. CO2/Annual (construction industry)

Kg. CO2/M3 (carbons per volume of materials)

Kg.CO2/ Kg (carbons per weight of materials)

14.Which stage or stages of construction works are the highest for emitting carbon emissions? (choose all what apply)

Excavation and levelling

Materials production (concrete, steel, aggregates, wood, etc..)

Transportation

Labour and staff

On-site equipment

Finishing (coating, plastering, ceilings, tiling)

Electro-mechanical works

15.According to the life cycle assessment (LCA) of a construction project, which one is the most environmentally important nowadays?

Cradle-to-Gate

Cradle-to-Site

Cradle-to-Use

Cradle-to-Grave

16.Which kind of practice can help most reducing embodied carbon emissions during the construction phase?

Off-site construction such as prefabrication, tilt up, and off-site manufacturing.

On-site practices such as 3D printing, Automated construction, carbon capturing, in-situ-casting

Managerial strategies such as Building Information Modelling (BIM) and Lean management

Optimised selection of materials

17.Which of the following materials promote (mostly) environmentally sustainable high-rise project?

Steel

Concrete

Timber

18. Are high-rise building projects capable of achieving environmentally sustainable construction in the design, construction, and operation (use)phases?

Yes

No

Maybe

19.What type of construction projects can be the best to apply sustainable solutions, and having the best tangible outcomes? (*choose all what apply)*

Pavement (roads, bridges, airport runways)

Infrastructure (water, sewage, cables)

High-rise buildings (commercial, residential, hospitals)

Dwellings (houses, small flats)

Halls (theatres, stadiums)

20.To what degree, construction projects' environmental impacts can affect climate change and global warming potential? (1 is less and 10 is max)

21. Is a zero net energy buildings (GHG emissions) 2050 goal possible?

according to the current situation of construction

Yes

No

22.Name three challenges associated with having net carbon construction projects

23. Will the construction industry play a positive role in climate change in the present and future?

Yes

No

Maybe

24. Do you think that construction projects will abandon fossil fuel resources in the near future?

Yes

No

Maybe

25. Which of the following organisations are most familiar to you?

BREEAM (Building Research Establishment Energy Assessment)

LEED (Leadership in Energy and Environmental Design)

EPD (Environment Product Declaration)

IPCC (Intergovernmental International Panel on Climate Change)

ICE (The Inventory of Carbon and Energy)

All of the above

None of the above

Appendix 2: Qualitative Interview Questions

Ethical approval/Protocol number: **SPECS/PGR/UH/05135**

Research Interview Questions

(60 Minutes)

Title of the research: Environmentally Sustainable Construction by Reducing Embodied Carbon Emissions in the Construction Process of Large-Scale Projects: a study on high-rise buildings
Name of the interviewer: Zaid Khalaf Al Raqqad
Purpose of questionnaire: Data collection for PhD research at University of Hertfordshire
Occupation: ____
Years of experience ____
Location ____
Date: ________________ Time: ___________________

Research Question

- The research's main questions are:

1. How can sustainable construction methods mitigate embodied carbons and help achieve sustainable modern buildings during the construction of large-scale projects, particularly high-rise buildings?

2. Can and how can modular construction practices help achieve carbon neutrality in the context of net zero high-rise buildings?

3. What is the level of standardising, awareness, and understanding in the construction industry for environmental sustainability topics and carbon emissions impacts, and what is the best unit to measure it?

Research objectives:

1. Quantify the environmental and carbon impact caused by the construction projects and propose mitigation strategies especially for embodied and operational carbons by collecting quantitative and qualitative data.
2. Reviewing off-site practices, on-site methods, managerial methods, and carbon mitigating technologies used in the construction industry by creating a database.
3. Investigating the role of embodied carbon emissions in construction projects.
4. Making construction projects of modern high-rise buildings as a reference and role model.
5. Standardizing the assessment criteria for decarbonizing the construction industry

Interview Questions:

1. **How can you define sustainability in a few words?**

2. **How can you define environmental sustainability in construction in one sentence?**

3. **Which are the most important environmental impacts caused by human activities?**
   a. Global warming
   b. Ice melting
   c. Sea levels
   d. Drought

4. **Which are mostly considered environmentally sustainable practices (the major long-term benefits):**
   e. Off-site construction
   f. On-site practices (3D printing, Additive manufacturing)
   g. Software such as BIM, PMP, Lean, LCA software SimaPro.
   h. Material selection or modification.

5. **What are the most important environmental impacts during construction stage of projects?**
   a. Waste generation
   b. Water wastage
   c. Threat on natural resources (flora and fauna)
   d. Depletion of natural resources (fossil fuel)
   e. Greenhouse gases: Carbon dioxides (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Sulphur dioxide SO_2, Perfluorocarbons (PFCs, and others)
   f. Desertification
   g. or other?

6. **What priority should be given now days, to the construction projects, is it for:**
   a. Embodied carbon emissions (why)
   b. Operational carbon emissions (why)
   c. Both
   d. Neither

7. **A bibliometric study of embodied carbons was made upon the following data collection methodology**

The results of Mean value were equal to <u>510.91 KgCO_2/m2,</u> while many other recent studies refer to the amount of <u>600 KgCO_2/m^2</u> in the construction phase, <u>why</u> do you think there was an increase in value?

8. **What is the best unit to measure embodied carbon emissions in construction projects?**

9. **What do you think is better to apply to mitigate carbon emissions; off-site construction technologies or on-site construction technologies or both?**

10. **If not combined throughout the whole lifecycle of the project, in which stage of the construction project priority should be given to apply environmentally mitigating practices.**
    a. Design
    b. Raw materials supply
    c. Manufacturing
    d. Transportation
    e. Construction stage
    f. Use
    g. Whole life cycle (WLC)

11. **Which material you would recommend between steel, concrete, and timber, in order to deliver an environmentally sustainable high-rise building project (from cradle to grave)?**

12. **What is the best type of project most need to apply environmentally sustainable solutions, And why?**
    a. Infrastructure
    b. Pavement
    c. Housing
    d. Mid-rise buildings
    e. High-rise buildings (more than 30 floors)
    f. Other (Specify)

13. **Are high-rise buildings considered a sustainable method of construction from cradle to grave?**

14. **Are environmentally sustainable construction practices responsible for low innovation uptake in the construction industry?**
    a. Yes
    b. No
    c. Not sure

15. **What is the awareness level of the construction industry's role in protecting the environment and climate change? Scale from 1 to 10 (where 1 is very limited awareness and 10 is fully aware).**

16. **Can you name three main challenges in building high-rise projects?**

17. **Do you believe in the ambitious objectives for climate change by achieving a net zero greenhouse gas emissions by 2050, through low carbon high rise buildings? and why?**

Appendix 3: Quantitative Data Figures

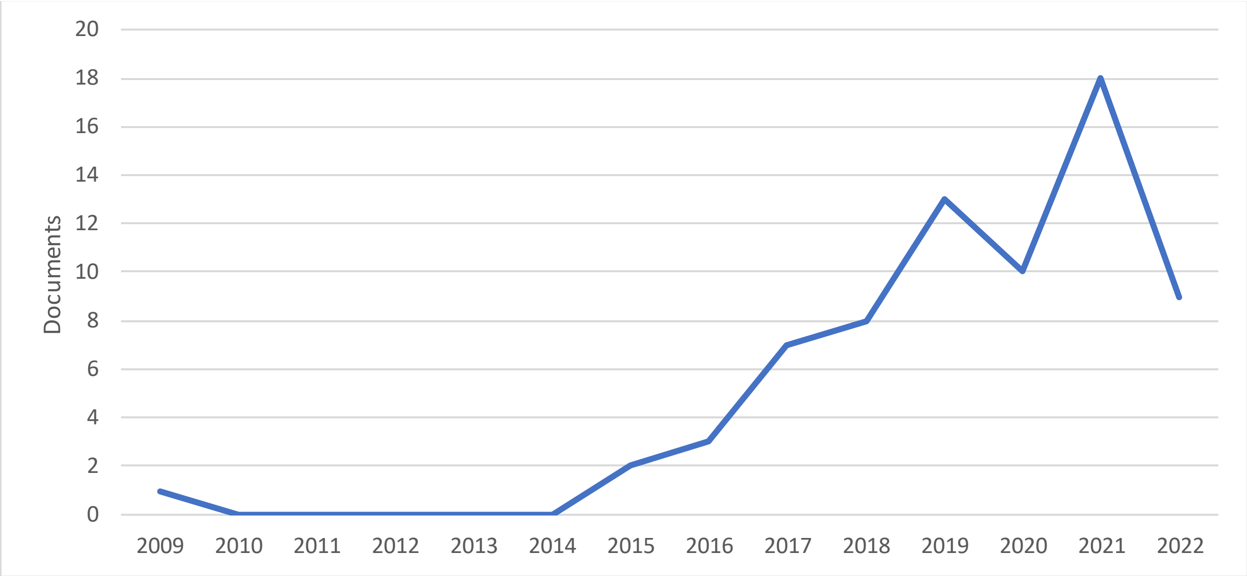


Figure 0-1 Number of research in environmentally sustainable construction since 2009 (Scopus)

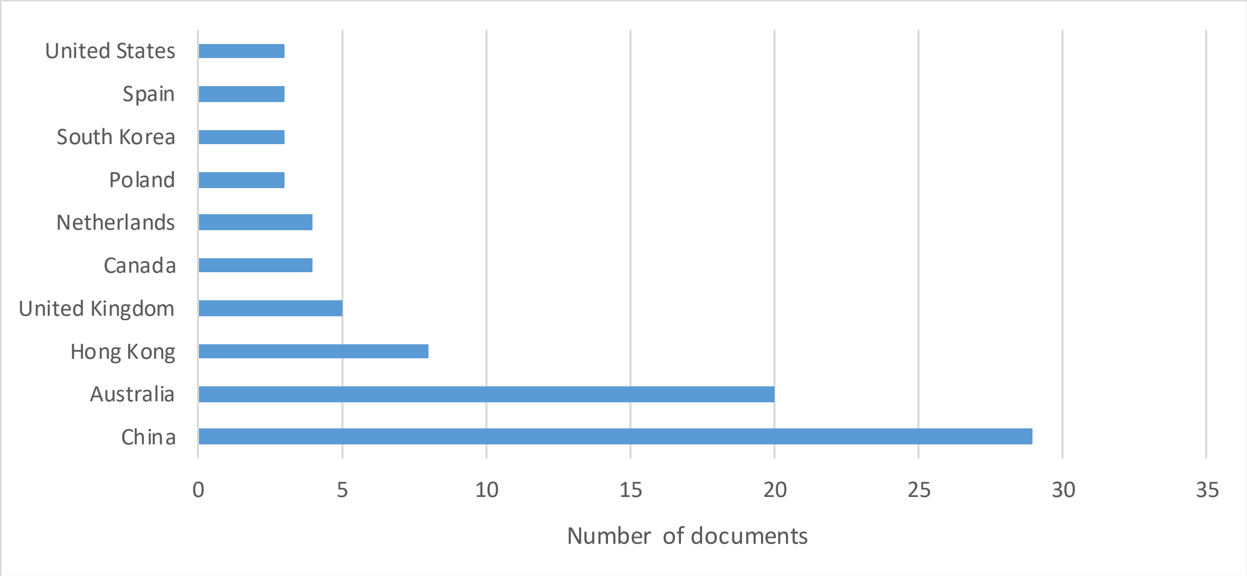


Figure 0-2 Number of documents upon country locations (Scopus)

Appendix 4: Quantitative Data Analysis

A4.1 “Environmentally Sustainable Construction”

Using Scopus, the first search was for “Environmentally Sustainable Construction”, which gave 16,000 results, then selecting only journals and books documents came up with 10,000 results. Filtering the subject area only environment science, engineering, energy, and material science has downsized the search to 8,542 results.

Selecting sustainability, environmental impact, and construction industry keywords has reduced the results to 3,841. Then, searching within the 3,841 results for the words “Off-Site Construction” and Embodied Carbon” resulted in 67 documents from 2009 to 2022.

Figure 0-1 illustrates the amount of research conducted over the years, while Figure 0-2 shows the amount of research conducted according to the location.

However, regional and location differences can affect the relationship between embodied energy and construction environmental impacts (Marzouk and Elshaboury, 2022).

China has the most significant population on the planet, with more than 1.4 billion population (world population, 2022), which makes it logical to develop a sustainable construction technology besides preserving the environment, while developed countries, such as the USA and European countries, are always looking for energy efficient and environmental solutions in the construction industry, especially with the increasing demand and limited fossil fuel resources.

A4.2 “Modular Construction and Off-Site Construction”

The other approach was used within the exact Scopus search. However, this time, the word “Off-Site construction and modular one” was used instead of “environmentally sustainable construction “, which was used the first time.

The limits and keywords were almost the same as the first search, as the search was limited to the years from 2012 to 2020, and the areas were engineering, construction, environmental sciences, prefabrication, off-site construction, modular construction, and project management.

The search resulted in 243 documents, surprisingly more than the first, despite the similarity in selecting areas and keywords, or perhaps because the word “embodied carbon” was used.

Figure 0-3 presents the number of publications from 2012 to 2022, and there was no surprising result compared to the first search, as only in the last two years was there an explained drop in the numbers.

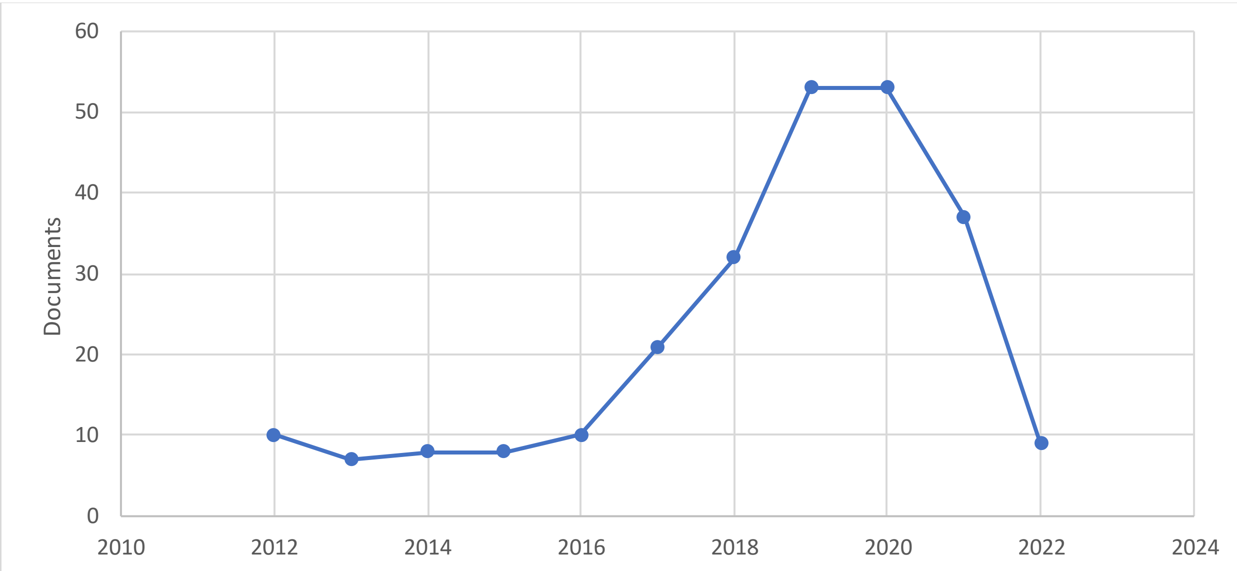


Figure 0-3 Number of publications in OSC in the past ten years (Scopus)

The changes appeared in Figure 0-3, which changed the organisation of leading regions in several research studies.

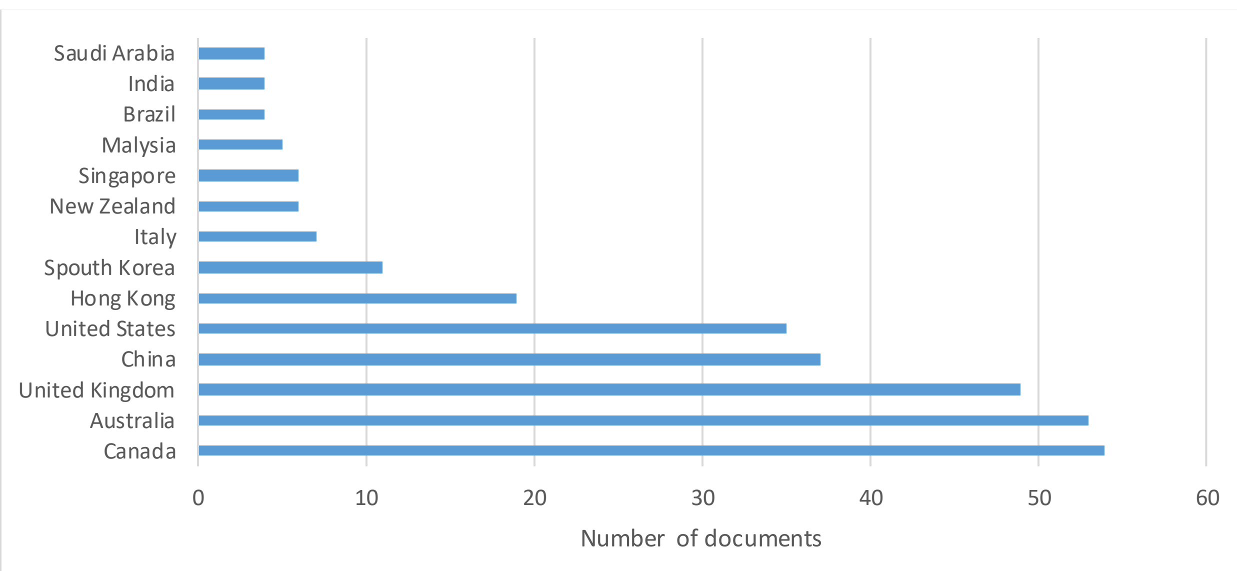


Figure 0-4 Number of documents in each country (Scopus)

The number of countries concluded in the diagram was increased intentionally due to the more significant amount of data obtained, so there were 14 countries instead of just 10 in the first search.

There was a dramatic change in the leading countries, especially China, which was number one in the first search and has now moved to number four. United States moved from the bottom in the first to number five in the second, whereas the UK, Hong Kong, and Australia maintained their top places in the numbers of publications.

It is hard to give a direct cause for this in the current stage, but the scope and number of searches might affect the study; moreover, the qualitative data of this research could give more accurate answers.

Figures 0-5 and 0-6 show analysis by subject area and document type, respectively.

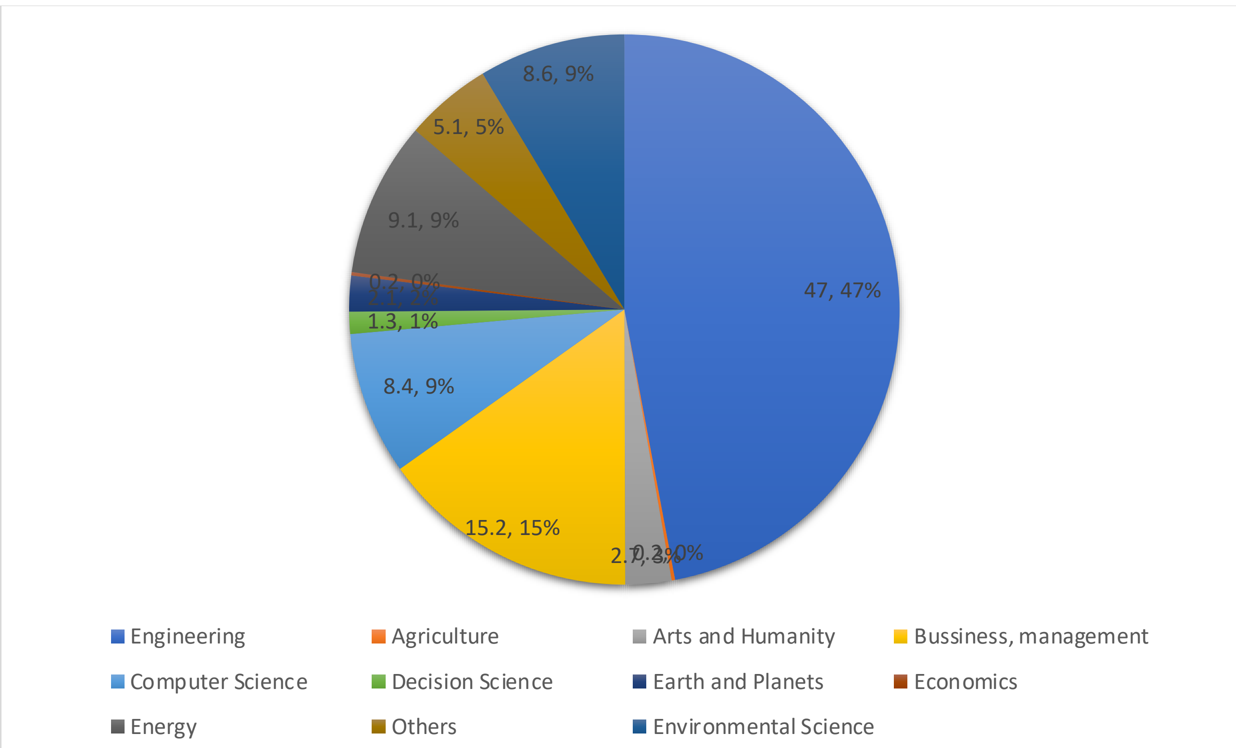


Figure 0-5 Scope of the area used to search for OSC (Scopus)

The engineering portion was the highest at 47%, which is logical. However, the environmental sciences only had 8.6%, which implies that more attention should be paid to the environmental impact of the construction and engineering sectors.

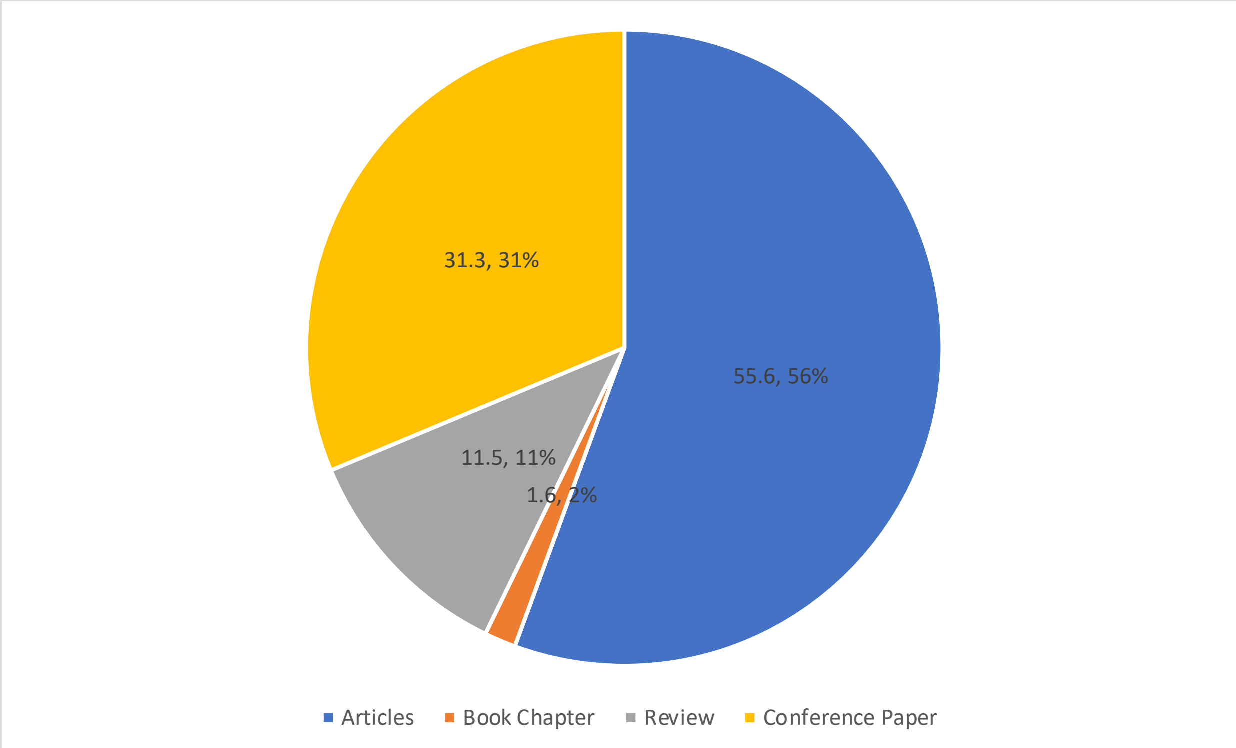


Figure 0-6 Document types in searching for OSC (Scopus)

In Figure 0-6, the Document type might have been a reason for the higher amount of data in the second search because it contained more conference papers (31.3%), which was not included in the first search, perhaps because of the broad topic of environmentally sustainable construction.

A 4.3 Citation

The increasing number of publications has created more citations over the years, and Figure 0-7 presents this harmony.

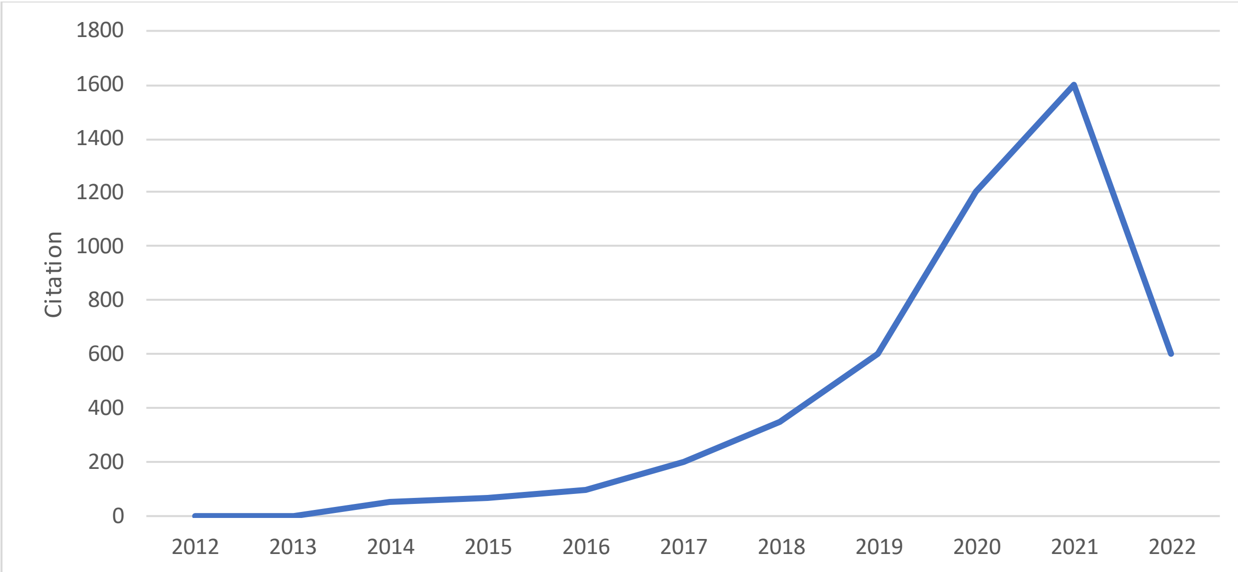


Figure 0-7 Number of citations for OSC publications in the last ten years (Scopus)

Using Wiley's online library for the word "Environmentally Sustainable Construction" from 2013 to 2023 generated 129,205 documents, downsized by selecting "Architecture and Planning" to 3,418. At the same time, IEEE was more meticulous by having the "Civil Engineering and Construction" option, which generated 45 articles. However, it was noticed that IEEE documents lacked carbon emissions, embodied carbons, or off-site construction content. Due to their focus on electrical engineering topics, Some of the IEEE articles:

1. **Ahmed, V., Saboor, S., Haif, J., Al Ali, K., Al Marri, M., & Al Salman, R.** (2022). Sustainable Practices in Construction SMEs in the UAE - A Scoping Study. In *2022 International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)* (pp. 515-522). doi: 10.1109/ISMSIT56059.2022.9932736.

2. **Alcock, A. C., Tartibu, L. K., & Jen, T. C.** (2017). Design and construction of a thermoacoustically driven thermoacoustic refrigerator (August 2017). In *2017 International Conference on the Industrial and Commercial Use of Energy (ICUE)* (pp. 1-7). doi: 10.23919/ICUE.2017.8103430.

3. **Al Fardan, A. S., Al Gahtani, K. S., & Asif, M.** (2017). Demand side management solution through new tariff structure to minimize excessive load growth and improve system load factor by improving commercial buildings energy performance in Saudi Arabia. In *2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE)* (pp. 302-308). doi: 10.1109/SEGE.2017.8052816.

4. **Alyami, S. H., & Alreshidi, E. J.** (2019). Holistic IoT Architecture for Smart Sustainable Cities Current Perspective and Future Directions. In *2019 6th International Conference on Computing for Sustainable Global Development (INDIACom)* (pp. 312-317).

5. **Chen, M., Sun, Z., He, X., & Ai, Q.** (2021). An Improved Comprehensive Benefit Evaluation Model for BESS Based on Project Pursuit and Simulated Annealing Algorithm. In *2021 IEEE Sustainable Power and Energy Conference (iSPEC)* (pp. 1318-1324). doi: 10.1109/iSPEC53008.2021.9736093.

6. **Dazahra, M. N., Elmariami, F., Belfqih, A., Boukherouaa, J., Cherkaoui, N., & Lekbich, A.** (2017). Modernization and Optimization of Traditional Substations for Integration in Smart Grid. In *2017 International Renewable and Sustainable Energy Conference (IRSEC)* (pp. 1-4). doi: 10.1109/IRSEC.2017.8477385.

7. **De la Cruz-Calderon, M. M., Taboada-Perez, C. E., Luque-Saico, A. A., & Bullon-Rosas, J. J.** (2023). Automation of Banana Fiber for the Improvement of the Mechanical Properties of Concrete. In *2023 9th International Conference on Control, Automation and Robotics (ICCAR)* (pp. 96-102). doi: 10.1109/ICCAR57134.2023.10151767.

8. **Fang, F., & Ding, W.** (2022). Intelligent research of intelligent building with computer big data technology. In *2022 IEEE International Conference on Advances in Electrical Engineering and Computer Applications (AEECA)* (pp. 1068-1072). doi: 10.1109/AEECA55500.2022.9918892.

9. **Finley, J. T., Verenikina, A. Y., & Verenikin, A. O.** (2019). Evaluation of Environmental Impact and Responsibility of Russian Largest Companies. In *2019 8th International Conference on Industrial Technology and Management (ICITM)* (pp. 95-99). doi: 10.1109/ICITM.2019.8710677.

10. **Geng, S., Chau, H. -W., & Yan, S.** (2020). Identify and Elucidating Urban Village Essentials Through Remodeling and Visualising a Social Housing Prototype in Guangzhou for Sustainable Residential Development in China. In *2020 24th International Conference Information Visualisation (IV)* (pp. 609-613). doi: 10.1109/IV51561.2020.00106.

Appendix 5: BSRIA Tables

[Embodied Carbon - The Inventory of Carbon and Energy (ICE) (greenbuildingencyclopaedia.uk)]

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO_2/kg	EC – (GHG) kgCO_2e/kg	EE = Embodied Energy, EC = Embodied Carbon
Coil, Galvanised - World Avg. Recy. Cont.	28·50	1·92	2·03	Comments on previous page apply. See material profile for further information.
Pipe - R.O.W. Avg. Recy. Cont.	25·80	1·90	2·01	
Pipe - World Avg. Recy. Cont.	24·90	1·83	1·94	
Plate - R.O.W. Avg. Recy. Cont.	33·20	2·15	2·31	
Plate - World Avg. Recy. Cont.	32·00	2·06	2·21	
Section - R.O.W. Avg. Recy. Cont.	28·10	1·97	2·12	
Section - World Avg. Recy. Cont.	27·10	1·89	2·03	
Stone	Data on stone was difficult to select, with high standard deviations and data ranges.			
General	1·26 (?)	0·073 (?)	0·079	ICE database average (statistic), uncertain. See material profile.
Granite	11·00	0·64	0·70	Estimated from Ref 116.
Limestone	1·50	0·087	0·09	Estimated from Ref 188.
Marble	2·00	0·116	0·13	
Marble tile	3·33	0·192	0·21	Ref. 40.
Sandstone	1·00 (?)	0·058 (?)	0·06	Uncertain estimate based on Ref. 262.
Shale	0·03	0·002	0·002	
Slate	0·1 to 1·0	0·006 to 0·058	0·007 to 0·063	Large data range.
Timber	Note: These values were difficult to estimate because timber has a high data variability. These values exclude the energy content of the wooden product (the Calorific Value (CV) from burning). See the timber material profile and the FAQs for guidance on the new data structure for embodied carbon ($_{fos}$ and $_{bio}$).			
General	10·00	0·30$_{fos}$+0·41$_{bio}$	0·31$_{fos}$+0·41$_{bio}$	Estimated from UK consumption mixture of timber products in 2007 (Timber Trade Federation statistics). Includes 4·3 MJ bio-energy. All values do not include the CV of timber and exclude carbon storage.
Glue Laminated timber	12·00	0·39$_{fos}$+0·45$_{bio}$	0·42$_{fos}$+0·45$_{bio}$	Includes 4·9 MJ bio-energy.
Hardboard	16·00	0·54$_{fos}$+0·51$_{bio}$	0·58$_{fos}$+0·51$_{bio}$	Hardboard is a type of fibreboard with a density above 800 kg/m^3. Includes 5·6 MJ bio-energy.
Laminated Veneer Lumber	9·50	0·31$_{fos}$+0·32$_{bio}$	0·33$_{fos}$+0·32$_{bio}$	Ref 150. Includes 3·5 MJ bio-energy.
MDF	11 (?)	0·37$_{fos}$+0·35$_{bio}$	0·39$_{fos}$+0·35$_{bio}$	Wide density range (350-800 kg/m^3). Includes 3·8 MJ bio-energy.
Oriented Strand Board (OSB)	15·00	0·42$_{fos}$+0·54$_{bio}$	0·45$_{fos}$+0·54$_{bio}$	Estimated from Refs. 103 and 150. Includes 5·9 MJ bio-energy.
Particle Board	14·50	0·52$_{fos}$+0·32$_{bio}$	0·54$_{fos}$+0·32$_{bio}$	Very large data range, difficult to select appropriate values. Modified from CORRIM reports. Includes 3·2 MJ bio-energy (uncertain estimate).
Plywood	15·00	0·42$_{fos}$+0·65$_{bio}$	0·45$_{fos}$+0·65$_{bio}$	Includes 7·1 MJ bio-energy.

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
Coil (Sheet), Galvanised - UK (EU) Average Recycled Content	**22·60**	**1·45**	**1·54**	**Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%.**
Virgin	40·00	2·84	3·01	
Engineering steel - Recycled	13·10	0·68	0·72	
Pipe- UK (EU) Average Recycled Content	**19·80**	**1·37**	**1·45**	**Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%.**
Virgin	34·70	2·71	2·87	
Recycled	Not Typical Production Route			
Plate- UK (EU) Average Recycled Content	**25.10**	**1·55**	**1·66**	**Effective recycled content because recycling route is not typical. EU 3-average recycled content of 59%.**
Virgin	45·40	3·05	3·27	
Recycled	Not Typical Production Route			
Section- UK (EU) Average Recycled Content	**21·50**	**1·42**	**1·53**	
Virgin	38·00	2·82	3·03	
Recycled	10·00	0·44	0·47	
Wire - Virgin	36·00 (?)	2·83 (?)	3·02	
Stainless	56·70	6·15	-	World average data from the Institute of Stainless Steel Forum (ISSF) life cycle inventory data. Selected data is for the most popular grade (304). Stainless steel does not have separate primary and recycled material production routes.
OTHER STEEL DATA - 'R.O.W' and 'World' average recycled contents - See material profile (and Annex B) for usage guide				
General - R.O.W. Avg. Recy. Cont.	26·20	1·90	2·03	Rest of World (non-E.U.) consumption of steel. Three year average recycled content of 35·5%.
General - World Avg. Recy. Cont.	25·30	1·82	1·95	Whole world Three year average recycled content of 39%.
Bar and rod- R.O.W. Avg. Recy. Cont.	22·30	1·82	1·95	
Bar and rod - World Avg. Recy. Cont.	21·60	1·74	1·86	
Coil - R.O.W. Avg. Recy. Cont.	24·40	1·81	1·92	Comments above apply. See material profile for further information.
Coil - World Avg. Recy. Cont.	23·50	1·74	1·85	
Coil, Galvanised - R.O.W. Avg. Recy. Cont.	29·50	2·00	2·12	

Materials	Embodied Energy and Carbon Coefficients			Comments
	EE - MJ/kg	EC - $kgCO_2/kg$	EC – (GHG) $kgCO_2e/kg$	EE = Embodied Energy, EC = Embodied Carbon
PRECAST (PREFABRICATED) CONCRETE - Modification Factors				
	For precast add this value to the selected coefficient of the appropriate concrete mix			
	0·45	0·027	0·029	For each 1 kg precast concrete. The example is using a RC 40/50 strength class and is not necessarily indicative of an average precast product. Includes UK recorded plant operations and estimated transportation of the constituents to the factory gate (38km aggregates, estimated 100km cement). Data is only cradle to factory gate but beyond this the average delivery distance of precast is 155 km by road (see Ref. 244). UK weighted average cement.
EXAMPLE: Precast RC 40/50 MPa	1·50 MJ/kg (1·00 + 0·50)	0·168 $kgCO_2/kg$ (0·141 + 0·027)	0·180 $kgCO_2/kg$ (0·151 + 0·029)	
EXAMPLE: Precast RC 40/50 with reinforcement (with 80kg per m^3)	2·33 MJ/kg (1·50 + 1·04 * 0·8)	0·229 $kgCO_2/kg$ (0·171 + 0·072 * 0·8)	0·242 $kgCO_2/kg$ (0·180 + 0·077 * 0·8)	
CONCRETE BLOCKS (ICE CMC Model Values)				
Block - 8 MPa Compressive Strength	0·59	0·059	0·063	Estimated from the concrete block mix proportions, plus an allowance for concrete block curing, plant operations and transport of materials to factory gate.
Block -10 MPa	0·67	0·073	0·078	
Block -12 MPa	0·72	0·082	0·088	
Block -13 MPa	0·83	0·100	0·107	
Autoclaved Aerated Blocks (AAC's)	3·50	0·24 to 0·375	-	Not ICE CMC model results.
NOMINAL PROPORTIONS METHOD (Volume), Proportions from BS 8500:2006 (ICE Cement, Mortar and Concrete Model Calculations)				
1:1:2 Cement:Sand: Aggregate	1·28	0·194	0·206	High strength concrete. All of these values were estimated assuming the UK average content of cementitious additions (i.e. fly ash, GGBS) for factory supplied cements in the UK, see Ref. 59, plus the proportions of other constituents.
1:1.5:3	0·99	0·145	0·155	Often used in floor slab, columns and load bearing structure.
1:2:4	0·82	0·116	0·124	Often used in construction of buildings under 3 storeys.
1:2.5:5	0·71	0·097	0·104	
1:3:6	0·63	0·084	0·090	Non-structural mass concrete.
1:4:8	0·54	0·069	0·074	
BY CEM I CEMENT CONTENT - kg CEM I cement content per cubic metre concrete (ICE CMC Model Results)				
120 kg / m^3 concrete	0·49	0·060	0·064	Assumed density of 2350 kg/m^3. Interpolation of the CEM I cement content is possible. These numbers assume the CEM I cement content (not the total cementitious content, i.e. they do not include cementitious additions). They may also be used for fly ash mixtures without modification, but they are likely to slightly underestimate mixtures that have additional GGBS due to the higher embodied energy and carbon of GGBS (in comparison to aggregates and fly ash).
200 kg / m^3 concrete	0·67	0·091	0·097	
300 kg / m^3 concrete	0·91	0·131	0·140	
400 kg / m^3 concrete	1·14	0·170	0·181	
500 kg / m^3 concrete	1·37	0·211	0·224	

Appendix 6: Equations

$$LCECb = IECb + c{=}n \sum c{=}i \ (RECi) \times BTc \times Lc + EECb$$

Equation 10

Where LCECb is the “cradle to grave” life-cycle embodied carbon of a building (kg CO_2 eq/m^2), IECb (kg CO_2 eq/m^2) is the initial embodied carbon, and RECi (kg CO_2 eq/m^2) is the recurring carbon of a building product or material (maintenance and repair). BTc is the building type factor; certain building types need more frequent maintenance and repair than others, such as those with swimming pools. Lc is the location (climatic) condition. EECb (kg CO_2 eq/m^2) is the end-of-life embodied carbon. (Hu and Esram 2021).

$$EC_{A13} = \sum_{i=1}^{n} [Q_i(ECF_{A13,i})]$$

Equation 11

Where ECA13 = total embodied carbon for life cycle Modules A1–A3 (kg CO_2 e), Qi = quantity of material (kg), ECFA13, i = Module A1–A3 embodied carbon factor for its material (kg CO_2 e/kg) (Institution of Structural Engineers (Great Britain) 2020).

Appendix 7: LCA SimaPro 9.5 Software

Title: Iron Sintering Process and Inventory Analysis

Introduction: The iron sintering process aims to enhance the permeability and reducibility of the blast furnace charge. This charge consists of a blend of fine ores, coke breeze, additives such as lime, and iron-bearing materials obtained from downstream iron and steelmaking operations. This reorganisation will provide an overview of the sintering process and the data sources used for inventory analysis.

Iron Sintering Process:

1. Raw Material Blending:
    - Raw materials are combined in a mixing drum
    - The mixture is placed on a conveyor belt over a layer of recycled sinter
2. Sintering:
    - The sinter mixture moves slowly along a continuously moving grate
    - A combustion front draws downwards through the mixture
    - This sintering process fuses the fine particles together

Modelling Approach: The data utilized for this analysis was primarily sourced from the IPPC Best Available Technology report by Remus et al. (2013). Whenever data ranges were provided, the geometric mean of the reported values was employed. The quantities of iron-bearing materials returned from downstream activities were based on the production and internal recycling figures provided by World Steel (2010). Notably, information on radionuclide emissions to the air, such as Polonium 210 and Lead 210, was not available and therefore not included in the inventory.

References:

- Remus, R., Aguado-Monsonet, M. A., Roudier, S., & Samcho, L. D. (2013). JRC reference report - Best available techniques (BAT) reference document for iron and steel production. Joint Research Centre - European Commission, Luxembourg
- Worldsteel (2010). Steel industry by-products. World Steel Association: Brussels, Belgium

Inventory Details:

- Production Volume: 1,164,315,852,800 kg
- Start Date: 01/01/2005
- End Date: 31/12/2022
- Technology Level: Current
- Technology: Average European technology, employing down draft sintering on continuous travelling grates
- Geography: The inventory is modelled for Rest-of-World

Included Activities: The inventory analysis encompasses the iron sintering process from the gate of the integrated sintering-blast furnace plant until the mixed, sintered iron-bearing mixture is prepared for charging into the blast furnace.

Energy Values: Undefined

Is data valid for entire period: True

Time period: Data are mostly compiled from reports published between 2007 and 2010 but are considered representative of modern operations.

Macro-economic scenario name: Business-as-Usual

Version: 8.3.0.0

Created: 3/16/2020 2:45:26 PM

Last edited: 8/17/2021 8:31:36 AM

Source: bbda23f8-3b41-552d-a7a7-0c107187b784_d4591183-a1ce-4c6d-80fa-761edfb78aec.spold

UUID: bbda23f8-3b41-552d-a7a7-0c107187b784

Appendix 8: Ethical Approval

UNIVERSITY OF HERTFORDSHIRE

ETHICS COMMITTEE FOR STUDIES INVOLVING THE USE OF HUMAN PARTICIPANTS
('ETHICS COMMITTEE')

FORM EC6: PARTICIPANT INFORMATION SHEET

1 **Title of study**

Environmentally sustainable construction by reducing embodied carbon emissions in the construction process of large-scale projects: a study on high-rise buildings

2 **Introduction**

You are being invited to take part in a study. Before you decide whether to do so, it is important that you understand the study that is being undertaken and what your involvement will include. Please take the time to read the following information carefully and discuss it with others if you wish. Do not hesitate to ask us anything that is not clear or for any further information you would like to help you make your decision. Please do take your time to decide whether you wish to take part. The University's regulation, UPR RE01, 'Studies Involving the Use of Human Participants' can be accessed via this link:

https://www.herts.ac.uk/about-us/governance/university-policies-and-regulations-uprs/uprs

(after accessing this website, scroll down to Letter S where you will find the regulation)

Thank you for reading this.

3 **What is the purpose of this study?**

Producing a PhD research thesis in making a more sustainable construction projects especially high-rise buildings, by adopting most environmental practices that reduce the impact of carbon emissions on the industry and on the planet represented in climate change.

4 **Do I have to take part?**

It is completely up to you whether or not you decide to take part in this study. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. Agreeing to join the study does not mean that you have to complete it. You are free to withdraw at any stage without giving a reason. A decision to withdraw at any time, or a decision not to take part at all, will not affect any treatment/care that you may receive (should this be relevant).

5 **Are there any age or other restrictions that may prevent me from participating?**

Under 25 years old are not favorable, as they might find it difficult to answer some questions.

6 **How long will my part in the study take?**

If you decide to take part in this study, you will be involved in it for *the duration of the research data collection period around 12 months.*

7 **What will happen to me if I take part?**

The first thing to happen will be *involving your contribution anonymously in the research data collection and analysis.*

8 **What are the possible disadvantages, risks or side effects of taking part?**

(Note: if appropriate for this particular study, you will be asked to agree to any required health screening questionnaire in advance of the study. Please also note that circumstances may arise that could result in the need for you to withdraw from the study; should such circumstances occur, the investigator will discuss the matter with you.)

No disadvantages or risks are supposed to rise in taking the study, but if so happened, you are free to reject or withdraw the study.

9 **What are the possible benefits of taking part?**

Findings and results will be given upon request, also credits can be given in names if permitted.

10 **How will my taking part in this study be kept confidential?**

The study will be saved in secured files on my cloud storage with highly level access system.

11 **Audio-visual material**

Any video or audio recordings will be discrete and used only exclusively and temporarily for this study.

12 **What will happen to the data collected within this study?**

- The data collected will be stored electronically, in a password-protected environment, for <> months, after which time it will be destroyed under secure conditions.

13 **Will the data be required for use in further studies?**

- The data will not be used in any further studies.

14 **Who has reviewed this study?**

This study has been reviewed by:

- The University of Hertfordshire Health, Science, Engineering and Technology Ethics Committee with Delegated Authority

The UH protocol number is **SPECS/PGR/UH/05135**

15 **Factors that might put others at risk**

Please note that if, during the study, any medical conditions or non-medical circumstances such as unlawful activity become apparent that might or had put others at risk, the University may refer the matter to the appropriate authorities and, under such circumstances, you will be withdrawn from the study.

16 **Who can I contact if I have any questions?**

If you would like further information or would like to discuss any details personally, please get in touch with:

Dr Antonios Kanellopoulos

a.kanellopoulos@herts.ac.uk

Tel +44 (0)1707 286479

Although we hope it is not the case, if you have any complaints or concerns about any aspect of the way you have been approached or treated during the course of this study, please write to the University's Secretary and Registrar at the following address:

Secretary and Registrar

University of Hertfordshire

College Lane

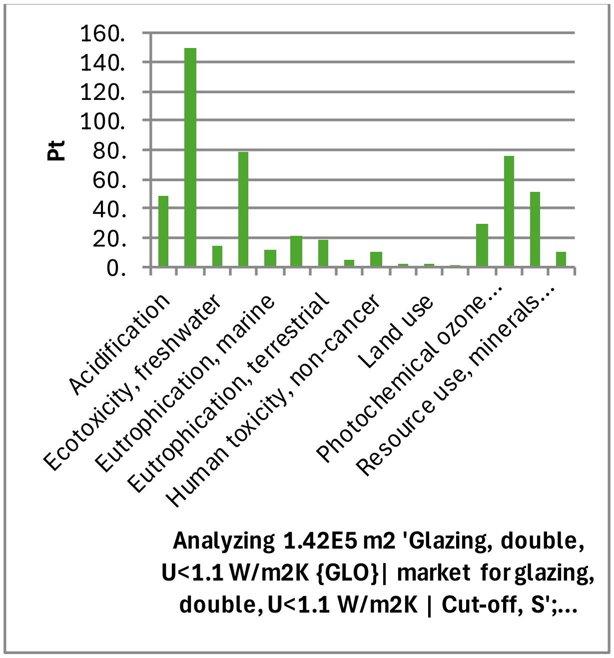
Hatfield

Herts

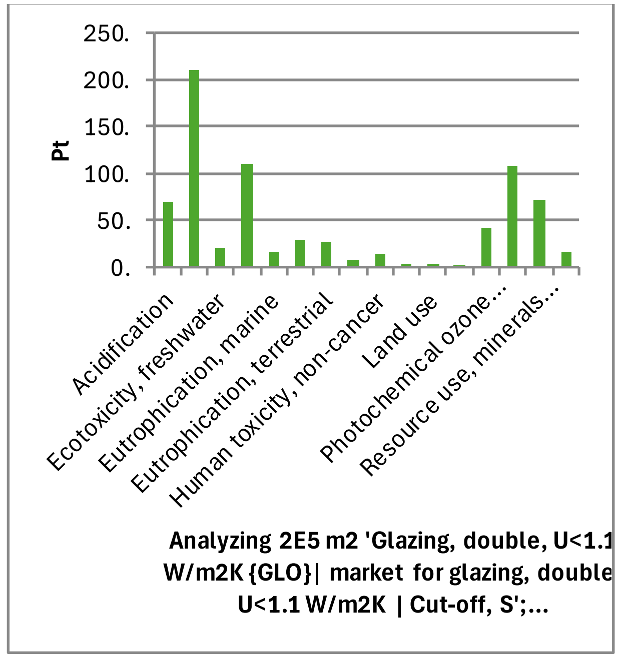
AL10 9AB

Thank you very much for reading this information and giving consideration to taking part in this study.

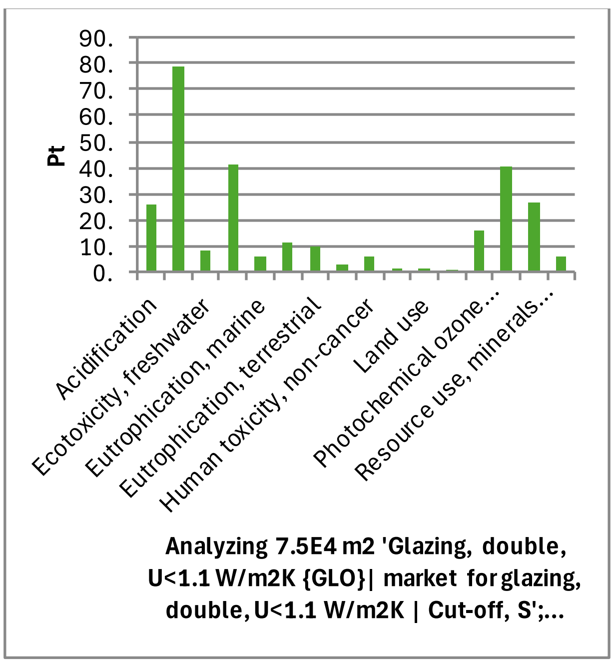
Appendix 9: Glass LCA Analysis



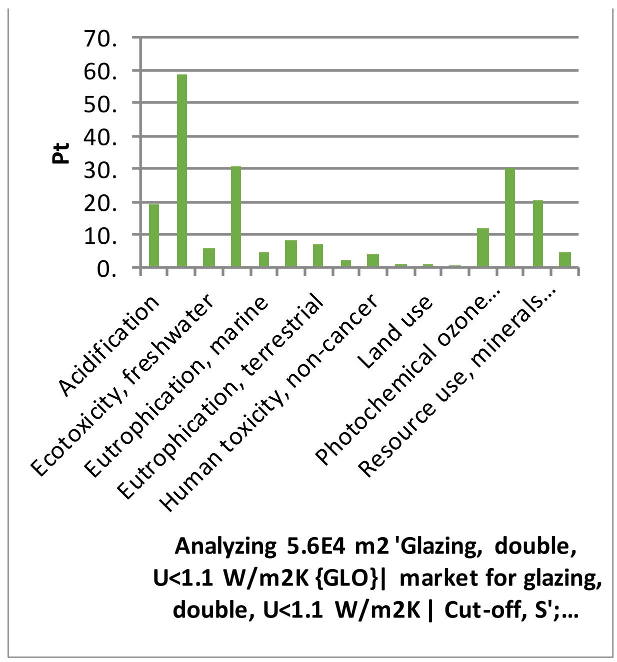
Khalifa



Shanghai



ESB*



Shard

Figure 0-8 Glass LCA Analysis **ESB glass amount was calculated proportionately to the size and dimensions of the building as no data was available*.

Shard Glass Environmental Impacts

Se	Damage category	Unit	Total	Glazing, double, U<1.1 W/m2K
	Total	Pt	210	210
☑	Acidification	Pt	19.4	19.4
☑	Climate change	Pt	58.9	58.9
☑	Ecotoxicity, freshwater	Pt	5.93	5.93
☑	Particulate matter	Pt	30.8	30.8
☑	Eutrophication, marine	Pt	4.65	4.65
☑	Eutrophication, freshwater	Pt	8.22	8.22
☑	Eutrophication, terrestrial	Pt	7.32	7.32
☑	Human toxicity, cancer	Pt	2.2	2.2
☑	Human toxicity, non-cancer	Pt	4.21	4.21
☑	Ionising radiation	Pt	1.07	1.07
☑	Land use	Pt	0.764	0.764
☑	Ozone depletion	Pt	0.118	0.118
☑	Photochemical ozone formation	Pt	11.9	11.9
☑	Resource use, fossils	Pt	30.2	30.2
☑	Resource use, minerals and metal	Pt	20.1	20.1
☑	Water use	Pt	4.35	4.35

Khalifa Glass Environmental Impacts

Se	Damage category	Unit	Total	Glazing, double, U<1.1 W/m2K
	Total	Pt	507	507
☑	Acidification	Pt	49.2	49.2
☑	Climate change	Pt	149	149
☑	Ecotoxicity, freshwater	Pt	15	15
☑	Particulate matter	Pt	72.9	72.9
☑	Eutrophication, marine	Pt	11.5	11.5
☑	Eutrophication, freshwater	Pt	2.39	2.39
☑	Eutrophication, terrestrial	Pt	18.6	18.6
☑	Human toxicity, cancer	Pt	5.57	5.57
☑	Human toxicity, non-cancer	Pt	10.7	10.7
☑	Ionising radiation	Pt	0.985	0.985
☑	Land use	Pt	1.94	1.94
☑	Ozone depletion	Pt	0.299	0.299
☑	Photochemical ozone formation	Pt	30.1	30.1
☑	Resource use, fossils	Pt	76.6	76.6
☑	Resource use, minerals and metal	Pt	51.1	51.1
☑	Water use	Pt	11	11

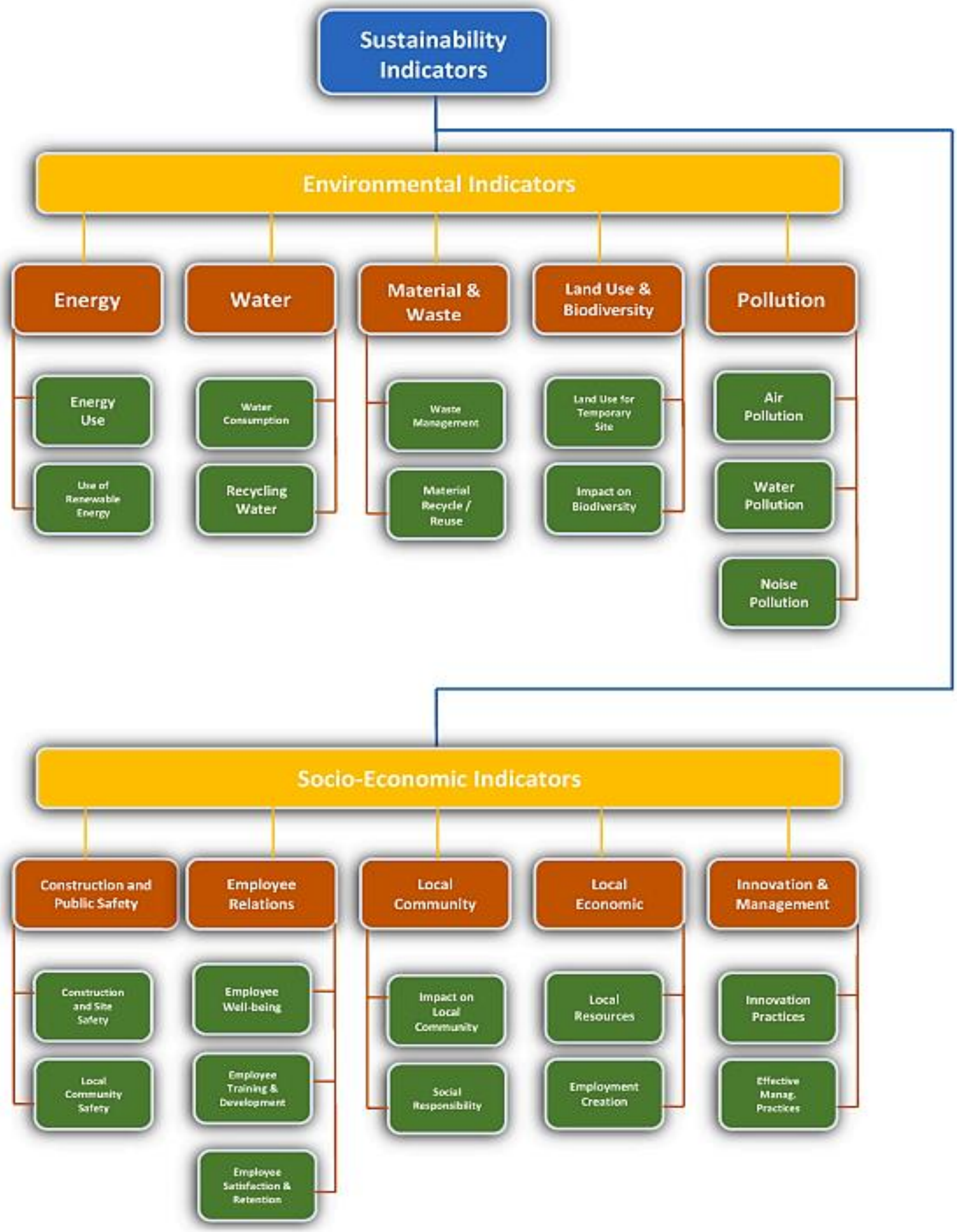
Shanghai Glass Environmental Impacts

Se	Damage category	Unit	Total	Glazing, double, U<1.1 W/m2K
	Total	Pt	750	750
☑	Acidification	Pt	69.3	69.3
☑	Climate change	Pt	210	210
☑	Ecotoxicity, freshwater	Pt	21.2	21.2
☑	Particulate matter	Pt	110	110
☑	Eutrophication, marine	Pt	16.6	16.6
☑	Eutrophication, freshwater	Pt	29.4	29.4
☑	Eutrophication, terrestrial	Pt	26.1	26.1
☑	Human toxicity, cancer	Pt	7.85	7.85
☑	Human toxicity, non-cancer	Pt	15	15
☑	Ionising radiation	Pt	3.82	3.82
☑	Land use	Pt	2.73	2.73
☑	Ozone depletion	Pt	0.421	0.421
☑	Photochemical ozone formation	Pt	42.3	42.3
☑	Resource use, fossils	Pt	108	108
☑	Resource use, minerals and metal	Pt	71.9	71.9
☑	Water use	Pt	15.5	15.5

ESB Glass Environmental Impacts

Se	Damage category	Unit	Total	Glazing, double,
	Total	Pt	281	281
☑	Acidification	Pt	26	26
☑	Climate change	Pt	78.8	78.8
☑	Ecotoxicity, freshwater	Pt	7.94	7.94
☑	Particulate matter	Pt	41.3	41.3
☑	Eutrophication, marine	Pt	6.23	6.23
☑	Eutrophication, freshwater	Pt	11	11
☑	Eutrophication, terrestrial	Pt	9.8	9.8
☑	Human toxicity, cancer	Pt	2.94	2.94
☑	Human toxicity, non-cance	Pt	5.63	5.63
☑	Ionising radiation	Pt	1.43	1.43
☑	Land use	Pt	1.02	1.02
☑	Ozone depletion	Pt	0.158	0.158
☑	Photochemical ozone form	Pt	15.9	15.9
☑	Resource use, fossils	Pt	40.5	40.5
☑	Resource use, minerals and	Pt	27	27
☑	Water use	Pt	5.82	5.82

Appendix 10: Sustainability Environmental and Economic Indicators (Rajabi et al., 2022)



Training, Conferences, and Courses

1.	Introduction to Research Impact	Oct 1st, 2021
2.	Introduction to Statistics	7th Oct 2021
3.	The Viva and Process of Research	7th Oct 2021
4.	Turnitin	7th Oct 2021
5.	Registration and Doctoral Review Assessment	13th Oct 2021
6.	Getting to know	14th Oct 2021
7.	Writing for and Submitting to a Journal	20th Oct 2021
8.	Becoming a Member of Your Discipline	21st Oct 2021
9.	How to Write an Effective Data Management Plan (DMP)	21st Oct 2021
10.	Quantitative Analysis of Survey Data	28th Oct 2021
11.	Critical Thinking	3rd Nov 2021
12.	Exploring and organizing your literature	3rd Nov 2021
13.	Getting Published and Promoting	4th Nov 2021
14.	Critical Reading and Writing	4th Nov 2021
15.	How to Stop Procrastinating	9th Nov 2021
16.	Writing for Publication in Scientific Journals	9th Nov 2021
17.	Thriving Resiliently	11th Nov 2021
18.	Qualitative Methods	25th Nov 2021
19.	Reference Management	1st Dec 2021
20.	Data Analysis	2nd Dec 2021
21.	Assertiveness Training	2nd Dec 2021
22.	Literature Searching: Using Online	8th Dec 2021
23.	PGR Conference UH	May 2021
24.	BRE Get It Right/ UK Conference	2021
25.	Sustainable Green Cities Summit in Middle East	2021
26.	Researchers conference UH	19 May 2022
27.	RDP Spring school sessions	26-28 May 2022
28.	Engineering research seminar: Thiazole Ladder Polymers	23 June 2022
29.	UK Construction Week 2023 London Excell	May 2023
30.	PG Learning module	September 2023
31.	One Click LCA conference, London	November 2023
32.	James Rennie ICE Medal Final, London	March 2024

Published Work

Status	Published: Architecture, Structures and Construction https://doi.org/10.1007/s44150-023-00099-4 ORIGINAL PAPER
Title	Environmentally sustainable construction by mitigating embodied carbon emissions of large-scale projects: a study on off-site practices on high-rise buildings
Details	Research paper, Zaid Khalaf Raqqad Received: 10 May 2023 / Accepted: 18 August 2023 © The Author(s), under exclusive licence to Springer Nature Switzerland AG 2023

Status	Under review
Title	Systematic Review of Embodied Carbon Emissions Status in Large-Scale- Construction Projects Using Life Cycle Assessment Approach
Details	Review paper, Zaid Khalaf Raqqad, Antonios Kanellopoulos CSCM-D-24-00673

Status	Presented SPECS Conference/ University of Hertfordshire, College Lane, May 2022
Title	Environmentally Sustainable Low Carbon High-Rise Projects
Details	Conference paper, Zaid Khalaf Raqqad, Antonios Kanellopoulos https://www.herts.ac.uk/about-us/events/2022/physics,-engineering-and-computer-science-research-conference-2022

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