國立臺灣大學工學院土木工程學系

碩士論文

Department of Civil Engineering

College of Engineering

National Taiwan University

Master's Thesis

應用建築資訊模型進行混凝土建築結構元件碳排放估算

BIM-driven carbon emissions estimation for concrete building structural elements

阮文通

Nguyen Van Thong (Thomas Nguyen)

指導教授：林之謙 博士

Advisor: Jacob Je-Chian LIN, PhD

中華民國 113 年 8 月

August, 2024

doi:10.6342/NTU202403587

Acknowledgement

I would like to express my deepest gratitude to everyone who supported and guided me throughout the completion of this thesis.

First and foremost, I sincerely thank my advisor, Assistant Professor Jacob Lin, for his invaluable guidance, encouragement, thorough feedback, and financial support during my research. His expertise, patience, and support were crucial to the completion of this thesis.

I would also like to extend my heartfelt thanks to all the faculty and staff of the Department of Construction Engineering and Management Faculty at the Department of Civil Engineering, National Taiwan University, for their support and for providing an excellent academic environment.

I am truly grateful to the experts and scholars who participated in my interviews and provided professional insights, especially Mr. Nguyen Van Quang, Dr. Le Thanh Trung, and Associate Professor Nguyen The Quan. Your valuable perspectives and knowledge greatly enriched this research.

I deeply appreciate my family's unwavering support and understanding. To my parents, thank you for your endless love, sacrifices, and encouragement. To my siblings and girlfriend, thank you for your constant support and faith in me.

Thank you to everyone for being a part of this journey!

doi:10.6342/NTU202403587

摘要

當前，建築行業顯著地貢獻了全球碳排放，迫切需要採取可持續的實踐來減輕環境影響。本論文提出了一個模型驅動的框架，用於估算和比較三種建築方法的碳排放：傳統現澆混凝土、預製構件和3D混凝土列印（3DCP）。該研究通過整合建築信息建模（BIM）和標準化建築數據庫，特別是RSMeans（適用於MasterFormat）和TT10-2019/BXD（適用於TCVN），來應對行業的環境挑戰。

研究方法涉及詳細的工程量計算、材料估算和結構元素（如柱、梁、板和牆）的排放計算。開發了一個Revit API來自動化這些過程，提高了效率和準確性。通過分析實驗室設施和講堂的兩個案例研究，驗證了該框架並提供了比較見解。

主要發現表明，傳統現澆混凝土和預製構件方法在環境影響上大致相同。然而，碳排放的分佈有所不同，現澆混凝土施工中約87-88%的碳排放被歸類爲材料排放，而在預製構件中這一比例上升到96-98.3%。造成這一轉變的主要原因是現澆混凝土施工中的模板和養護過程的碳排放被分類爲過程排放，而在預製構件中，這些排放被轉移到材料排放類別，因爲組件是在場外生產的。儘管3DCP因其精確性和減少材料浪費而提供了最高的材料效率和最低的碳排放，但其廣泛應用仍面臨許多障礙，如缺乏正式的法規。

本論文通過提供一個可靠的碳排放估算工具，爲可持續建築實踐做出了貢獻，促進行業利益相關者的知情決策。該研究強調了制定標準化法規以支持創新技術（如3DCP）採用的重要性。未來的研究應擴展該框架，涵蓋更多的建築元素和區域變異，並納入全生命周期評估，以提供對環境影響的全面視圖。

關鍵字: 碳排放。建築資訊模型。預製構件。傳統建築。*3D*列印混凝土。

doi:10.6342/NTU202403587

Abstract

The construction industry significantly contributes to global carbon emissions, necessitating sustainable practices to mitigate environmental impacts. This thesis presents a model-driven framework for estimating and comparing carbon emissions across three construction methods: traditional cast-in-place, prefabricated, and 3D concrete printing (3DCP). The study addresses the industry's environmental challenges by integrating Building Information Modeling (BIM) with standardized construction databases, specifically RSMeans for MasterFormat and TT10-2019/BXD for TCVN.

The methodology involves a detailed quantity takeoff, material estimation, and emissions calculation for structural elements, including columns, beams, slabs, and walls. A Revit API was developed to automate these processes, enhancing efficiency and accuracy. Two case studies, a laboratory facility and a lecture hall, were analyzed to validate the framework and provide comparative insights.

Key findings indicate that conventional cast-in-place and prefabrication methods exhibit relatively the same environmental impacts. However, the distribution of carbon emissions differs, with around 87-88% of carbon emissions in cast-in-place construction categorized as material emissions, while this percentage increases to 96-98.3% in prefabrication. A major cause of this shift is the transfer of carbon emissions from the formwork and curing processes in cast-in-place construction, classified as process emissions, to the material emissions category in prefabrication due to off-site production. Although 3DCP offers the highest material efficiency and the lowest carbon emissions due to its precision and reduced material waste, it still faces many obstacles to widespread implementation, such as the lack of official regulations.

This thesis contributes to sustainable construction practices by providing a robust tool for carbon emissions estimation, facilitating informed decision-making for industry stakeholders. The research underscores the need for standardized regulations to support the adoption of innovative technologies like 3DCP. Future studies should expand the framework to include additional construction elements and regional variations, incorporating full lifecycle assessments for a holistic view of environmental impacts.

Keywords: *Carbon Emission* ; *Building Information Model (BIM)* ; *Prefabrication* ; *Conventional Construction* ; *3D Concrete Printing (3DCP)*

doi:10.6342/NTU202403587

Table of Contents

doi:10.6342/NTU202403587

doi:10.6342/NTU202403587

List of Tables

doi:10.6342/NTU202403587

List of Figures

doi:10.6342/NTU202403587

Chapter 1

Introduction

1.1 Background

Currently, there are more than 8 billion people worldwide, with over 55% living in big cities. This figure is expected to grow to over 10 billion, with 68% of which is urban residents over the next twenty-five years. The swift rise in population and urbanization drives substantial infrastructure and housing development. Economic advancements, especially in developing countries, further amplify construction activities [33].

However, the built environment is a significant consumer of natural resources, using vast quantities of materials such as sand, steel, and aluminum,... The energy required to produce these materials is considerable, contributing to the sector's substantial environmental footprint. In 2022, the operational energy demand in buildings constituted approximately 30% of the total final energy demand, rising to 34% when including the energy used for material production[8]. Furthermore, construction activities generate substantial amounts of waste, which, if not managed properly, can lead to severe environmental pollution.

Carbon emissions from the AEC sector are also alarming, In 2022, CO_2 emissions generated from building operations phase hit record levels, comprising 37% of the total global carbon emissions. This figure includes emissions from electricity use and direct emissions from buildings. Additionally, The production of construction materials such as cement, steel, and aluminum contributes substantially to embodied carbon emission, contributing 2.5 $GtCO_2$, with brick and glass production adding another 1.2 $GtCO_2$[9]. Despite some improvements in energy efficiency, overall energy demand and emissions in the sector have continued to rise, highlighting the urgent need for larger research investments and policies to enhance energy efficiency and reduce carbon emissions in the industry.

doi:10.6342/NTU202403587

1.2 Problems Statement and Research Motivation

1.2.1 Problems Statement

Despite several promising technological innovations, the built environment is still heavily reliant on traditional on-site construction methods. Traditional construction, characterized by high material waste, intensive labor, and substantial energy consumption, has established detailed practices, standards, and codes that are widely accepted and understood across the industry. The low initial investments, low requirements for labor skills, and the ability to use local materials and workforce contribute to making conventional construction methods the most widely practiced globally. Although alternative construction methods offer substantial benefits, their adoption is limited by several barriers, including high initial costs, lack of standardized implementation frameworks, and limited understanding of their long-term environmental benefits.

One of the most critical obstacles is the absence of robust, standardized methods for estimating and comparing the carbon emissions of these innovative construcion techniques with traditional methods. Without reliable data and comprehensive frameworks, stakeholders in the construction industry are hesitant to transition from well-established traditional practices to newer, more sustainable methods. This hesitation is exacerbated by the risk and uncertainty associated with adopting unproven technologies without clear evidence of their environmental advantages.

To overcome these challenges, there is an urgent need for a robust framework that can accurately calculate the carbon emissions associated with different construction methods. Such a framework would provide essential insights, enabling stakeholders to make informed decisions based on environmental impact assessments and promoting the broader adoption of sustainable construction practices. The development and implementation of innovative construction methods like prefabrication and 3DCP are essential for reducing the industry's carbon emissions. However, without a reliable framework for estimating and comparing the carbon emissions of these methods, their potential benefits cannot be fully realized.

1.2.2 Motivation

This study is driven by the necessity to address a significant gap in the construction industry: the absence of comprehensive, standardized methods for estimating and comparing carbon emissions across different construction techniques. This gap hinders the ability of stakeholders to make informed decisions about adopting more sustainable construction practices.

Innovative methods such as 3D concrete printing (3DCP) and prefabrication promise substantial environmental benefits, including reduced material waste, lower energy con-

doi:10.6342/NTU202403587

sumption, and decreased labor requirements. However, without robust frameworks to quantify these benefits, their adoption remains limited. Stakeholders often revert to traditional construction methods due to the perceived risks and uncertainties associated with new technologies.

Developing a BIM-based framework that accurately calculate carbon emissions for various construction methods, particularly focusing on the feasibility of 3D concrete printing, is essential. Such a framework will provide crucial data and insights, enabling stakeholders to evaluate the environmental impacts effectively and make data-driven decisions. By contributing to the development of reliable tools for carbon emission estimation, this research will support efforts to reduce the sector's overall carbon footprint. This aligns with global sustainability goals and addresses the urgent need for environmental stewardship in construction practices. The impact of this study is hoped to extend beyond academia, influencing practical construction projects.

1.3 Objectives

The main objective of this study is to create a BIM-based framework for accurately and comprehensively calculating and comparing the carbon emissions of different construction methods, with a particular focus on the carbon emissions of concrete structural components, including columns, beams, slabs, and walls, from the material production phase to the end of the construction phase of construction projects. This framework aims to provide reliable and comprehensive data on the carbon emissions associated with traditional, prefabricated, and 3D concrete printing construction methods. By offering a clear comparison of total carbon emissions during the construction phase of these methods, it will facilitate informed decision-making for stakeholders in the construction projects. Additionally, this study aims to promote the adoption of sustainable construction practices by demonstrating the potential environmental benefits of innovative technologies like prefabrication and 3D concrete printing.

To accomplish the primary objectives, the study will carry out the research by following these steps:

- **Conduct a Quantity Takeoff:** Start with a designed 3D model and perform a quantity takeoff for structural concrete elements such as columns, beams, slabs, and walls.

- **Estimate Material Needed for Each Method:** Estimate the main material (concrete and reinforcing rebar) needed to construct the building with three different construction methods: on-site traditional construction, prefabrication, and 3D concrete printing.

doi:10.6342/NTU202403587

- **Define Construction Activities:** Define construction activities for each element in all three methods and align the construction activities with their respective construction standards code from MasterFormat and TCVN.

- **Link Activities to Databases:** Based on those standardized codes, the construction activities are linked to construction databases such as RSMeans for MasterFormat and TT10-2019/BXD for TCVN.

- **Identify Necessary Resources:** Identify necessary machines and equipment and calculate the working hours needed based on quantity takeoffs and construction norms.

- **Calculate Carbon Emissions:** Calculate the required resources and use carbon emission factors to determine the carbon emissions for each construction method.

- **Conduct a Comparative Analysis:** Conduct an analysis to compare the carbon emissions of the different construction methods.

To guide the investigation and ensure a focused approach, this study formulates specific research questions. These questions are designed to explore the core aspects of carbon emissions in construction methods and the potential benefits of 3D concrete printing. They aim to uncover critical insights that will support the development of a model-driven framework for carbon emissions estimation.

- How do different construction methods impact the structural and material usage aspects?

- What are the carbon emissions associated with traditional, prefabricated, and 3D concrete printing construction methods during the construction phase?

- How can the carbon emissions of different construction methods be compared effectively?

- How can a model-driven framework improve the accuracy and reliability of carbon emissions estimation in construction projects?

1.4 Research Scope

The scope of this study centers on the analysis and comparison of carbon emissions from three different construction methods: on-site traditional construction, prefabrication, and 3D concrete printing (3DCP). This involves performing a quantity takeoff for structural concrete components includings columns, beams, floor slabs, and walls using 3D models. A model-driven framework for estimating and comparing carbon emissions is developed by

doi:10.6342/NTU202403587

integrating data from construction standards (e.g., MasterFormat and TCVN), construction databases (e.g., RSMeans, TT10-2019/BXD), and the carbon emissions database. To streamline these processes, the study includes the development of a Revit API using PyRevit to automate tasks such as quantity takeoff, resource identification, carbon emissions calculation, and generating comparative analysis reports. This research is conducted within the context of current construction practices and technologies, without accounting for future advancements or changes in regulatory frameworks.

This study assumes that the building frame in the framework is either a conventional cast-in-place concrete frame or a precast concrete frame. While 3D concrete printing (3DCP) offers innovative solutions, it is currently unsuitable for load-bearing frames in buildings designed to support large live loads, such as schools.

This unsuitability is due to several factors, including weak interlayer bonding, inferior material properties, difficulty in integrating reinforcement, and regulatory approval challenges. The layer-by-layer construction method of 3DCP can result in weak points between layers, compromising structural integrity. Additionally, printed concrete often has poorer material properties compared to traditional mold-cast concrete, affecting overall structural performance. Installing reinforcement in 3DCP is challenging because the printing process necessitates a clear space above the extruded layer to accommodate the movement of the machine head. Moreover, building codes and standards for load-bearing structures are well-established for conventional methods, but there are currently no design codes available for 3DCP, making it difficult to meet regulatory requirements for large-scale load-bearing buildings. Therefore, 3DCP techniques will only be applied to the wall element of this framework.

For conventional concrete and prefabricated frame with the same material properties (concrete and rebar grades), the design structure of a precast frame (columns, beams, slabs) is equivalent to the design structure of a cast-in-place frame (columns, beams, slabs). The performance of a structure relies on the properties of the materials used and the design specifications. Both precast and cast-in-place methods utilize concrete and rebar, which are essential for structural integrity. By maintaining consistent material properties, it is expected that the structural performance, including load-bearing capacity, durability, and safety, will be comparable between the two methods.

Regardless of the construction method used (cast-in-place, precast, or 3D concrete printing), the final building will maintain the same architectural aesthetics and HVAC utilities, resulting in similar operational carbon emissions across all methods. This hypothesis assumes that the end-use and functionality of buildings remain consistent irrespective of the construction method. While the construction methods may differ, the architectural design, interior finishes, and installation of HVAC systems are standardized to meet specific requirements and performance standards.

The carbon emissions associated with building operations, including heating, cooling,

doi:10.6342/NTU202403587

and lighting, are determined by the efficiency of the installed systems and the building's energy use patterns. Since these systems and usage patterns are consistent across different construction methods, the operational carbon emissions are expected to be similar.

1.5 Thesis Structure

The thesis is divided into multiple chapters, each dedicated to a distinct facet of the research. This organization is intended to lead the reader methodically through the study, starting with the introduction of the problem and progressing to the detailed analysis and conclusions. Below is an outline of the main chapters:

- **Chapter 1: Introduction:** This chapter presents the background of the study, articulates the problem statement, defines the objectives, delineates the scope, and outlines the structure of the thesis.
- **Chapter 2: Related Works:** This chapter offers an overview of relevant works, key concepts, and theories related to carbon emissions in construction. It examines previous research on conventional cast-in-place, prefabricated, and 3D concrete printing methods, and identifies gaps in the existing literature.
- **Chapter 3: Methodology:** This chapter details the research design, data collection methods, and data analysis techniques utilized in the study. It outlines the tools and software employed, including the methodologies for estimating carbon emissions based on established standards.
- **Chapter 4: Case Studies:** This chapter showcases the study's results through the examination of two case studies. It includes a comparative analysis of the carbon emissions associated with traditional, prefabricated, and 3D concrete printing methods. The chapter interprets the results and discusses their implications for sustainable construction practices.
- **Chapter 5: Discussion:** This chapter delves into the principal outcomes of the research, discussing their broader implications.
- **Chapter 6: Conclusion:** This chapter concludes the study by highlighting the key conclusions and practical implications. It discusses the study's limitations and provides recommendations for future research. Additionally, it provides final remarks on the significance of the research and suggests potential areas for further investigation.

doi:10.6342/NTU202403587

Chapter 2

Related Works

The primary objective of this chapter is to provide a comprehensive overview of existing research related to carbon emissions in the construction industry, with a particular focus on three construction practices: conventional construction methods, prefabricated construction, and 3D Concrete Printing (3DCP). By examining the current state of knowledge, this review aims to identify gaps and areas for further research, thereby laying a solid foundation for the current study.

2.1 Carbon Emission Estimation

2.1.1 Overview of the construction industry

The 2023 Global Status Report for Buildings and Construction highlights the substantial environmental impact of the construction sector. The buildings and construction sector significantly contributes to global greenhouse gas emissions, representing roughly 34% of global energy usage and producing 34% of process-related carbon dioxide (CO_2) emissions in 2022. While there has been an improvement in energy intensity per square meter, which decreased by 3.5% in 2021, the overall energy demand and emissions in the buildings sector have continued to rise by 1%, reaching a peak of nearly 10 gigatonnes (Gt) of CO_2. Figure 2.1 illustrates Share of Global Energy Demand and Carbon Emissions in Construction Industry

To address the severe environmental problems, the global construction industry is increasingly prioritizing sustainability, driven by the need to reduce environmental impacts and meet climate goals. Key trends include the widespread adoption of green building standards, technological innovations, and strengthening policy frameworks.

International agreements such as the Paris Agreement play a crucial role in driving sustainability. The Paris Agreement strives to reduce climate change to well below 2°C, preferably to 1.5°C, by significantly reducing greenhouse gas emissions across all sectors, including construction [44]. Similarly, the United Nations' Sustainable Develop-

doi:10.6342/NTU202403587

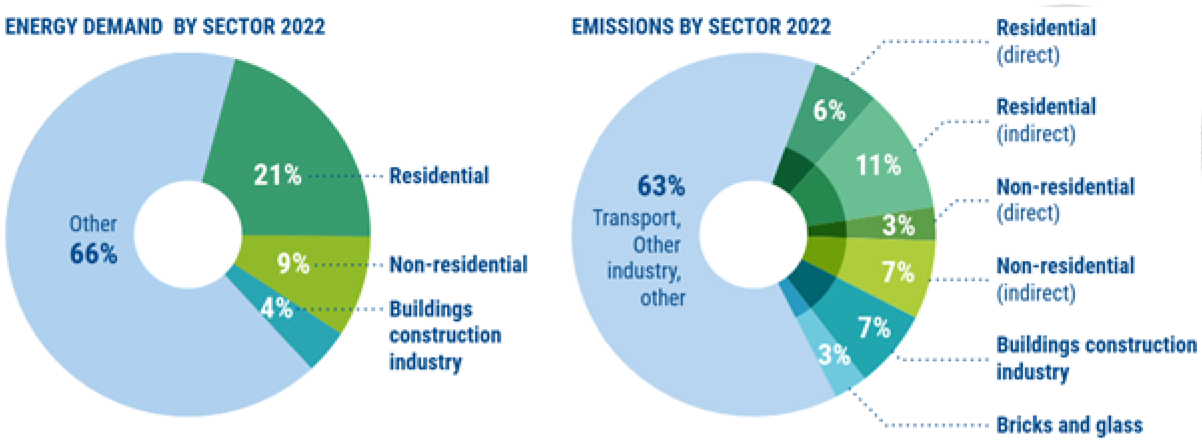

Figure 2.1: Share of Global Energy Demand and Carbon Emissions in Construction Industry[9]

ment Goals, particularly Goals 11 (Sustainable Cities and Communities) and 13 (Climate Action), emphasize sustainable urban development and climate resilience, encouraging countries to integrate sustainability into construction practices [32].

To meet these international goals, governments worldwide are implementing robust policy and regulatory frameworks to support sustainable construction. The European Union's Energy Performance of Buildings Directive (EPBD) sets ambitious energy performance standards, mandating nearly zero-energy buildings (NZEB) for all new constructions by 2020[12]. Nationally Determined Contributions (NDCs) are also incorporating specific actions for the construction sector, including updating building codes to improve energy efficiency and setting targets for reducing carbon emissions from buildings[44].

2.1.2 Green building evaluation system

The implementation of green building standards and certifications, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), is becoming increasingly common. These frameworks guide the creation of energy-efficient and environmentally friendly buildings. National initiatives like Vietnam's LOTUS and China's Green Building Evaluation Standard further emphasize the global dedication to sustainable construction practices. Various green building rating systems have been established to mitigate the negative environmental impacts of construction activities, offering standardized criteria for evaluating the environmental performance of buildings throughout their lifecycle. Table 2.1 summerizes some of the main characteristics of LEED, LOTUS and BREAAM green building rating systems. These tools encourage sustainable practices in design, construction, and operation by promoting reduced energy consumption, decreased carbon emissions, and

doi:10.6342/NTU202403587

more efficient resource utilization [49].

These systems adopt a comprehensive approach, assessing multiple facets of a building's attributes, including energy efficiency, water usage, indoor environmental quality, material selection, and site sustainability, while considering the entire lifecycle of a building.[10].

Green building rating systems, while promoting sustainability, face a few disadvantages. The complexity and bureaucracy of the certification process, such as seen in LEED, lead to delays and increased costs, deterring some projects. Additionally, there are significant inconsistencies between different rating systems, making it difficult to compare certifications across regions and undermining their credibility. These systems often emphasize design over actual performance, limiting their real-world impact. Moreover, high costs, limited adoption, regional variability, and the need for continuous improvement further challenge the effectiveness of green building certifications. Addressing these issues is crucial for enhancing their role in sustainable development [37].

2.1.3 Estimation Methods

Beyond the sustainability assessment systems created by various organizations and institutes, researchers have conducted numerous studies to evaluate the sustainability contributions of construction projects. Often, these studies utilize a single criterion or a very limited number of criteria as symbols of sustainability. Carbon emissions, in particular, are frequently used to represent the environmental impact of building projects on their surrounding environments.

According to life cycle theory [4], a building's carbon emissions can be divided into three main stages: construction phase, operation phase, and demolition phase. The construction stage includes activities such as sourcing raw materials, producing building materials, transportation, and the actual construction work. During the operational stage, CO_2 emissions primarily originate from the use of climate control systems (heating, ventilation, and air conditioning), lighting, office appliances, elevators, and water pumps.The demolition stage includes the dismantling of the building and the recycling and processing of the resulting waste materials. Figure 2.2 illustrate carbon emission components during the life cycles of built projects.

Structural engineers play a crucial role in reducing building carbon emissions, primarily by minimizing the embodied carbon of structures and other building elements [2]. Hence, it is vital to assess the embodied carbon of a building project at the very start of the design phase. This allows engineers to focus on reducing carbon emissions by choosing appropriate construction methods, materials, specifications, efficiency measures, and reuse strategies, and to make necessary adjustments based on the assessment results.

The core principle of calculating embodied carbon involves multiplying the amount

doi:10.6342/NTU202403587

Table 2.1: Green Building Certification Systems: LEED, LOTUS, and BREEAM

Description	**LEED**	**LOTUS**	**BREAAM**
Parent Organization	U.S. Green Building Council (USGBC)	Vietnam Green Building Council (VGBC)	Building Research Establishment (BRE)
Type of Ratings	LEED Certified LEED Silver LEED Gold LEED Platinum	LOTUS Certified LOTUS Silver LOTUS Gold LOTUS Platinum	Pass Good Very Good Excellent Outstanding
Type of Schemes Available	•LEED BD+C (Building Design and Construction) •LEED ID+C (Interior Design and Construction) •LEED O+M (Building Operations and Maintenance) •LEED ND (Neighborhood Development) •LEED Homes	•LOTUS New Construction (NC) •LOTUS BIO •LOTUS Homes •LOTUS SB (Small Buildings) •LOTUS Interiors •LOTUS Small Interiors	•BREEAM New Construction •BREEAM Refurbishment and Fit-Out •BREEAM In-Use •BREEAM Communities •BREEAM Infrastructure •BREEAM International
Main Credit Categories	•Location and Transportation •Sustainable Sites •Water Efficiency •Energy and Atmosphere •Materials and Resources •Indoor Environmental Quality Quality •Innovation •Regional Priority	•Energy •Water •Materials & Resources •Health & Comfort •Site & Environment •Project Management •Exceptional Performance	•Management •Health and Wellbeing •Energy •Transport •Water •Materials •Waste •Land Use and Ecology •Pollution •Innovation

doi:10.6342/NTU202403587

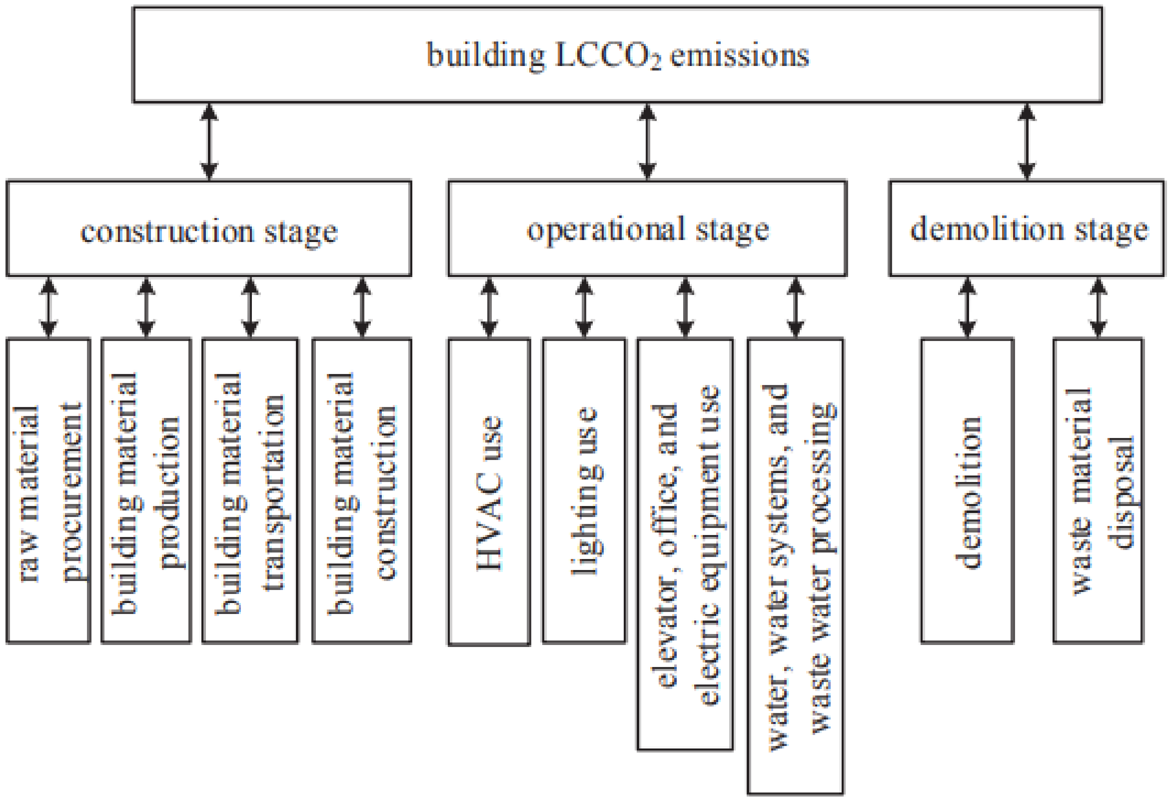

Figure 2.2: Carbon Emission in Building lifecycle [34]

of each material or product by a carbon factor (usually measured in $kgCO_2e$ per kg of material) for each life-cycle module considered. Two aspects needs to consider in this principle is the carbon emissions factors and the traditional quantity surveying process.

A carbon emission factor is a measure used to estimate the amount of carbon dioxide (CO2) emissions associated with a specific material, activity, or process. It is typically expressed in units of mass (e.g., kilograms or metric tons) of CO2 emitted per unit of activity (e.g., per kilogram of material used, per kilowatt-hour of electricity consumed, per gallon of fuel burned). These factors are crucial for calculating the environmental impact of various activities and for developing strategies to reduce greenhouse gas emissions. They can vary by source, scope (direct, indirect, value chain), and region.

Another aspects to consider is the traditional quantity surveying process. This process, being a manual process, is prone to errors and can be time-consuming. However, these problems can be alleviated through automation. Building Information Modeling (BIM), a comprehensive database of engineering information, can provide accurate material quantity data. This enables BIM to automatically generate a precise bill of quantities, thereby reducing the need for tedious manual operations and minimizing the likelihood of errors.

Although research on utilizing BIM for carbon emissions estimation is limited, there

doi:10.6342/NTU202403587

are even fewer studies that directly compare the sustainability performance of construction processes using different construction methods in building projects.

2.2 Construction Method and Technology

Technological innovations are key to advancing sustainability in construction. Alternative construction methods such as prefabrication and modular construction offer significant benefits in terms of efficiency and waste reduction. These techniques allow for the production of building components in controlled environments, minimizing waste and ensuring higher precision in assembly. 3D concrete printing is another innovative technology that presents opportunities to further reduce material waste, lower labor costs, and minimize carbon emissions by optimizing construction processes. Additionally, the implementation of BIM technologies in built project enhance project planning, design, and management by providing a comprehensive digital representation of a building's physical and functional characteristics. These technologies collectively contribute to more sustainable construction processes by improving precision, reducing material waste, and optimizing resource use.

2.2.1 Construction Method

Conventional Construction

According to McCormac and Brown in "Design of Reinforced Concrete" [23], conventional reinforced concrete or traditional cast-in-place concrete is a composite material mainly made up of concrete mixture and steel reinforcement rebar. The concrete provides the compressive capacity, while the steel rebar imparts tensile ability of concrete components, making it a versatile and widely utilized material in construction.

Reinforced concrete is considered to be the most prevalent and essential materials for building construction projects due to its numerous significant advantages, which include high compressive strength, durability, flexibility in design, economic viability, fire resistance, and sound insulation. It can withstand significant compressive forces, making it suitable for various structural applications such as buildings, bridges, and dams. Its great resistance to fire, water, and environmental degradation ensures a long lifespan with minimal maintenance. Additionally, concrete can be cast into a wide variety of shapes and sizes, allowing for innovative architectural designs. Locally available materials can be used for its production, which reduces transportation costs and often requires less skilled labor compared to other construction materials. Concrete is highly fire-resistant and can protect the steel reinforcement from high temperatures during a fire. Its dense nature provides good sound insulation, which is beneficial in residential and commercial buildings.

doi:10.6342/NTU202403587

However, traditional cast-in-place concrete also has several drawbacks. Concrete itself has low tensile strength, necessitating the use of steel reinforcement to counteract tensile forces. The high density of concrete results in a heavy material, which can lead to higher foundation costs and challenges in handling and transport. The process of setting up formwork, placing reinforcement, pouring, and curing concrete is time-intensive. A significant portion of the total cost of reinforced concrete structures is attributed to the formwork required to shape and support the concrete until it hardens. Concrete is susceptible to cracking because of shrinkage, thermal fluctuations, and load-induced stress, which can compromise its durability and structural integrity.

In addition to these structural drawbacks, conventional construction materials also have severe environmental impacts. The production of cement, a primary component of concrete, is energy-intensive and contributes significantly to CO_2 emissions, with approximately 8% of global CO_2 emissions attributed to cement production [9]. The extraction of raw materials such as limestone, clay, sand, and gravel for concrete production can lead to habitat destruction and resource depletion. Manufacturing, transporting, and processing the materials for reinforced concrete require substantial energy, contributing to its overall environmental footprint. Construction processes generate waste, including unused concrete, formwork materials, and debris, necessitating proper disposal and recycling practices to mitigate environmental impact. Additionally, concrete production is water-intensive, and the curing process requires substantial amounts of water, which can be a concern in water-scarce regions.

With the widespread use of conventional cast-in-place construction methods, the carbon emission rate is projected to double over the next two decades [39]. There is an urgent need to find more sustainable approaches for carrying out construction projects.

Prefabrication Construction

Among all alternative construction methods, modular construction, also known as prefabrication or precast construction, is frequently mentioned as a viable approach. Prefabrication construction entails producing building components in a factory setting and subsequently transporting them to the construction site for assembly and installation. [13]. Figure 2.3 illustrates the prefabrication process, highlighting its difference in stages in comparison to traditional construction methods.

The process begins with the off-site production of components in industrial production halls under ideal conditions. These components undergo rigorous quality checks, ensuring higher precision and consistency. After fabrication, the components are transported to the construction site. This stage involves long transports, but efficient logistics management ensures timely delivery and assembly. On-site assembly of these prefabricated components is then carried out, resulting in the completion of the construction project.

doi:10.6342/NTU202403587

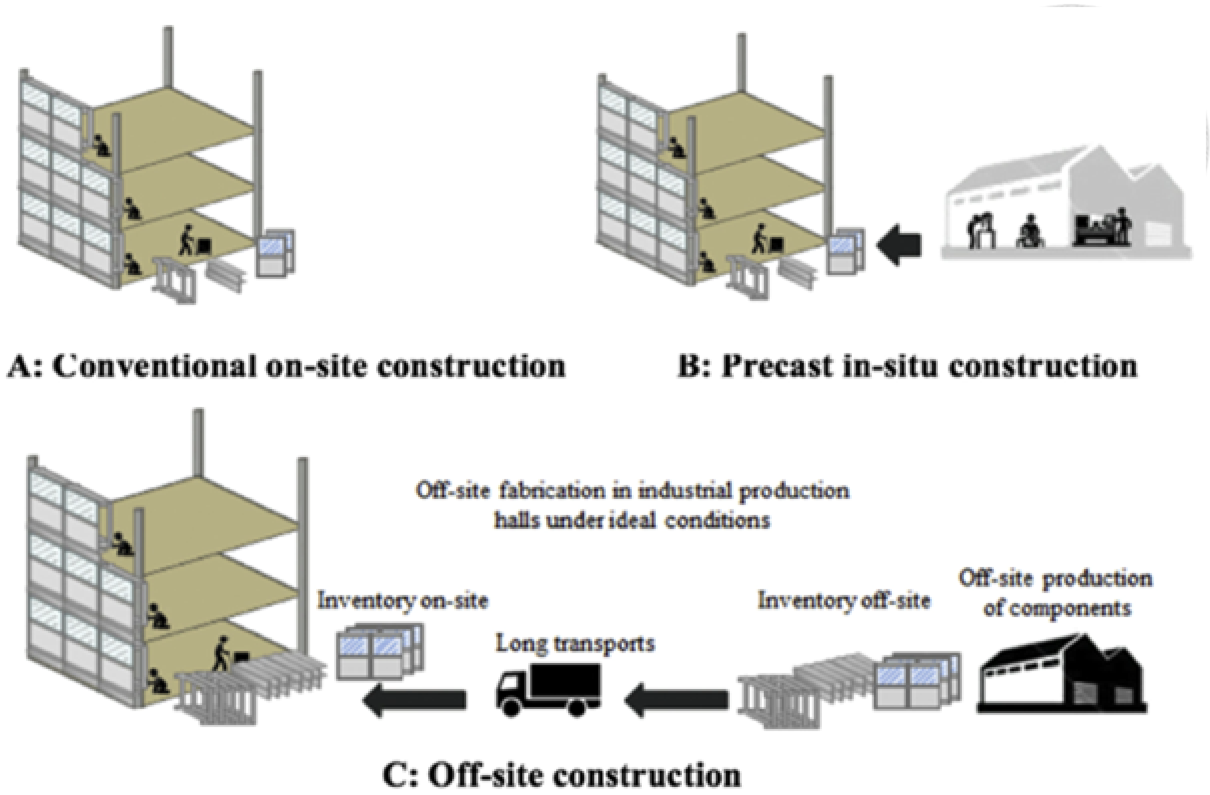

Figure 2.3: Prefabrication Construction Method Process [48]

In contrast to traditional on-site construction, which is subject to weather conditions and other site-related challenges, prefabrication offers several advantages. Efficiency and speed are significantly improved, as components are produced simultaneously in the factory, independent of on-site conditions. This automated process reduces the negative effects of outdoor environments and the workload of on-site construction activities. Quality control is enhanced because components manufactured in a controlled environment undergo rigorous quality checks, resulting in higher precision and consistency, reducing the likelihood of defects. Waste reduction is achieved by optimizing the use of resources during the manufacturing process, allowing for better recycling and reuse of materials, leading to more sustainable construction practices. Additionally, by decreasing on-site activities and optimizing material usage, prefabrication lessens the disturbance to the local environment and cuts down on greenhouse gas emissions from construction activities.

Prefabrication also offers design flexibility, as long-span precast components create larger open spaces and fewer piers, supporting various shapes and sizes for innovative and economical designs. The method provides inherent fire resistance, enhancing safety and lowering insurance premiums. The durability of precast concrete is notable, often lasting over 100 years with lower life cycle costs. Material efficiency is another benefit, with prestressing enhancing span-to-depth ratios, performance, and material usage. Aesthetic flexibility is a key advantage, with a wide range of textures, colors, and finishes that

doi:10.6342/NTU202403587

can mimic materials like granite and brick. Precast concrete is effective for acoustical control, providing sound insulation suitable for pleasant living and working environments. Its high thermal mass improves energy efficiency, further enhanced with insulated panels. Moreover, prefabrication supports sustainability through efficient use of materials and energy, improved quality control from factory production, modular construction for future reuse, and the ability to design redundancy for blast resistance [6].

A case study of an educational school [35] concluded that prefabricated systems offer significant sustainability benefits over traditional construction methods, primarily through reduced environmental impacts during construction and end-of-life stages. However, the sustainability of prefabricated technology largely depends on the specific case, particularly the distance between the factory and the building site. In some scenarios, non-prefabricated technologies may be more sustainable, especially if the construction site is far from manufacturing facilities or if the initial cost and construction time are primary considerations.

Despite these advantages, the use of prefabrication construction remains limited, with less than 3% of all residential buildings in the US being constructed using precast concrete materials [18]. This limited adoption is likely due to the fact that the advantages of prefabrication construction methods compared to on-site construction are not well recognized by many construction professionals and the general public [29].

3D Concrete Printing (3DCP)

Digital manufacturing technology, usually referred to as 3D printing or additive manufacturing, constructs physical objects from geometric designs by incrementally adding material layer by layer [41]. A variety of 3D printing technologies have been developed, each with unique capabilities. According to ASTM Standard F2792 [15], these technologies are classified into seven categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. Table 2.2 states some main features related to benefits, drawbacks and application of those 6 common method of 3D Printing technologies.

- **Binder Jetting:** A fast prototyping method where a liquid binder is selectively applied to join powder particles. It is used to create casting patterns, raw sintered parts, and large-volume items from materials such as metals, sands, polymers, hybrids, and ceramics.

- **Directed Energy Deposition:** A sophisticated process for repairing or adding material to existing parts, offering precise control over grain structure. Typically uses metals and metal-based hybrids in wire or powder form. Examples include Laser Deposition and Laser Engineered Net Shaping (LENS).

doi:10.6342/NTU202403587

- **Material Extrusion:** A process that builds objects by extruding heated thermoplastic filament layer by layer. It is commonly used for printing plastics, food, or living cells. An example of this technology is Fused Deposition Modelling (FDM).

- **Material Jetting:** This method involves selectively depositing droplets of material that solidify under UV light to construct parts layer by layer. It is ideal for multi-material printing with a variety of materials, including polymers, ceramics, composites, and biologicals.

- **Powder Bed Fusion:** A technique that uses an electron beam or laser to melt or fuse powder materials together. This category includes Electron Beam Melting (EBM), Selective Laser Sintering (SLS), and Selective Heat Sintering (SHS).

- **Sheet Lamination:** A process that creates objects by bonding sheets of material together. Examples include Laminated Object Manufacturing (LOM) and Ultrasound Additive Manufacturing (UAM).

- **Vat Photopolymerization:** Utilizes a laser or light to cure photo-reactive polymers. Examples of this technology include Stereolithography (SLA) and Digital Light Processing (DLP).

Table 2.2: Benefits, Constraints, and Applications of 3D Printing Technologies [43]

Technology	**Benefits**	**Constraints**	**Applications**
Powder Bed Fusion (PBF)	High precision, strong parts, large build capacity	Limited material variety, expensive, complex procedures	Building components, intricate structures, custom parts
Material Jetting	High accuracy, excellent surface quality, diverse materials	Small build size, costly, requires post-processing	Architectural models, building components, small-scale objects
Binder Jetting	Fast production, cost-effective, versatile materials	Lower strength, subpar surface quality, needs post-processing	Building components, decorative objects, small-scale models
Fused Deposition Modeling (FDM)	Economical, easy to use, supports various materials	Reduced accuracy, inferior surface finish	Prototyping, small-scale models, building components
Stereolithography (SLA)	High accuracy, excellent surface quality	Limited material options, costly, slower production	Concept models, prototyping, architectural models
Selective Laser Sintering (SLS)	Versatile materials, high accuracy, strong parts	Expensive, complex, requires post-processing	Custom parts, building components, structural elements

Among the various 3D printing techniques, 3D concrete printing (3DCP) is an innovative construction technology that automates the building process by creating structures layer by layer from a digital model. This method leverages advanced software and

doi:10.6342/NTU202403587

specially formulated concrete mixtures to produce complex, precise, and customized designs efficiently. 3DCP represents a significant advancement over traditional construction methods, offering enhanced material efficiency, design flexibility, and sustainability.

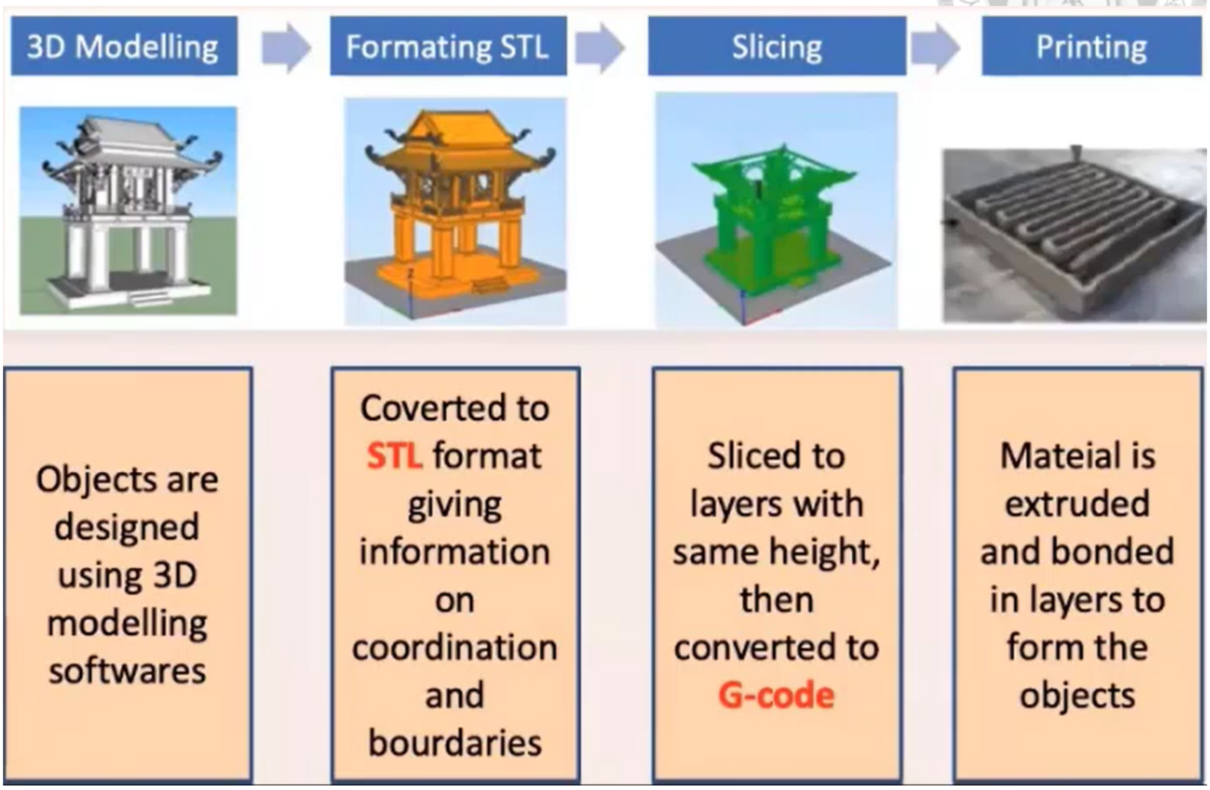

Figure 2.4: 3D concrete printing process [21]

Figure 2.4 show the process of 3D Concrete Printing. The 3D printing process begins with the design phase, where objects are designed using 3D modeling software. This model is then converted to STL format, which provides detailed information on the coordination and boundaries of the structure. Once in STL format, the model is sliced into layers of the same height and then converted to G-code, which directs the printer on how to construct each layer.

Next, the printing process commences, wherein a suitable concrete mixture is extruded and bonded in layers to form the object. The 3D printer, set up on-site, follows the programmed paths based on the digital model layers. The structure is "printed" layer by layer according to the model's specifications. This automated process is continuously monitored to ensure accuracy and to address any issues that arise. Finally, in the post-processing phase, the printed concrete is cured to achieve full strength, and any necessary finishing touches are applied to meet structural and aesthetic requirements.

3D Concrete Printing (3DCP) offers significant environmental benefits by reducing material usage and waste, cutting energy consumption, and lowering CO_2 emissions compared to traditional construction methods. The process also minimizes noise pollution

doi:10.6342/NTU202403587

and fuel consumption by reducing the need for heavy machinery. Additionally, 3DCP supports the use of renewable and recycled materials, enhancing overall sustainability and improving the durability and longevity of structures.

3DCP can reduce material usage by up to 40% and material waste by 30% compared to traditional casting methods, primarily due to the precision of the printing process, which ensures that only the necessary amount of material is used [?]. Life cycle assessment (LCA) studies indicate that 3DCP can decrease cumulative energy consumption by 41-64%, directly contributing to lower CO_2 emissions and minimizing other environmental impacts [16]. Furthermore, 3DCP has the potential to reduce the environmental impact by 50% compared to cast concrete techniques, including a significant reduction in CO_2 emissions. The production process for 3DCP involves fewer emissions because it optimizes material usage and reduces waste. The construction process using 3DCP also eliminates noise pollution associated with traditional construction methods, creating a more pleasant and less disruptive environment for surrounding communities.

3DCP reduces the need for heavy construction equipment, thereby lowering fuel consumption and transportation-related emissions. The reduction in required machinery also lessens the environmental footprint of construction sites. The potential of using alternative materials in 3DCP, such as soil mixed with straw, recycled glass, and organic materials, enhances the sustainability of concrete by reducing reliance on traditional energy-intensive materials. Increasing the durability of 3D-printed structures extends their service life, reducing the frequency of repairs and replacements, and further contributing to the overall reduction of environmental impacts associated with construction activities. Examples such as the Holstebro-House in Denmark demonstrate innovative approaches to improving the environmental sustainability of 3DCP, such as the use of solar roofs, which could further enhance the environmental benefits by reducing energy consumption and promoting renewable energy use.

While 3D concrete printing (3DCP) offers numerous environmental advantages, the transition from traditional construction methods to 3DCP is not without its challenges. These benefits highlight the potential of 3DCP to revolutionize the construction industry by promoting sustainability and efficiency. However, the implementation of this innovative technology encounters several obstacles that need to be addressed to fully realize its environmental and practical benefits [24].

Social challenges include the impact on employment, as automation reduces the number of construction workers, potentially causing societal issues in areas dependent on construction jobs. Aesthetic and design limitations, such as the rougher surface finish of 3D printed structures compared to conventional construction, and geometric limitations, as current 3D printing technologies may not be suitable for larger-scale constructions, are also concerns.

The initial investment required for 3D printing equipment and setup is substantial,

doi:10.6342/NTU202403587

including the cost of printers, materials, and the adaptation of existing construction sites for 3D printing. The logistics of transporting and setting up 3D printing equipment in remote areas pose significant challenges, and the materials and specifications must be tailored to the local environment. Material standards and specifications need to match the requirements of the technology, and the availability of suitable materials in remote areas can be limited. If local materials cannot meet the specifications, importing materials becomes necessary, increasing costs and complexity. The integration of utilities, such as plumbing and electrical systems, into 3D printed buildings is complex and not always feasible with the current state of technology. Ensuring the structural integrity and stability of 3D printed structures, especially in extreme conditions like cyclones, earthquakes, and floods, is challenging. The mechanical properties of 3D printed elements can vary significantly, affecting their long-term durability and structural performance.

The lack of standardized building codes and regulations specific to 3D printed constructions complicates the approval and implementation processes. Implementing 3DCP requires new knowledge and methods for construction scheduling and project management, including adapting to the unique requirements of the technology, such as material preparation and delivery systems. Setting up on-site fabrication for 3D printing can be challenging and time-consuming, impacting overall project timelines. Construction workers need to be trained in operating and maintaining 3D printing equipment, requiring new skills compared to traditional construction methods. The cost of materials suitable for 3D printing can be higher compared to traditional construction materials, affecting the overall cost-efficiency of projects. In some cases, the economic feasibility of 3D printing in construction, especially in remote or low-income areas, remains a concern.

3D concrete printing (3DCP) offers significant environmental benefits, including reduced material waste, lower energy consumption, and the use of sustainable materials. However, its adoption faces several challenges, such as high initial costs, material limitations, integration of building services, and ensuring structural integrity. A critical barrier is the lack of established building codes and standardized regulations, complicating approval and implementation. Addressing these regulatory challenges is essential to fully realizing the potential of 3DCP in sustainable construction.

2.2.2 Building Information Model (BIM)

Building Information Modeling (BIM) is described as a collaborative digital model representing the physical and functional attributes of any constructed entity, providing a reliable basis for decision-making throughout its entire lifecycle [40]. Originating from product models [5] used in industries like petrochemical, automotive, and shipbuilding, BIM digitally replicates real buildings as coherent, semantically enriched models[46]. Implemented through object-oriented software, BIM comprises parametric objects that

doi:10.6342/NTU202403587

represent building components, each containing spatial or non-spatial attributes, such as operational, contextual, or structural information. BIM can be applied to both new constructions and existing buildings, supporting various phases from design and construction to maintenance and deconstruction. Figure 2.5 show the way to apply BIM technique and the creation of BIM model in both new and existing building projects.

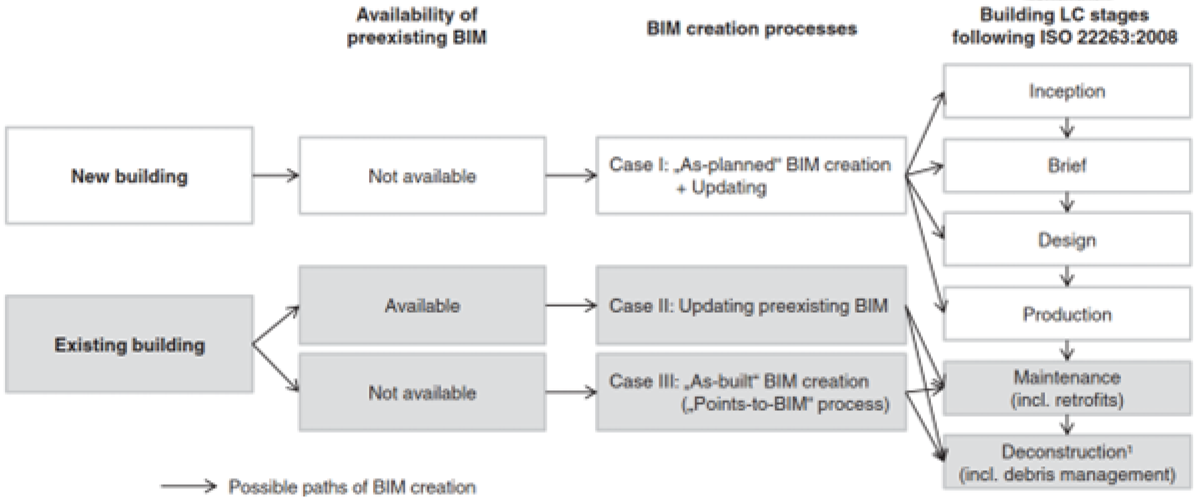

Figure 2.5: BIM model creation processes. [36]

Building Information Modeling (BIM) offers numerous benefits that enhance project outcomes in various ways. One significant advantage is the reduction of risk and costs. BIM reduces risks by providing better information management throughout the project lifecycle, leading to fewer schedule and budget overruns and minimizing claims. Efficient clash detection and coordination help avoid costly errors during construction, resulting in lower net costs for owners, designers, and engineers.

BIM also improves productivity and coordination. Easy retrieval of information and improved coordination of construction documents enhance overall productivity. The ability to generate accurate and consistent 2D drawings at any stage reduces the time needed for construction drawings and minimizes potential errors.

Enhanced project performance is another key benefit of BIM. Schematic models enable a more accurate assessment of proposed designs, ensuring they meet functional and sustainable requirements, thus improving project performance and quality. BIM allows for visualization of the design at any stage, ensuring dimensional consistency and enhancing monitoring efficiency, which reduces operating costs.

The speed and efficiency of project delivery are greatly enhanced through BIM. Improved coordination among design disciplines and early detection of design issues accelerate project delivery. Embedding and linking vital information, such as material quantities and vendor details, streamline estimation and tendering processes, making the overall construction process more efficient.

doi:10.6342/NTU202403587

BIM also promotes better collaboration and communication among project stakeholders, leading to more efficient project execution. Enhanced design coordination reduces construction time and the number of change orders, resulting in faster project completion.

BIM has significant potential to enhance sustainable construction practices. The integration of BIM with green building practices offers several advantages that contribute to environmental sustainability. BIM facilitates energy simulations and performance analyses during the design phase, enabling more energy-efficient building designs. This helps in reducing energy consumption and improving the overall energy performance of buildings [45]. Furthermore, BIM supports the incorporation of renewable energy sources, such as solar panels and geothermal systems, enhancing the building's sustainable energy generation [38].

BIM also improves resource efficiency by aiding in the selection of sustainable materials with low embodied carbon and high recycled content. It helps in choosing materials that emit low levels of volatile organic compounds (VOCs), improving indoor air quality [3]. Comprehensive life cycle assessments (LCA) enabled by BIM evaluate the environmental impacts of building materials and construction methods from cradle to grave, helping to identify the most sustainable options for materials and construction techniques [25].

Waste reduction is another significant advantage of BIM. Precise material estimates provided by BIM reduce surplus material and minimize construction and demolition waste, contributing to more efficient resource use on construction sites [7]. BIM-driven prefabrication techniques streamline construction processes, reducing waste and construction time, and enhancing the energy performance of buildings.

BIM also fosters collaborative decision-making by promoting better collaboration among stakeholders, ensuring that sustainability goals are considered at every stage of the project. This leads to more efficient project execution and sustainable outcomes [22]. Early-stage design decisions supported by BIM optimize energy efficiency, resource use, and environmental impact, resulting in more sustainable building designs and improved project performance [19].

Furthermore, BIM-supported sustainability reporting improves transparency and accountability in green building projects. It provides clear information about materials used and their environmental impacts, aiding in compliance with green building certifications like LEED and BREEAM.

Building Information Modeling (BIM) holds significant potential for promoting sustainable construction practices, particularly in analyzing and reducing carbon emissions. By enhancing energy efficiency, improving resource efficiency, reducing waste, and enabling comprehensive life cycle assessments (LCA), BIM ensures sustainability goals are met at every project stage. Overall, BIM is a crucial tool for advancing sustainable construction and reducing the industry's carbon footprint.

doi:10.6342/NTU202403587

2.3 Gaps in Knowledge

Selecting the optimal construction method for each building project is crucial for achieving sustainability goals. Wey and Wu [47] indicate that choosing inappropriate construction methods can lead to negative environmental and financial impacts, such as resource waste and cost overruns. Despite this, the process of selecting a construction method, such as an off-site method, is often based on historical experience and anecdotal evidence, primarily due to a lack of convenient tools to analyze the environmental impact of each option [30]. Therefore, it is essential to develop and utilize tools that can comparatively assess the lifecycle sustainability performance of different construction methods [20].

Despite the growing interest in 3D Concrete Printing (3DCP) as an innovative construction technology, there is still significant room for exploration, particularly in comprehensively analyzing its carbon emissions compared to traditional and prefabrication construction methods. Most existing studies focus on structural performance, cost, and efficiency. While there are some studies on the environmental impacts of these practices, this research often focuses on the carbon emissions of the material but neglects the emissions during the print process.

Another gap in existing research is the inadequate consideration of regional variations. Construction practices, material availability, and regulatory standards vary significantly across different regions, affecting the carbon emissions of construction methods. However, most studies generalize findings without accounting for these regional differences. This limits the applicability of the research outcomes to specific contexts.

The lack of standardized measurement frameworks further complicates the comparative analysis of construction methods. Different studies often use varying methodologies and metrics to measure the environmental impacts of construction projects, making it challenging to compare results across studies. This inconsistency hinders the ability to draw generalizable conclusions about the sustainability of different construction methods.

To address these gaps, future research should adopt a Life Cycle Assessment (LCA) approach to systematically compare the carbon emissions of different construction methods, covering all stages from material production to disposal in line with current international standards. Additionally, it should consider regional variations by accounting for differences in construction practices, material availability, and regulatory standards, providing more accurate and applicable sustainability assessments. Furthermore, developing and using a standardized measurement methodology is crucial to ensure a consistent framework for measuring carbon emissions, facilitating comparability across studies. By addressing these issues, the construction industry can better understand the environmental implications of 3DCP and other methods, promoting truly sustainable practices and reducing the overall environmental footprint.

In an attempt to address these gaps, this study aims to provide a comprehensive anal-

doi:10.6342/NTU202403587

ysis of carbon emissions associated with different construction methods, focusing on conventional cast-in-place, prefabrication, and 3D Concrete Printing (3DCP) construction methods. The contributions of this study include the development of a general framework that conducts a thorough carbon emissions analysis from the production phase until the end of construction phases of traditional cast-in-place concrete, prefab concrete, and 3D concrete printing technologies. By evaluating carbon emissions during the production and construction phases, the research provides a holistic view of the environmental impacts, specifically focusing on carbon emissions.

Additionally, the primary innovation of this research is the integration of Building Information Modeling (BIM) with carbon emission estimation frameworks and official construction standards, including those from the American Construction Institute and Vietnamese construction standards. This integration enhances the accuracy and efficiency of carbon emission estimations by standardizing the process, addressing a significant gap in current research practices. The study also takes into account regional variations in construction practices and regulatory standards, providing more accurate and context-specific sustainability assessments. This approach ensures that the findings are applicable to various regions.

doi:10.6342/NTU202403587

Chapter 3

Methodoglogy

To develop and propose a framework to estimate carbon emissions comprehensively, the study carry out estimating carbon emissions of two case studies. One is laboratory facilities and the other is the lecture hall. The details steps on how to the estimation is explained in details of this chapter 3: Methodology and the results will be demonstrated in chapter 4: Case Studies

3.1 Overview

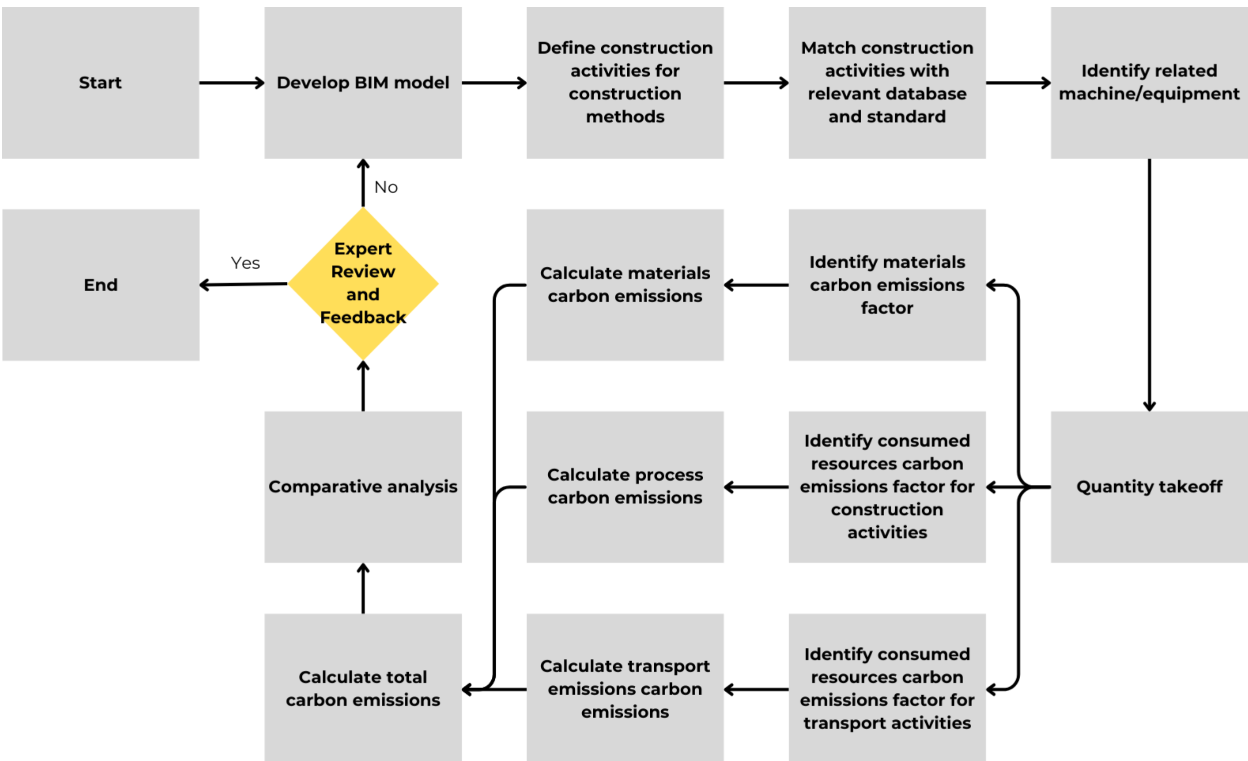

Figure 3.1: Carbon Emission Estimation Methodology

doi:10.6342/NTU202403587

The Carbon Emissions Estimation Framework, illustrated in figure 3.1, is designed to systematically evaluate the carbon footprint associated with different construction methods. Its primary aim is to provide a comprehensive and replicable methodology for assessing and comparing the environmental impact of conventional cast-in-place concrete, prefabricated concrete, and 3D concrete printing methods. The framework is structured into several key steps as illustrated in the methodology diagram.

The process begins with developing a initial BIM model on Autodesk Revit Software. The model used in this research is available model from research department.

The next step is identifying the construction activities for each type of building element in each construction method. This foundational step ensures that all relevant activities are clearly outlined and understood, setting the stage for a detailed and accurate analysis of each method's specific requirements and impacts. Construction activities are meticulously mapped to specific types of building elements for each construction method. This step utilizes building standards and existing databases to ensure a comprehensive and precise mapping of the elements and activities involved.

Using a design 3D BIM model, a quantity takeoff is performed to determine the material quantities required for each construction method. This step is essential for quantifying the resources needed and serves as the basis for carbon emissions estimation.

At this stage, carbon emissions are estimated based on the material quantities and the associated construction activities. This step provides a quantifiable measure of the carbon footprint for each construction method, enabling a comparative analysis.

The estimated carbon emissions are reviewed by experts who provide feedback on the accuracy and reliability of the results. If necessary, the model is updated based on this feedback to ensure the validity and robustness of the findings. Based on the expert feedback, the model may be iterated and refined to address any identified issues or inaccuracies. This step also serves as a basis for deciding which construction methods are chosen for the building project.

Once the model is finalized, a comparative analysis is conducted to evaluate and compare the carbon emissions across different construction methods. This analysis highlights the most sustainable construction approach, considering both direct and indirect emissions throughout the construction lifecycle.

3.2 Building Element and Construction Activities Association

The process begins with a crucial step: defining on-site construction activities for each type of building element in every construction method. This foundational step involves a thorough identification and categorization of the activities associated with each building

doi:10.6342/NTU202403587

element, such as walls, columns, beams, and slabs.

The first step is activity identification which involves pinpointing the main on-site activities required for constructing each building element. For example, in cast-in-place concrete construction, the activities include formwork preparation, rebar installation, concrete pouring, and curing. For prefabricated concrete elements, the primary activities involve the installation of the prefabricated components. In 3D concrete printing (3DCP), the main on-site activities primarily consist of printing the concrete elements layer by layer. Each construction method has unique on-site activities that are crucial to its specific process, highlighting differences in how the elements are constructed and assembled. The detailed breakdown of activities is illustrated in Table 3.1. By meticulously defining on-site construction activities, a solid foundation for the entire Carbon Emissions Estimation Framework is established, ensuring precision and reliability in the subsequent analysis.

Table 3.1: On-site Activities for Concrete Elements by Construction Method

Method	Concrete Element	Main On-site Activities
Traditional Cast-in-place Concrete	Columns	Reinforcing in place, Columns
		Forming in place, Columns
		Placing in place, Columns
		Curing concrete, Columns
	Beams	Forming in place, Beams
		Reinforcing in place, Beams
		Placing in place, Beams
		Curing concrete, Beams
	Slabs	Forming in place, Slabs
		Reinforcing in place, Slabs
		Placing in place, Slabs
		Curing concrete, Slabs
	Walls	Reinforcing in place, Walls
		Forming in place, Walls
		Placing in place, Walls
		Curing concrete, Walls
Prefabricated Concrete	Columns	Installing Prefabricated Columns
	Beams	Installing Prefabricated Beams
	Slabs	Installing Slabs
	Walls	Installing Prefabricated Wall Panels
3DCP	Walls	Printing 3DCP Walls

The next step is task sequencing. This entails arranging the identified on-site activities in a logical sequence that reflects the actual construction process. Understanding the workflow and dependencies between activities ensures that all steps are accounted for in the correct order.

Following the detailed identification and categorization of on-site construction activities, the next crucial step involves associating these activities with their respective

doi:10.6342/NTU202403587

building standards and construction database. This association is done in accordance with two building standard systems: MasterFormat by the Construction Specifications Institute (CSI) and TCVN by the Vietnamese government. This structured approach ensures that the construction process is accurately reflected and facilitates a thorough analysis of each method's unique requirements and impacts based on a standardized database. Additionally, it leverages construction databases, specifically RSMeans for MasterFormat and TT10-2019/BXD for TCVN. Notably, while cast-in-place and prefabricated methods follow these standards, 3D concrete printing (3DCP) currently lacks established standards.

Corresponding codes are first identified. This involves associating the identified construction activities from the previous step with specific codes in building standards such as MasterFormat and TCVN. Each activity is accurately matched with the relevant code for each construction method, utilizing the assigned codes for construction activities to obtain detailed information about the type of labor, activity norms, and other standardized data.

Next, machinery requirements are identified and documented for each construction activity, such as concrete mixers for concrete pouring, cranes for prefabricated element installation, and 3D printers for 3DCP walls. The identified machinery requirements are validated to ensure they match the actual needs of the construction activities. The detailed building element and construction activities association results, with all relevant codes and machine/equipments, are illustrated in tables 3.2, 3.3, 3.4, and 3.5. By systematically associating construction activities with their corresponding codes in recognized standards, machinery requirements of each construction activities defined are identified. This supports accurate data collection, analysis, and comparison in the later phases of the study. While cast-in-place and prefabricated methods benefit from established standards and databases, the 3DCP method will need to be evaluated without such established guidelines.

3.3 Quantity Takeoff

After associating construction activities with their corresponding building element codes and identifying the necessary machinery requirements, the next crucial step is to accurately quantify the materials required for each construction method. This phase, known as Quantity Takeoff, involves detailed measurement to calculate material quantities, ensuring consistency and reliability across different construction techniques. The results from this step are essential for the subsequent estimation of carbon emissions and comparison of the environmental impact of each construction method.

The first step is to obtain detailed design models of the building using Building Information Modeling (BIM) software, such as Autodesk Revit. These models should

doi:10.6342/NTU202403587

Table 3.2: Conventional Construction Activities - RSmean - MasterFormat

Construction Activity Description	Code	Machine
Forming in place, columns	031113.25	None
Reinforcing in place, columns	032111.60	None
Placing in place, columns	033113.70	2 Gas Engine Vibrators 1 Concrete Pump (Small)
Curing concrete, columns	033913.50	None
Forming in place, beams	031113.20	None
Reinforcing in place, beams	032111.60	None
Placing in place, beams	033113.70	2 Gas Engine Vibrators 1 Concrete Pump (Small)
Curing concrete, beams	033913.50	None
Forming in place, floors	031113.35	None
Reinforcing in place, floors	032111.60	None
Placing in place, floors	033113.70	2 Gas Engine Vibrators 1 Concrete Pump (Small)
Curing concrete, floors	033913.50	None
Forming in place, walls	031113.85	None
Reinforcing in place, walls	032111.60	None
Placing in place, walls	033113.70	2 Gas Engine Vibrators 1 Concrete Pump (Small)
Curing concrete, walls	033913.50	None

accurately represent the geometry and dimensions of each concrete structural building element, including columns, beams, slabs, and walls.

Next steps is to perform the Quantity Takeoff using the design model to quantify the materials required for each building element, including calculating the volumes of concrete, quantities of rebar, and other necessary materials. The quantified material quantities are adjusted to account for the waste percentages specific to each construction method. The waste percentages/ material loss for each construction method are illustrated in Table 3.6. These percentages result from a literature review and consultations with construction experts. The table highlights the material waste percentages for different construction methods: Conventional Cast-in-place (5%), Prefabricated (1%). Conventional Cast-in-place has the highest material loss due to on-site mixing and manual labor, leading to excess material usage and errors. Prefabricated construction has a lower material loss because components are manufactured in controlled environments, reducing waste during assembly. 3DCP has almost no material waste due to its precise automated process that places concrete exactly where needed, minimizing waste and human error.

To accurately quantify the rebar needed for concrete structural elements, the reinforcement ratios are assumed based on a combination of expert interviews and established construction standards. This ensures that the values used are optimal for structural performance and material efficiency. Table 3.7 illustrates the reinforcement ratios for

doi:10.6342/NTU202403587

Table 3.3: Conventional Construction Activities - TT10-2019/BXD - TCVN

Construction Activity Description	Code	Machine
Forming in place, columns	AF.81130	None
Reinforcing in place, columns	AF.61400	23kW Welding Machine 5kW Cutting and Bending Machine
Placing in place, columns	AF.32200	50 m^3/h Concrete Pump 1.5kW Vibrator
Forming in place, beams	AF.81140	None
Reinforcing in place, beams	AF.61500	23kW Welding Machine 5kW Cutting and Bending Machine
Placing in place, beams	AF.32300	50 m^3/h Concrete Pump 1.5kW Vibrator
Forming in place, floors	AF.81150	None
Reinforcing in place, floors	AF.61700	25-ton Tower Crane 3-ton Cage Hoist 5kW Cutting and Bending Machine 50 m^3/h Concrete Pump
Placing in place, floors	AF.32300	50 m^3/h Concrete Pump 1.5kW Vibrator
Forming in place, walls	AF.81300	None
Reinforcing in place, walls	AF.61300	23kW Welding Machine 5kW Cutting and Bending Machine
Placing in place, walls	AF.32100	50 m^3/h Concrete Pump 1.5kW Vibrator

Table 3.4: Prefabrication Activities - RSmean - MasterFormat

Construction Activity Description	Code	Machine
Installing Precast Column	034133.15	1 Lattice Boom Crane, 150 ton
Installing Precast Beam	034133.10	1 Lattice Boom Crane, 150 ton
Installing Precast Hollow Core Plank	034113.50	1 Lattice Boom Crane, 150 ton
Installing Precast Wall	034513.50	1 Lattice Boom Crane, 150 ton

Table 3.5: Prefabrication Activities - TT10-2019/BXD - TCVN

Construction Activity Description	Code	Machine
Installing Precast Column	AG.41100	10-ton Crane 23 kW Welding Machine
Installing Precast Beam	AG.41200	16-ton Crane 23 kW Welding Machine
Installing Precast Slab	AG.21200	Concrete Mixer 250l Cement Pump 6 m^3/h 1.5kW Vibrator
Installing Precast Wall	AG.41500	10-ton Crane 23 kW Welding Machine

different building elements: Columns (3%), Beams (2%), Slabs (1%), and Walls (0.6%).

doi:10.6342/NTU202403587

Table 3.6: Material loss/waste percentage for each construction method

Construction method	Material Loss
Conventional Cast-in-place	5% [17]
Prefabricated	1% [17]

Table 3.7: Reinforcement Ratios for Structural Elements

Building Element	Reinforcement Ratio
Columns	3%
Beams	2%
Slabs	1%
Wall	0.6%

3D concrete printing (3DCP) will only be applied to the wall elements of the framework. The configuration of the printed walls was selected based on standard industry practices in 3DCP [28]. The thickness was set at 300 mm for external walls and 180 mm for internal walls, despite some references indicating thicknesses of 400 mm and 500 mm in existing 3DCP buildings [11] [26]. A layer thickness of 40 mm was chosen within the typical range of 35 mm to 45 mm recorded [26]. The increased thickness in these case studies is due to the incorporation of steel reinforcement for structural elements. However, for this project, a thicker wall is unnecessary as the printed walls, which are unreinforced 3D printed wall, is not the main component to bear the loads.

To calculate the volume of 3DCP walls, first determine the net cross-sectional area by subtracting the area of the voids (triangles) from the total cross-sectional area. With a layer thickness of 40 mm, the volume of 3DCP is calculated as follows:

$$V = S \times 0.12 \tag{3.1}$$

where V is the volume of the 3DCP wall (m^3) and S is the area of the wall (m^2).

By conducting a detailed and accurate quantity takeoff based on the design model and adjusting for waste percentages, the material requirements for each construction method are precisely quantified. This step is critical for the subsequent analysis of carbon emissions, enabling a reliable comparison of the environmental impact of different construction techniques.

3.4 Carbon Emission Estimation

Following the detailed quantification of materials through the quantity takeoff process, the next critical step involves estimating the carbon emissions associated with each construction method. Understanding carbon emissions is essential for evaluating the environmental impact of different construction techniques. This phase focuses on quantifying the

doi:10.6342/NTU202403587

carbon footprint from material production, on-site activities, and transportation, thereby facilitating a comprehensive comparison of the sustainability of each construction method.

The process begins with thorough data collection related to materials, machinery, transportation, and emission factors. From the quantity takeoff results, the total quantity of materials required for each construction method is first identified, including the volume and weight of concrete and rebar for conventional and prefabricated construction and the volume of concrete for 3D concrete printing (3DCP). Accurate quantification of these materials is crucial as it forms the basis for subsequent emission calculations.

Next, the types of machines and equipment required for each construction activity are documented along with their consumption rates, derived from the Building Element and Construction Activities Association results and mechanical parameters published by manufacturers. Table 3.8 shows the information that helps estimate energy usage and associated emissions during on-site construction activities. The types of vehicles used for transporting materials and elements to the construction site are identified, the result is illustrated in table 3.9. The consumption rates of these vehicles are determined based on manufacturer-published information, allowing for accurate calculation of emissions from transportation activities. For conventional cast-in-place concrete elements, transported materials include ready-mixed concrete and steel rebar, which are transported by concrete mixer trucks and dump trucks, respectively. For prefabrication construction, prefabricated building elements are transported by specialized trailers. For 3DCP concrete mixture, the concrete is assumed to be mixed in a nearby concrete factory and transported to the site by concrete mixers.

Table 3.8: Machine/Equipment specs associated with each method process

Machine Type	Resources	Unit	Consumption Rate
Gas Engine Vibrators	Gasoline	l/h	0.71
Concrete Pump (Small)	Diesel	l/h	16
23 kW Welding Machine	Electricity	kW	23
5 kW Cutting and Bending Machine	Electricity	kW	5
50 m^3/h Concrete Pump	Diesel	l/h	10
1.5 kW Vibrator	Electricity	kW	1.5
3-ton Cage Hoist	Diesel	l/h	3.4
25-ton Tower Crane	Electricity	kW	132
1 Lattice Boom Crane, 150 ton	Diesel	l/h	22
10-ton Crane	Diesel	l/h	12
23 kW Welding Machine	Electricity	kW	23
16-ton Crane	Electricity	kW	120
Concrete Mixer 250l	Gasoline	l/h	1
Cement Pump 6 m^3/h	Diesel	l/h	12
1.5 kW Vibrator	Electricity	kW	1.5
Robotic Arm	Electricity	kW.h/m^3	22

doi:10.6342/NTU202403587

Table 3.9: Vehicle specs for transportation

Vehicle	Capacity	Resources	Unit	Consumption Rate
Concrete Mixer Truck	8 m^3	Diesel	l/100 km	30
Trailers	29 tons	Diesel	l/100km	35
Heavy Dump Truck	27	Diesel	l/100km	30

Finally, the carbon emission factors for all materials and resources consumed during the construction and transportation process are gathered. These factors indicate the amount of carbon emissions produced during the production of those materials. Typically, they are sourced from literature, environmental databases, and industry reports. The By integrating these emission factors with the material quantities and consumption rates, the total carbon emissions associated with each construction method can be accurately calculated. The carbon emission factors used in this research are derived from a literature review, indicating the average carbon emissions of resources worldwide, or from technical reports by international organizations. All the carbon emissions is mentioned in table 3.10.

Table 3.10: Carbon emissions factors of material

Material	Unit	Carbon Emissions Factor
Cast-in-place unreinforced concrete	kg CO_2/m^3	340.9 [42]
	kg CO_2/kg	0.136 [42]
Prefabricated unreinforced concrete	kg CO_2/kg	0.178 [17]
Rebar	kg CO_2/kg	1.99 [17]
Wooden Formworks	kg CO_2/m^3	522 [31]
Diesel	kg CO_2/l	2.68 [14]
Gasoline	kg CO_2/l	2.31 [14]
Electricity	kg CO_2/kWh	1.35 [1]

Numerous studies have estimated the carbon emissions for 3DCP concrete, considering various concrete mix components. As a result, 3DCP concrete exhibits different carbon emission factors. For instance, one composition with cement (864 kg/m^3), silica fume (36 kg/m^3), fine aggregate (900 kg/m^3), water (315 L/m^3), and 0.3% admixture has a carbon emission factor of 631 kg CO_2e/m^3. Another mix, consisting of cement (430 kg/m^3), fly ash (170 kg/m^3), fine aggregate (1420 kg/m^3), water (180 L/m^3), and superplasticizer (10 L/m^3), has a lower carbon emission factor of 345 kg CO_2e/m^3. Considering these variations, the average carbon emissions factor for the provided compositions is used in this study to calculate the carbon emissions of a 3DCP wall. This average carbon emissions factor is approximately 440 kg CO_2e/m^3.

Based on the quantity takeoff results, the volume and weight of materials required for each construction method can be estimated, taking into account the waste material percentage. The materials considered include unreinforced concrete and rebar for dif-

doi:10.6342/NTU202403587

ferent construction methods: ready-made concrete and rebar for cast-in-place concrete, unreinforced concrete and rebar for precast, and 3DCP concrete for the 3DCP method. The total quantity of materials is then multiplied by the corresponding carbon emission factors to calculate the total material carbon emissions for each construction method. The formula used for this calculation is as follows:

$$Material\ Emissions = \sum (Material\ Quantity \times Carbon\ Factor) \tag{3.2}$$

Process emissions refer to the carbon dioxide produced during the burning of resources to operate machinery and equipment in various construction phases. Using quantity take-off data, the number of shifts required for each construction activity and the corresponding machinery and equipment are calculated. These calculations are combined with the consumption rates of the machinery and equipment to estimate the total resources required for each construction method. The total quantity of resources is then multiplied by the corresponding carbon emission factors to determine the total process carbon emissions for each construction method. For conventional cast-in-place concrete, process carbon emissions include those generated by the formwork used and consumed during the process. According to Pronk et al., formwork can be reused up to seven times, provided it remains flat and undamaged, and the project characteristics allow for such reuse. However, due to the complex conditions on construction sites, the reuse time of formwork is assumed to be two times. The thickness of wooden formwork is approximately 18 mm. By using this thickness and the formwork area from the quantity takeoff, the volume of formwork can be estimated, and the carbon emissions related to the formwork can be calculated. The formula used for this calculation is as follows:

For conventional construction method:

$$\begin{aligned} Process\ Emissions = & \sum \left(\frac{Work\ Quantity}{Machine\ Norm} \times Consumption\ Rate \times Carbon\ Factor \right) \\ & + (Formwork\ Area \times Thickness \times Carbon\ Factor) \end{aligned} \tag{3.3}$$

For other construction method:

$$Process\ Emissions = \sum \left(\frac{Work\ Quantity}{Machine\ Norm} \times Consumption\ Rate \times Carbon\ Factor \right) \tag{3.4}$$

From the material quantity obtained in the quantity takeoff process, the number of transporting trips is calculated. This is then combined with the vehicles' travel consumption rate to estimate the total resources consumed in the transportation process, and the associated carbon emissions are measured. The formula for calculating transport carbon

doi:10.6342/NTU202403587

emissions is as follows:

$$Transport\ Emissions = \sum \left(\frac{Material\ Quantity}{Truck\ Capacity} \times Consumption\ Rate \times Carbon\ Factor \right) \tag{3.5}$$

The total carbon emissions encompass three main components: material carbon emissions, process carbon emissions, and transport carbon emissions. Material carbon emissions are derived from the production and use of construction materials. Process carbon emissions result from the activities and equipment used during the construction process. Transport carbon emissions are generated from the transportation of materials to the construction site. The formula for total carbon emissions is:

$$\begin{aligned} Total\ Carbon\ Emissions = &\ Material\ Emissions + Process\ Emissions \\ &+ Transport\ Emissions \end{aligned} \tag{3.6}$$

The carbon estimation steps will provide a comprehensive analysis of material quantities, process emissions, transport emissions, and total carbon emissions for each construction method. This detailed assessment will enable accurate comparisons, highlighting the most sustainable construction method.

3.5 Expert Review, Feedback and Model Update

The expert review feedback and model update steps are crucial for validating and refining the carbon emission estimation results. Engaging industry experts ensures that the methodology and findings align with current standards and practices, while the model update step incorporates this feedback to enhance accuracy, reliability and sustainability.

The first step involves selecting experts from academia, industry, and research institutions with relevant expertise in sustainable construction and carbon emissions. Once the experts are identified, detailed reports of the findings are prepared and presented, including all data, methodologies, assumptions, and preliminary conclusions. This thorough presentation ensures that experts have all the necessary information to provide informed feedback.

Following the presentation, detailed comments on data accuracy and project sustainability are collected from the experts. This feedback is essential for identifying any potential gaps or inaccuracies in the initial estimation process, as well as for determining the most sustainable methods for carrying out the construction projects. The next step involves analyzing the feedback and integrating it into the model and methodology. This process ensures that expert suggestions are thoroughly considered and that the necessary improvements are made to enhance the project's sustainability.

doi:10.6342/NTU202403587

Once the feedback is analyzed and integrated, the model update process begins. Necessary modifications to the carbon emission estimation model are implemented based on the expert feedback. It is essential to address all significant points raised by the experts and ensure they are fully incorporated into the updated model to make the project more sustainable.

Finally, if there are major changes, follow-up adjustments are conducted, starting again from the re-definition of construction activities and their associated data, to ensure that the feedback has been appropriately integrated and that the updated model enhances the sustainability of the building project. This rigorous process of expert review and model updating enhances the study's credibility and reliability, ultimately contributing to more sustainable building practices and providing a strong foundation for sustainable construction.

3.6 Comparative Analysis

After finalizing the design model with integrated expert review, it is essential to demonstrate the comparative analysis of carbon emissions to all project members and stakeholders. This ensures a common understanding of the carbon emissions and supports the correct implementation of sustainable practices in the projects. This process involves a detailed examination of the carbon footprints associated with conventional, prefabrication, and 3D printing construction methods.

The comparative analysis begins with data aggregation, where carbon emissions data for each construction method, obtained from previous steps, is consolidated. This includes compiling all relevant emissions data related to materials, processes, and transportation. By centralizing this information, a comprehensive view of the emissions profile for each construction method can be developed. This centralized data aggregation allows for a thorough and accurate comparison of the sustainability of different construction methods.

Using a detailed breakdown of carbon emissions, the consolidated data is analyzed to identify patterns and significant differences in carbon emissions among different construction methods. This analysis highlights specific areas where each method excels or falls short in terms of sustainability. Interpreting the results allows for an understanding of the underlying causes of emission variations and the sustainability implications of each method.

To effectively communicate the findings, visual aids such as charts, graphs, and tables are created to present the comparative analysis results clearly. These visuals highlight key findings and make the comparisons easily understandable.

Finally, the comparative analysis findings are compiled into a comprehensive report. This report summarizes the key insights, patterns, and expert recommendations for the most sustainable construction practices based on the analysis. It outlines the comparative

doi:10.6342/NTU202403587

carbon emissions of each method and provides actionable recommendations for reducing emissions in the construction industry. By offering a detailed comparison and highlighting the most sustainable construction practices, this analysis provides valuable insights on how to make projects more sustainable.

doi:10.6342/NTU202403587

Chapter 4

Case Study

In this chapter, the practical application of the developed model-driven carbon emissions estimation framework is explored by examining its use in two distinct building projects in Taipei, Taiwan. One is a laboratory facility, and the other is a lecture hall of a university. These case studies provide valuable insights into the framework's functionality, accuracy, and practical implications for sustainable construction practices.

The primary objective of these case studies is to evaluate the feasibility and accuracy of the carbon emissions estimation framework when applied to different buildings constructed using various methods. These buildings serve as prime examples of modern, research-oriented facilities, providing an ideal environment to test the framework's capabilities in complex construction scenarios.

To conduct the case studies, detailed structural concrete elements and material data are first collected from the project's Building Information Modeling (BIM) files. This comprehensive data collection ensures that all relevant information is captured for accurate analysis.

Next, the developed framework is utilized to automate quantity takeoff and calculate carbon emissions based on the collected data. The software used in this study is limited to Autodesk Revit.

Finally, the estimated carbon emissions associated with different construction methods are compared to evaluate the sustainability and feasibility of each method. This comparison provides valuable insights into the environmental impact of various construction techniques and helps identify the most sustainable practices for future projects. The calculation is also conducted manually using data-driven methods, with Excel as the base software assisting the manual calculation.

doi:10.6342/NTU202403587

4.1 Case Study of Laboratory Facility

4.1.1 Project information

The project, located at a university in Taipei City of Taiwan, exemplifies modern construction techniques through the use of prefabrication. Spanning a site area of 3719 square meters, this building encompasses a total floor area of 8716 square meters and reaches a height of 35.7 meters. The structure includes eight floors above ground and one floor below ground. Completed between August 2007 and June 2008, this project highlights the efficiency and innovation possible in prefabrication construction practices

Figure 4.1: Case study of laboratory facility

4.1.2 Material Quantity Takeoff

To accurately calculate the materials required for the construction of the building, a detailed quantity takeoff was performed. This process involved listing all the concrete structural elements, including columns, beams, slabs, and walls of the design model.

doi:10.6342/NTU202403587

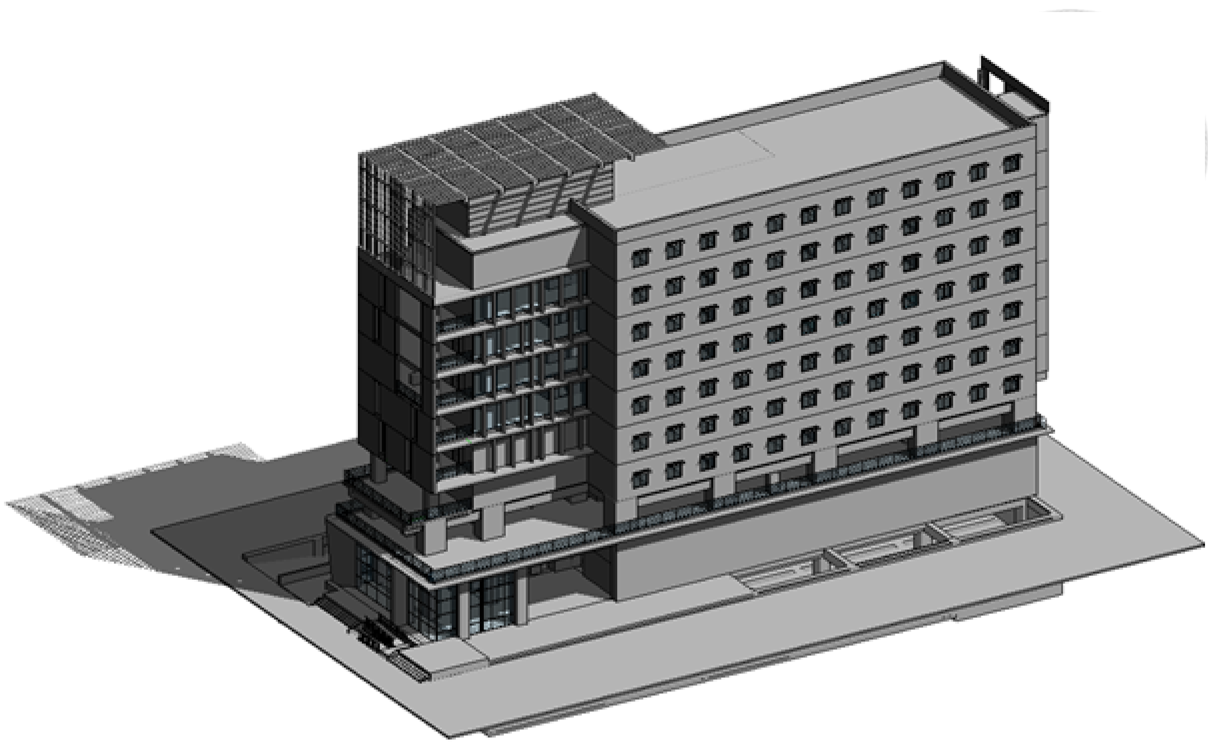

Figure 4.2: Case study of laboratory facility

The volumes of these elements were meticulously calculated and summed to provide a comprehensive overview of the concrete needed.

The estimated volumes were then combined with the waste percentages specific to each construction method to determine the constructed quantity of each type of element. The waste percentages are as follows: 5% for cast-in-place (CIP), 1% for prefabrication, and 0% for 3D concrete printing (3DCP). It is important to note that the 3DCP method is applied exclusively to the walls.

By incorporating these waste percentages, it ensures a more accurate representation of the actual material usage for each construction method. This adjustment is crucial for effective planning and resource allocation in the project's construction phase. Quantity Takeoff of laboratory facility of different construction method. The results are shown in table 4.1.

For 3D Concrete Printing, this technique is only applied to construct wall elements. Applying formula 3.1, with a total wall area of 14,252.48 m^2, the volume of 3D printed walls is 1,710.3 m^3

doi:10.6342/NTU202403587

Table 4.1: Quantity Takeoff of laboratory facility of different construction method

Element	Design		Conventional Cast-in-place			Prefabrication	
	Concrete (m^3)	Rebar (m^3)	Concrete (m^3)	Rebar (m^3)	Formwork (m^2)	Concrete (m^3)	Rebar (m^3)
Columns	1,057.90	31.74	1,110.80	33.33	3,804.99	1,068.48	32.06
Beams	1,302.56	26.05	1,367.69	27.35	6,170.25	1,315.59	26.31
Slabs	2,013.16	20.13	2,113.82	21.14	10,006.24	2,033.29	20.33
Walls	2,017.97	12.11	2,118.87	12.78	28,504.96	2,038.15	12.23
Total	**6,391.59**	**90.03**	**6,711.17**	**94.53**	**48,486.44**	**6,455.51**	**90.93**

4.1.3 Carbon Emissions

Material Emissions

Based on quantity takeoff results for each construction method combined with the carbon emissions factors, the total material required and carbon emissions associated with activities to produce the required material of each construction method are calculated.

Table 4.2: Carbon Emissions by Construction Method

Construction Method	Material	Volume (m^3)	Weight (tons)	Carbon Emission (kg CO_2)
Cast-in-place Concrete	Concrete	6,711.17	16,035.85	2,287,837.68
	Steel (rebar)	94.53	742.07	1,476,723.83
	Total		16,777.92	3,764,561.51
Prefabrication	Concrete	6,455.51	15,424.96	2,745,643.22
	Steel (rebar)	713.80	713.80	752,532.00
	Total		16,138.76	3,498,175.22
3DCP	Concrete	1,710.30	3,933.69	752,532.00

Table 4.2 provides a comprehensive comparison of the material quantities and associated carbon emissions for the laboratory facility using three construction methods: Conventional Cast-in-place, Prefabrication, and 3D Concrete Printing (3DCP). It details the total weight of concrete and rebar required for each method, along with their respective carbon emissions in kilograms of CO_2 equivalent (kg CO_2ee).

The Prefabrication method, although using slightly less concrete overall compared to the Conventional Cast-in-place method (15,424.96 tons vs. 16,035.85 tons), results in higher carbon emissions. The concrete emissions for Prefabrication are 2,745,643.22 kg CO_2ee, compared to 2,287,837.68 kg CO_2ee for Conventional Cast-in-place. Additionally, the rebar emissions are substantial in Prefabrication, totaling 1,420,467.68 kg CO_2ee from 713.80 tons of rebar, compared to 1,476,723.83 kg CO_2ee from 742.07 tons of rebar in Conventional Cast-in-place. The increased emissions in Prefabrication are attributed to the additional carbon footprint from the formwork and the energy-intensive processes of curing concrete during production in a controlled environment.

doi:10.6342/NTU202403587

For the 3DCP method, used only for walls, the concrete required is 1,710.30 cubic meters, with associated carbon emissions of 752,532.00 kg CO_2ee.

This table highlights the significant carbon emissions associated with each construction method. The results emphasize that Prefabrication, while using less concrete, results in more carbon emissions due to the consideration of carbon emissions from formwork and the curing process in the production process.

Process Emissions

Following the detailed analysis of material emissions, the next crucial step in assessing the environmental impact of different construction methods is to evaluate the process emissions. While material emissions account for the carbon footprint associated with the production of construction materials, process emissions focus on the carbon emissions generated during the actual construction activities on-site. This includes emissions from the use of machinery, energy consumption, and various construction processes such as pouring and curing concrete. Examining both material and process emissions provides a comprehensive view of the total carbon footprint for each construction method. This detailed assessment allows for a more informed comparison of the overall sustainability of Conventional Cast-in-place, Prefabrication, and 3D Concrete Printing (3DCP) methods.

To accurately calculate process emissions, the quantity takeoff results and construction standard data are first analyzed to calculate the number of shifts during which construction machines operate. Based on these shifts, the total working hours for each type of machine are estimated. These working hours are then combined with the specific consumption rates of each machine to determine the amounts of resources used during the construction process. By applying the appropriate carbon emissions factors to these resource quantities, the total carbon emissions generated by the machinery are calculated. This thorough approach ensures that all aspects of machine operation and resource consumption are accounted for in the process emissions calculation.

Table 4.3 illustrated the detail of consumed resources and carbon emissions and carbon emissions by construction methods. For cast-in-place concrete methods, the process emissions also include the carbon emissions produced during the manufacturing of formwork used in on-site construction activities. While some studies claim that wooden formwork can be reused up to seven times, due to the complicated conditions on the construction site, the reuse times of formwork in this study are assumed to be two times. The thickness of the wooden formwork is 18 mm. The volume of formwork is calculated by multiplying the area of formwork required by the thickness of the formwork and then multiplying by the carbon emissions factor of the formwork to get the total carbon emissions. Table 4.4 show the calculation of carbon emissions related to formwork used in this case for conventional cast-in-place concrete

doi:10.6342/NTU202403587

Table 4.3: Consumed Resources and Carbon Emissions by Construction Method

Construction Method	Construction Standard	Resources	Unit	Consumed Resources	Carbon Emissions (kg CO_2)
Cast-in-place Concrete	RSmean - MasterFormat	Gasoline	1	6,367.20	14,708.23
		Diesel	1	13,440.00	36,019.20
		Total			50,727.43
	TT10-2019 BXD	Electricity	kW.h	37,708.00	50,905.80
		Diesel	1	17,921.60	48,029.89
		Total			98,935.69
Prefabrication	RSmean - MasterFormat	Diesel	1	12,298.00	32,958.64
		Total			32,958.64
	TT10-2019 BXD	Diesel	1	24,996.00	66,989.82
		Electricity	kW.h	50,044.00	67,559.40
		Total			134,548.68
3DCP	N/A	Electricity	kW.h	37,626.60	50,795.91

Table 4.4: Formwork Carbon Emissions Calculation

Formwork Area (m^2)	Thickness (m)	Formwork Volume (m^3)	Emission Factors (kg CO_2/m^3)	Carbon Emissions (kg CO_2)
48,486.44	0.018	872.76	522	455,578.62

Transport Emissions

After thoroughly examining the material emissions and process emissions associated with different construction methods, it is essential to consider the transport emissions to gain a comprehensive understanding of the total carbon footprint. Material emissions covered the carbon footprint from producing and transporting construction materials, while process emissions focused on the emissions generated during on-site construction activities. Transport emissions, the final component, account for the carbon emissions resulting from the transportation of materials and equipment to the construction site. This includes emissions from vehicles used to transport concrete, rebar, prefabricated elements, and other necessary materials.

For the Conventional Cast-in-place (CIP) method, the calculated materials include ready-made concrete and steel rebar reinforcement. The distance for transporting these materials is assumed to be 10 km due to a lack of specific data. For the Prefabrication method, the transport process includes moving prefabricated concrete elements from the manufacturer which is 60.7 km away from the construction site. For the 3D Concrete Printing (3DCP) method, the special design concrete is made in the factory and transported to the site by concrete mixer truck with the distance also assumed to be 10 km. The calculation is illustrated in table 4.5.

By integrating material, process, and transport emissions, we can accurately assess the environmental impact of each construction method, allowing for a more informed

doi:10.6342/NTU202403587

comparison of their overall sustainability.

Table 4.5: Transportation Carbon Emissions by Construction Method

Construction Method	Material	Unit	Volume	Distances (km)	Total Consumption (l)	Carbon Emissions (kg CO_2)
Cast-in-place	Concrete	m^3	6,711.17	10	2,517.00	6,745.56
	Rebar	tons	742.07	10	84.00	225.12
Prefabrication	Concrete Element	tons	15,515.89	60.7	11,387.32	30,518.02
3DCP	Concrete	m^3	1,710.30	10	642.00	1,720.56

Total Emissions

After individually analyzing the material emissions, process emissions, and transport emissions for each construction method, it is essential to consider the combined impact to understand the total carbon footprint. Material emissions covered the carbon footprint from the production of construction materials, process emissions focused on the emissions generated during on-site activities, and transport emissions addressed the carbon produced by transporting materials to the site. Table 4.6 illustrated the carbon emission related to construction phases of laboratory facilities.

Table 4.6: Carbon Emissions for Cast-in-place Concrete and Prefabrication

Carbon Emissions	**Cast-in-place Concrete**	**Prefabrication**
Material Emissions	3,764,561.51	4,166,110.90
Process Emissions (MasterFormat)	506,306.05	55,658.24
Process Emissions (TCVN)	554,514.31	142,254.48
Transport Emissions	6,970.68	30,518.02
Total (MasterFormat)	4,277,838.24	4,252,287.16
Total (TCVN)	4,326,046.50	4,338,883.40

The total carbon emissions represent the sum of these three components, offering a comprehensive measure of the environmental impact for each construction method: Conventional Cast-in-place (CIP), Prefabrication, and 3D Concrete Printing (3DCP). This complete assessment allows for a thorough comparison of the overall sustainability of each method, revealing which is the most eco-friendly. Understanding the total carbon emissions helps to identify key areas for improvement and develop strategies to minimize the carbon footprint of future projects. The following sections present a detailed analysis of the total carbon emissions, highlighting the contributions from material, process, and transport emissions for each construction technique.

The bar chart in figure 4.3 and table 4.6 together provide a comprehensive comparison of the total carbon emissions for the whole building using two construction methods:

doi:10.6342/NTU202403587

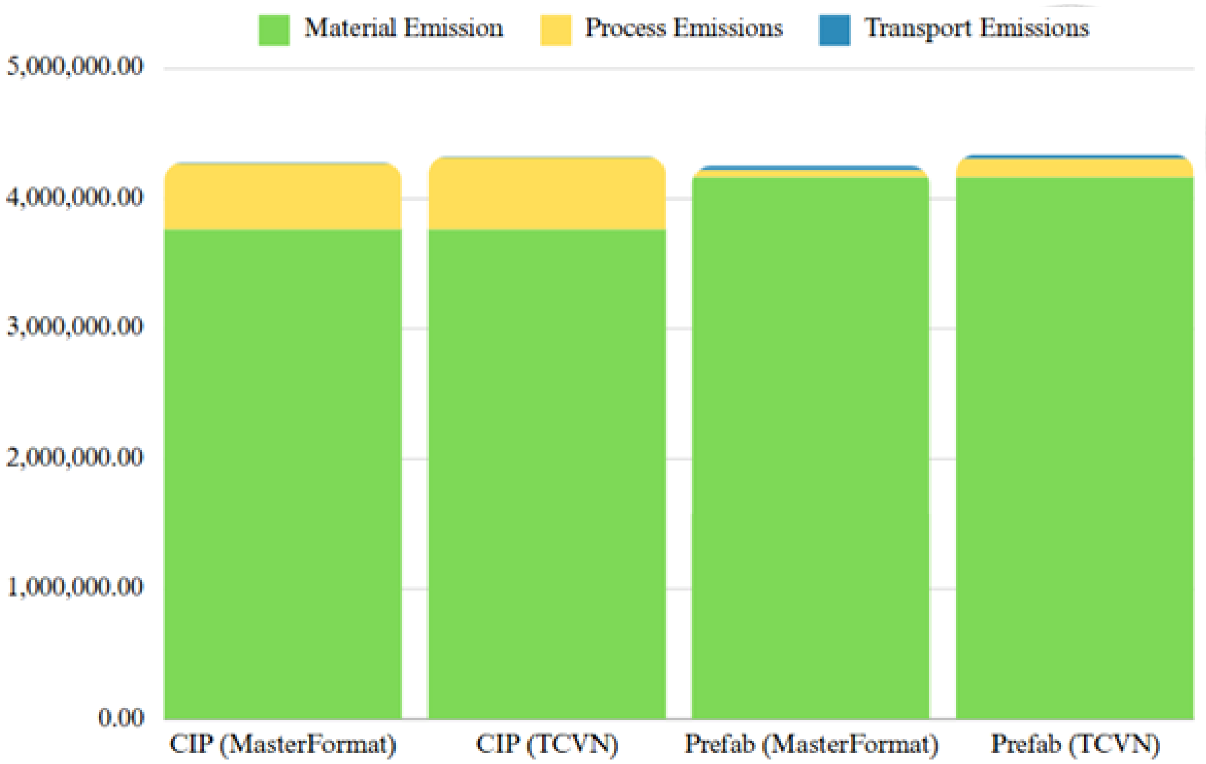

Figure 4.3: Total Carbon Emissions of laboratory facility

Cast-in-place Concrete (CIP) and Prefabrication. Emissions are broken down into three categories: Material Emissions, Process Emissions, and Transport Emissions, with data presented for both MasterFormat and TCVN standards.

For Material Emissions, the chart shows that they constitute the largest portion of the total emissions for both construction methods. CIP has material emissions of 3,764,561.51 kg CO_2, representing about 88-98% of its total emissions. Prefabrication has slightly higher material emissions at 4,166,110.90 kg CO_2e, making up around 94-98% of its total emissions. This dominance of material emissions highlights the significant environmental impact of producing and transporting the concrete and rebar needed for construction.

Process Emissions differ significantly between the two methods. For CIP, process emissions are relatively high, with 506,306.05 kg CO_2e (MasterFormat) and 554,514.31 kg CO_2e (TCVN), constituting approximately 11.8% and 12.8% of the total emissions, respectively. In contrast, Prefabrication shows much lower process emissions: 55,658.24 kg CO_2e (MasterFormat) and 142,254.48 kg CO_2e (TCVN), accounting for only about 1.3% and 3.3% of its total emissions. This difference underscores the efficiency of prefabrication processes in reducing on-site construction emissions.

Transport Emissions are relatively minor for both methods but are notably higher for Prefabrication due to the need to transport prefabricated elements from the manufacturing site to the construction site. CIP transport emissions are minimal, at 6,970.68 kg CO_2e, while Prefabrication transport emissions are higher at 30,518.02 kg CO_2e. Despite

doi:10.6342/NTU202403587

their small contribution to the total emissions (less than 1% for both methods), transport emissions highlight the logistical challenges associated with prefabrication.

Overall, the total carbon emissions are quite similar between the two methods. CIP's total emissions are 4,277,838.24 kg CO_2e (MasterFormat) and 4,326,046.50 kg CO_2e (TCVN). Prefabrication's total emissions are 4,252,287.16 kg CO_2e (MasterFormat) and 4,338,883.40 kg CO_2e (TCVN). The small differences in total emissions, less than 1% between the methods and standards, indicate that both methods have comparable environmental impacts when considering material, process, and transport emissions together.

This analysis highlights the importance of considering all emission sources to fully understand the environmental impact of different construction methods. While CIP and Prefabrication have similar total emissions, the distribution of these emissions across different sources varies significantly, providing insights into where improvements can be made to reduce the overall carbon footprint.

4.2 Case Study of Lecture Hall

4.2.1 Project information

The developed framework was applied to another building – the new-built lecture hall, another building in Taipei, Taiwan. Different from the prefabrication concrete structure of laboratory facility, this building employs a cast-in-place construction method combined with a steel structure, ensuring robustness and durability. Currently in the completion phase, the lecture hall stands as a testament to advanced construction techniques and modern architectural design. This building, along with the laboratory facility, forms part of a broader study aimed at analyzing and comparing carbon emissions associated with different construction methods. The lecture hall, in particular, highlights the application of developed tools when applied to cast-in-place combined with steel structure construction, as well as its application during its construction phases, providing more insights into the environmental impacts of the developed framework.

4.2.2 Material Quantity Takeoff

The table 4.7 provides a comparison of the material quantities needed for the lecture hall across different construction methods: Conventional Cast-in-place, Prefabrication. The table highlights several key points. The Conventional Cast-in-place method requires the highest quantities of concrete and rebar, along with significant formwork, especially for walls, which demand 33163.52 m^2 of formwork. In contrast, Prefabrication uses slightly less concrete and rebar than the Conventional method, indicating more efficient material usage. Notably, 3DCP, which is applied only to walls, shows a significant reduction

doi:10.6342/NTU202403587

Figure 4.4: Case study of lecture hall

Table 4.7: Concrete and Rebar Quantities for Different Construction Methods

Element	Design		Conventional Cast-in-place			Prefabrication	
	Concrete (m^3)	Rebar (m^3)	Concrete (m^3)	Rebar (m^3)	Formwork (m^2)	Concrete (m^3)	Rebar (m^3)
Columns	615.84	18.48	646.63	19.40	4,146.72	622.00	18.66
Beams	304.63	6.09	319.86	6.40	1,713.31	307.68	6.15
Slabs	3,933.67	39.34	4,130.35	41.31	20,622.92	3,973.01	39.73
Walls	3,972.59	23.84	4,171.22	25.03	33,163.52	4,012.32	24.08
Total	**8,826.73**	**87.75**	**9,268.07**	**92.14**	**59,646.47**	**8,915.00**	**88.63**

in concrete usage, with a total of 1989.81 m^3 of concrete needed. Overall, the table emphasizes the material efficiency of Prefabrication and the considerable reduction in concrete required for walls using 3DCP compared to traditional construction methods. For 3D Concrete Printing, applying formula 3.1, with a total wall area of 16,581.76 m^2, the volume of 3D printed walls is 1,989.81 m^3

doi:10.6342/NTU202403587

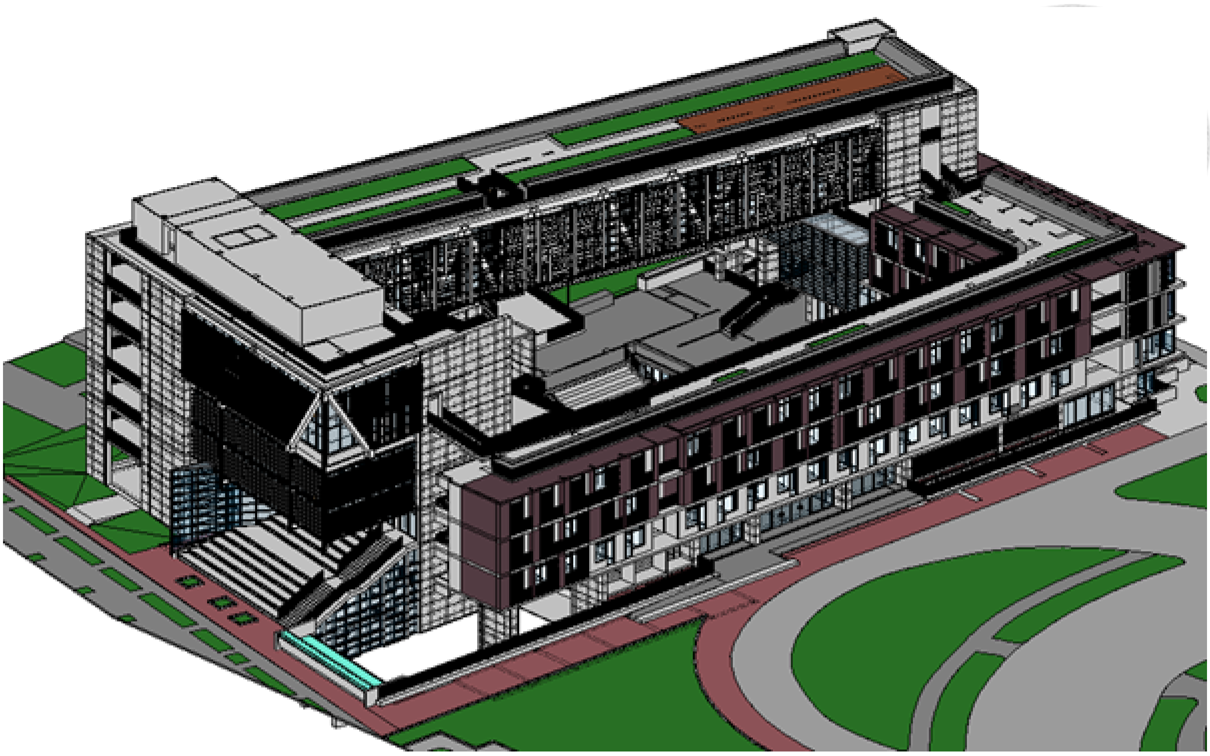

Figure 4.5: BIM model of lecture hall

4.2.3 Carbon Emissions

Material Emission

Table 4.8: Carbon Emissions by Construction Method

Construction Method	Material	Volume (m^3)	Weight (tons)	Carbon Emission (kg CO_2)
Cast-in-place Concrete	Concrete	9,268.07	22,446.91	3,159,483.87
	Steel (rebar)	92.14	723.26	1,439,289.87
	Total		23,170.17	4,598,773.74
Prefabrication	Concrete	8,915.00	21,591.78	3,843,337.70
	Steel (rebar)	695.71	695.71	875,516.83
	Total		22,287.49	4,718,854.53
3DCP	Concrete	1,989.81	4,576.57	875,516.83

The table 4.8 compares the volume, weight, and carbon emissions of materials used in the lecture hall for three construction methods: Cast-in-place Concrete, Prefabrication, and 3D Concrete Printing (3DCP). Cast-in-place Concrete requires the highest volume and weight of materials, leading to total carbon emissions of 4598773.74 kg CO_2. Prefabrication uses slightly less material but results in higher carbon emissions at 4718854.53 kg CO_2. In contrast, 3DCP, used only for walls, requires significantly less concrete, resulting in the lowest carbon emissions of 875516.83 kg CO_2. This table highlights 3DCP's

doi:10.6342/NTU202403587

efficiency in reducing material usage and associated carbon emissions compared to traditional methods.

Process Emissions

Table 4.9: Consumed Resources and Carbon Emissions by Construction Method

Construction Method	Construction Standard	Resources	Unit	Consumed Resources	Carbon Emissions (kg CO_2)
Cast-in-place Concrete	RSmean MasterFormat	Gasoline	1	7,216.16	16,669.33
		Diesel	1	15,232.00	40,821.76
		Total			57,491.09
	TT10-2019 BXD	Electricity	kW.h	35,472.00	47,887.20
		Diesel	1	24,803.20	66,472.58
		Total			114,359.78
Prefabrication	RSmean MasterFormat	Diesel	1	17,138.00	45,929.84
		Total			45,929.84
	TT10-2019 BXD	Diesel	1	34,140.00	91,495.20
		Electricity	kW.h	42,252.00	57,040.20
		Total			148,535.40
3DCP	N/A	Electricity	kW.h	43,775.84	59,097.39

Table 4.9 compares the resources required and carbon emissions during the construction phases of the Study hall for different methods. Cast-in-place Concrete consumes significant gasoline and diesel, resulting in emissions of 57,491.09 kg CO_2 (Rsmean-MasterFormat) and 114,359.78 kg CO_2 (TT10-2019/BXD) due to high electricity and diesel usage. Prefabrication primarily uses diesel and electricity, leading to 45,929.84 kg CO_2 (Rsmean-MasterFormat) and 148,535.40 kg CO_2 (TT10-2019/BXD). 3DCP relies on electricity, with total emissions of 59,097.39 kg CO_2, highlighting it as the method with the lowest emissions.

Table 4.10: Formwork Carbon Emissions Calculation

Formwork Area (m^2)	Thickness (m)	Formwork Volume (m^3)	Emission Factors (kg CO_2/m^3)	Carbon Emissions (kg CO_2)
59,646.47	0.018	1,073.64	522	560,438.20

Table 4.10 provides the calculation of carbon emissions associated with the use of formwork in the lecture hall during cast-in-place concrete construction. The table includes the total formwork area (59646.47 m^2), the thickness of the wooden formwork (0.018 m), resulting in a formwork volume of 1073.64 m^3. With an emission factor of 522 kg CO_2e/m^3, the total carbon emissions from the formwork amount to 560438.20 kg CO_2e. This table highlights the significant impact of formwork on the overall carbon footprint of the construction process.

doi:10.6342/NTU202403587

Transport Emission

Table 4.11: Transportation Carbon Emissions by Construction Method

Construction Method	Material	Unit	Volume	Distances (km)	Total Consumption (l)	Carbon Emissions (kg CO_2)
Cast-in-place Concrete	Concrete	m^3	9,268.07	10	3,477.00	9,318.36
	Rebar	tons	723.26	10	81.00	217.08
Prefabrication	Concrete Element	tons	22,287.49	21.9	5,894.39	15,796.95
3DCP	Concrete	m^3	1,989.81	10	747.00	2,001.96

Table 4.11 compares the resources required and associated carbon emissions during the transport process for different construction methods used in the lecture hall. For Cast-in-place Concrete, the transportation of 9268.07 m^3 of ready-made concrete and 723.26 tons of rebar over a distance of 10 km results in total diesel consumption of 3558 liters and carbon emissions of 9535.44 kg CO_2e. Prefabrication involves transporting 22287.49 tons of concrete elements from other chosen nearby precast and prestressed factory located 21.9 km away from the construction site. This process leads to diesel consumption of 5894 liters and emissions of 15796.95 kg CO_2e. The 3DCP method, used for transporting 1989.81 m^3 of ready-made concrete over 10 km, consumes 747 liters of diesel, resulting in the lowest emissions of 2001.96 kg CO_2e. This table highlights the significant variations in transport emissions among the different construction methods, with 3DCP showing the lowest carbon footprint.

Total Emissions

Table 4.12: Whole Building Carbon Emissions

Carbon Emissions	Cast-in-place Concrete	Prefabrication
Material Emissions	4,598,773.74	5,227,797.48
Process Emissions (MasterFormat)	617,929.29	73,582.08
Process Emissions (TCVN)	674,797.97	164,276.40
Transport Emissions	9,535.44	15,796.95
Total (MasterFormat)	5,226,238.47	5,317,176.51
Total (TCVN)	5,283,107.15	5,407,870.83

The bar chart in figure 4.6 and accompanying table 4.12 provide a comparison of the total carbon emissions for the whole building using two construction methods: Cast-in-place Concrete and Prefabrication. Emissions are broken down into three categories: Material Emissions, Process Emissions, and Transport Emissions, with data presented for both MasterFormat and TCVN standards.

doi:10.6342/NTU202403587

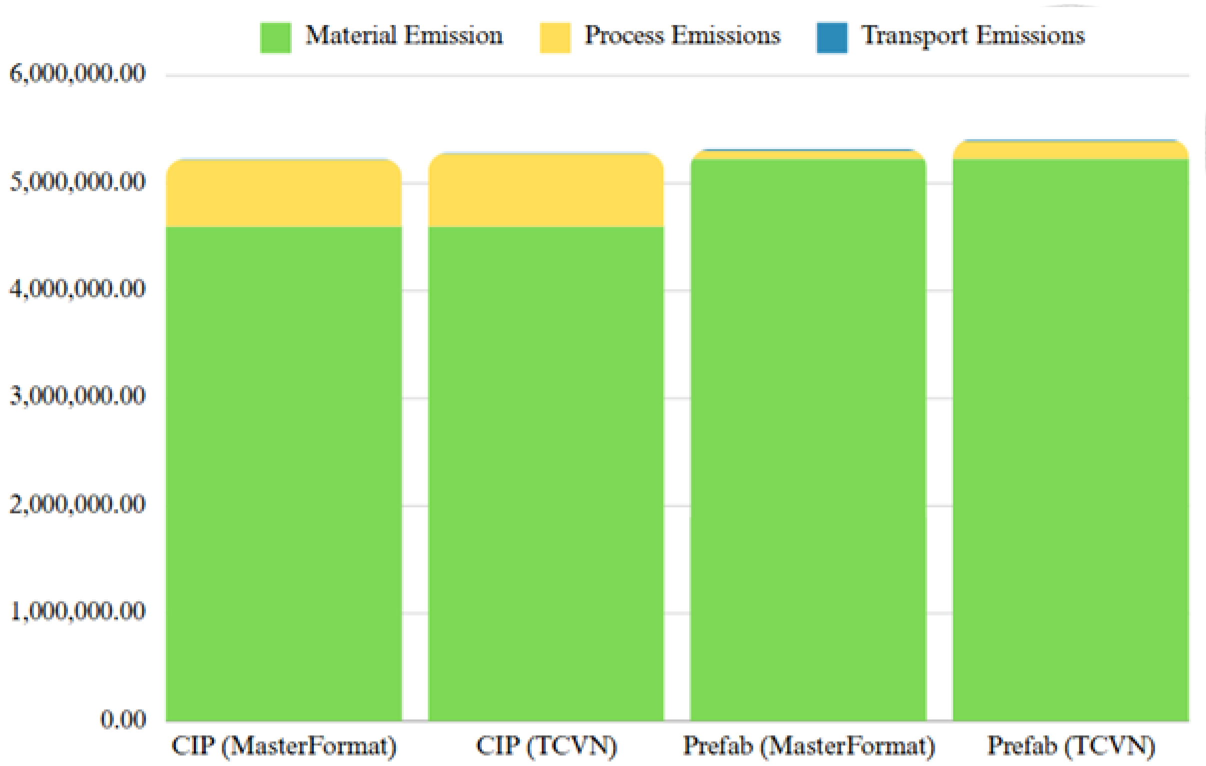

Figure 4.6: Total Carbon Emissions of lecture Hall

For Material Emissions, Prefabrication shows higher emissions at 5227797.48 kg CO_2e compared to Cast-in-place Concrete at 4598773.74 kg CO_2e. Material emissions constitute a significant portion of the total emissions, accounting for approximately 88% of the total for Cast-in-place Concrete and about 98% for Prefabrication under the MasterFormat standard. Under the TCVN standard, the percentages are similar, with material emissions making up about 87% for Cast-in-place Concrete and 97% for Prefabrication.

In terms of Process Emissions, Cast-in-place Concrete has significantly higher values. The process emissions for Cast-in-place Concrete are 617929.29 kg CO_2e (MasterFormat) and 674797.97 kg CO_2e (TCVN), representing approximately 12% and 13% of the total emissions, respectively. In contrast, Prefabrication has much lower process emissions at 73582.08 kg CO_2e (MasterFormat) and 164276.40 kg CO_2e (TCVN), which constitute around 1.4% and 3% of the total emissions, respectively.

Transport Emissions are relatively minor but still noteworthy. For Cast-in-place Concrete, transport emissions are 9535.44 kg CO_2e, making up about 0.18% of the total emissions. Prefabrication has higher transport emissions at 15796.95 kg CO_2e, accounting for approximately 0.3% of the total emissions.

When looking at the Total Emissions, Prefabrication results in slightly higher overall emissions compared to Cast-in-place Concrete. For Cast-in-place Concrete, the total emissions are 5226238.47 kg CO_2e (MasterFormat) and 5283107.15 kg CO_2e (TCVN). For Prefabrication, the total emissions are 5317176.51 kg CO_2e (MasterFormat) and

doi:10.6342/NTU202403587

5407870.83 kg CO_2e (TCVN). This indicates that Prefabrication has a higher carbon footprint by about 1.7% (MasterFormat) and 2.4% (TCVN) compared to Cast-in-place Concrete.

doi:10.6342/NTU202403587

Chapter 5

Discussion

5.1 Carbon Emissions

Through the case studies of the Civil Engineering Research Building and the Liberal Arts Building at National Taiwan University, it can be observed that the emissions from conventional cast-in-place (Cast-in-Place) concrete structures and prefabrication structures are approximately the same. However, these emissions are distributed differently across materials, processes, and transportation.

Figure 5.1 including four pie charts displays the carbon emissions distribution for cast-in-place construction, specifically comparing two different buildings (Laboratory Facility and Study Hall) and two classification systems (MasterFormat and TCVN). Across all four charts, material emissions dominate the total carbon emissions, consistently comprising around 87-88%. Process emissions are a smaller contributor, making up approximately 11.8-12.8% of the total emissions. Transport emissions are minimal and nearly negligible in all cases. These charts highlight that material emissions are the dominant source of carbon emissions, with process emissions also contributing significantly, while transport emissions are relatively minor.

Figure 5.2 illustrated carbon emissions distribution for prefabrication construction. The most notable difference is the higher percentage of material emissions in prefabrication construction, which ranges from 96% to 98.3% compared to 87% to 88% in Cast-in-Place construction. Conversely, process emissions in prefabrication are significantly lower, ranging from 1.3% to 3.3%, while in Cast-in-Place construction, they range from 11.8% to 12.8%.

In prefabrication construction, material emissions are dominated by the production and manufacturing of prefab concrete elements, which include forming, curing, and transporting these elements to the construction site. This consolidation of emissions into the material category explains the high percentage of material emissions in prefabrication.

In Cast-in-place concrete construction, material emissions primarily come from the

doi:10.6342/NTU202403587

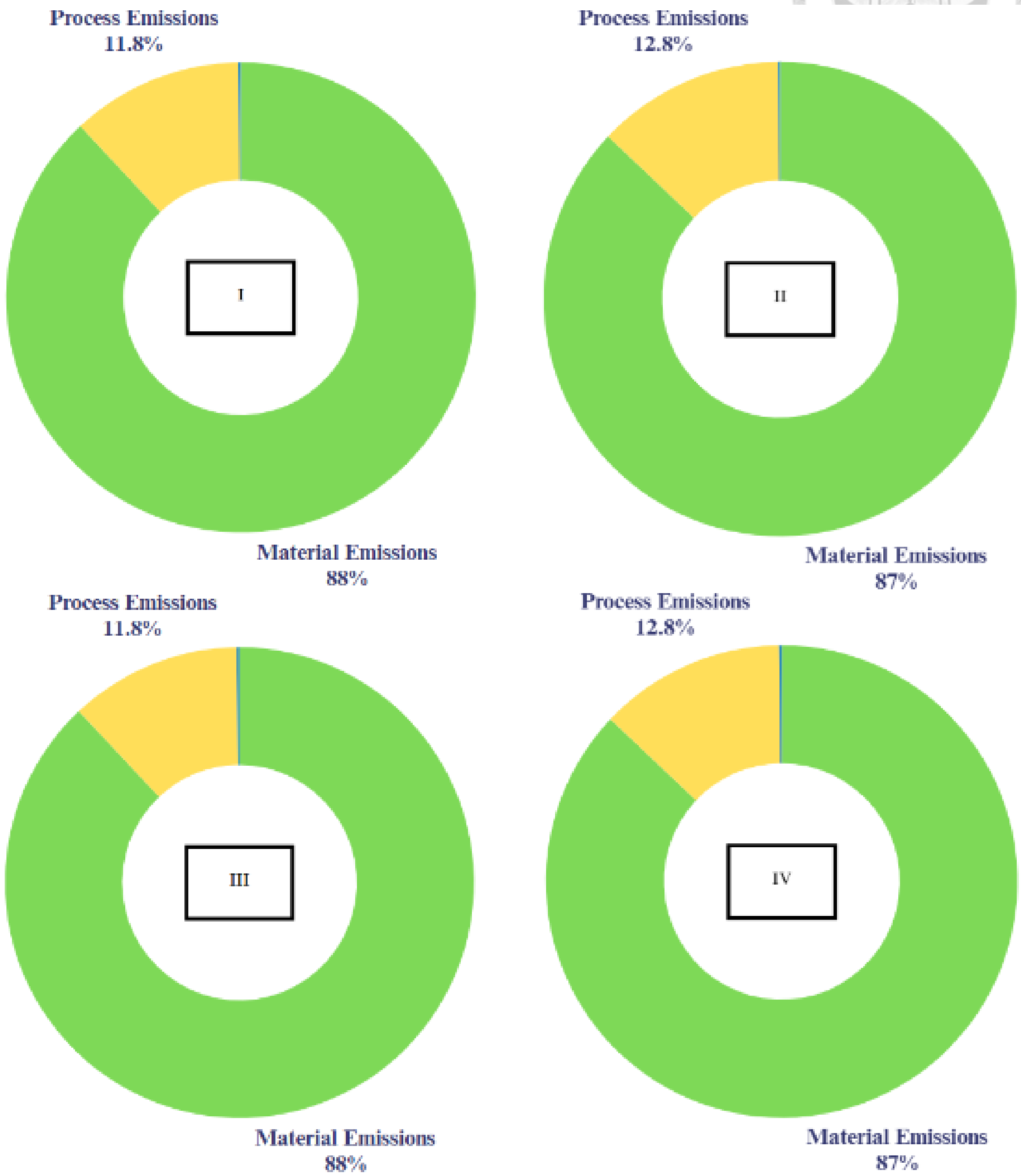

Figure 5.1: Carbon Emissions Distribution for Cast-in-Place Construction (I - Laboratory Facility - MasterFormat; II - Laboratory Facility - TCVN; III- Lecture Hall - MasterFormat; IV - Lecture Hall - TCVN)

doi:10.6342/NTU202403587

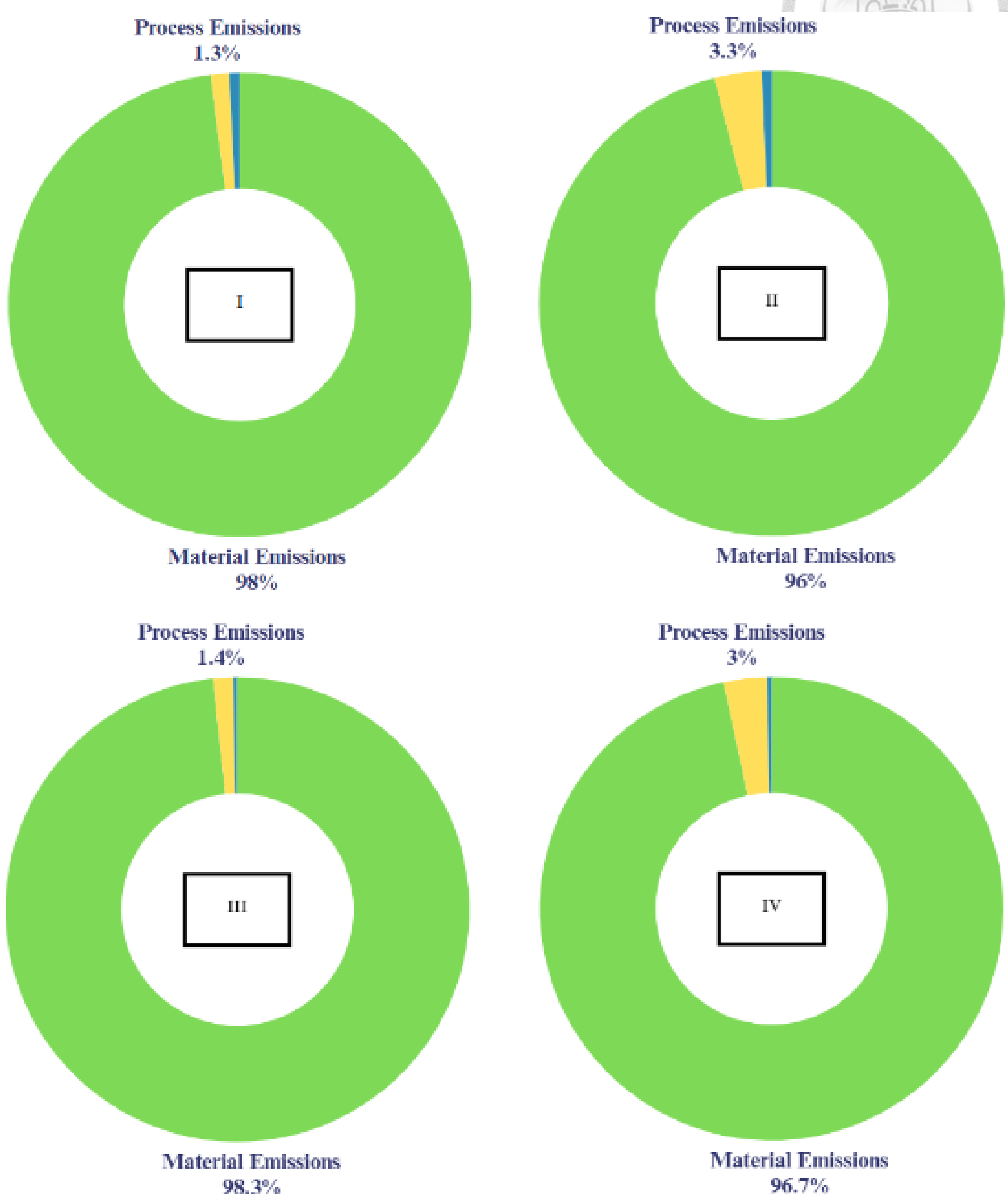

Figure 5.2: Carbon Emissions Distribution for Prefabrication Construction (I - Laboratory Facility - MasterFormat; II - Laboratory Facility - TCVN; III- Lecture Hall - MasterFormat; IV - Lecture Hall - TCVN)

doi:10.6342/NTU202403587

production of ready-made concrete used onsite. However, since formwork and curing processes are considered part of the onsite activities, they fall under process emissions. This distinction in categorization leads to a higher process emissions percentage in Cast-in-Place construction compared to prefabrication.

Prefabrication construction methods demonstrate a substantial reduction in process emissions because the carbon emissions related to forming and curing concrete elements are included in the production and manufacturing of prefab concrete elements. This reduces the need for extensive onsite activities. In contrast, Cast-in-Place construction includes emissions from the formwork consumed in the process, making the onsite processes more labor-intensive and contributing more significantly to carbon emissions.

Both buildings (Laboratory Facility and Study Hall) and classification systems (MasterFormat and TCVN) show similar patterns within each construction method. The carbon emissions related to prefabrication construction are slightly higher than the conventional method, but the difference is minimal. In prefabrication construction, material emissions dominate the total carbon footprint, whereas in Cast-in-Place construction, process emissions have a more significant impact. While the prefabrication method uses less material than the conventional methods, the carbon emission factor associated with the production of elements is significantly higher, which leads to the higher carbon emissions associated with prefabrication methods. Other research by Batikha et al. [27] also showed significantly higher carbon emissions related to material production of prefabrication methods, with around 13.5% of total carbon emissions compared to conventional methods. However, it should be noted that the current research only considers the carbon emissions related to concrete structural elements; overall emissions of the methods need to be studied further to conclude which construction method is more sustainable.

In summary, while prefabrication construction methods offer advantages in reducing process emissions, the high dependency on material emissions necessitates careful material selection to minimize the overall carbon footprint. This comparison emphasizes the importance of adopting sustainable materials and construction practices to achieve more environmentally friendly building processes.

Based on the discussion results and methodology, the general framework is developed and presented in the figure 5.3. This framework outlines the process for calculating and analyzing the carbon emissions of construction activities using a Building Information Modeling (BIM) approach. The process begins with the development of a detailed BIM model for the project. Next, specific construction activities required for different methods are identified and defined. These activities are then matched with established databases and standards to ensure alignment. The necessary machinery and equipment for each activity are determined, followed by a quantity takeoff to measure and quantify the materials and resources needed.

Once the quantities are established, the framework calculates the carbon emissions

doi:10.6342/NTU202403587

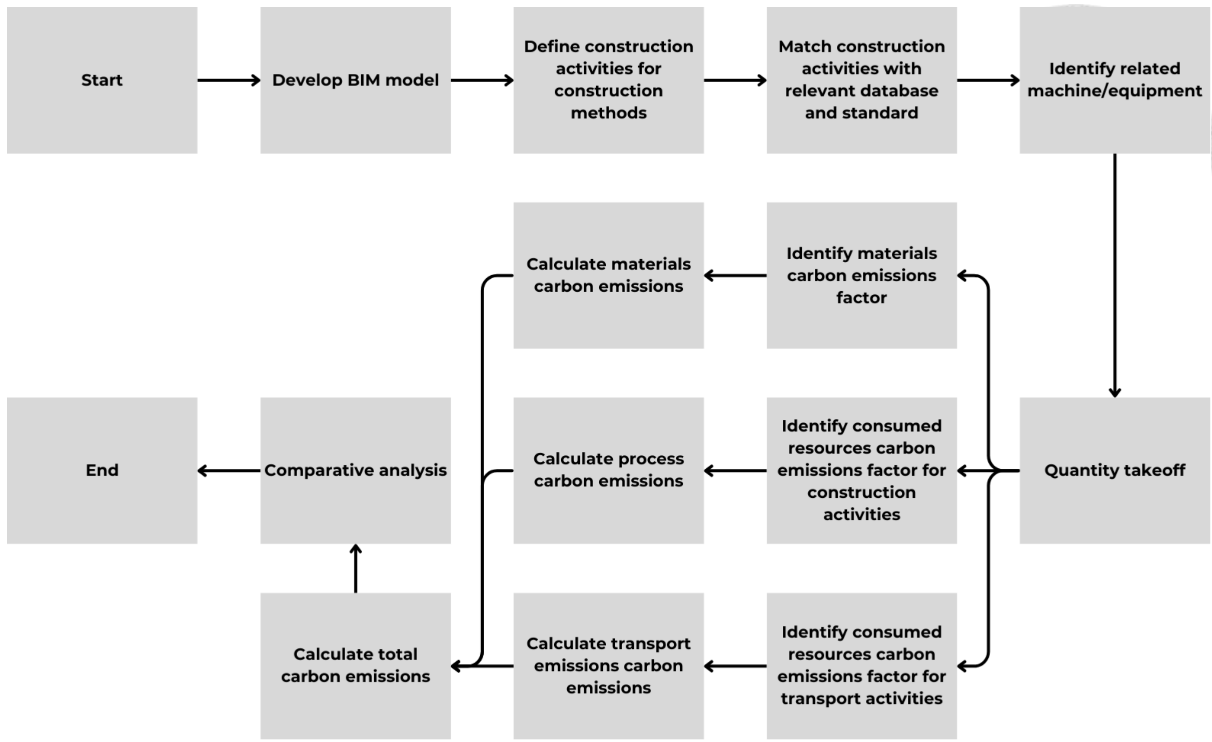

Figure 5.3: General framework for carbon emissions estimation

associated with the materials used, identifying the appropriate emissions factors for each material. It also computes emissions from construction processes, taking into account the emissions factors for resources consumed during these activities. Additionally, the framework calculates emissions from transportation activities, identifying the emissions factors for transport-related resources.

The total carbon emissions are then calculated by summing up emissions from materials, processes, and transport. This comprehensive calculation allows for a comparative analysis of the total carbon emissions of different construction methods, providing insights into their environmental impact. The framework concludes with the completion of this analysis, offering a structured approach to assess and compare carbon emissions across various construction methods.

5.2 3D Concrete Printing Feasibility

3D Concrete Printing (3DCP) has emerged as a groundbreaking technology with significant potential to reduce carbon emissions in the construction industry. The feasibility of 3DCP in achieving these reductions can be illustrated by examining the relative differences in carbon emissions between 3DCP and traditional construction methods, as evidenced by data from the carbon emissions estimation of the Civil Engineering Research Building and Lecture Hall.

doi:10.6342/NTU202403587

The potential and feasibility of 3D Concrete Printing (3DCP) techniques are highlighted through two case studies. When applied exclusively to wall elements, 3DCP demonstrates the lowest emissions among the construction methods.

In the first case study, Material emissions for 3DCP are 752532.00 kg CO_2ee, significantly lower than both Cast-in-Place and Prefabrication. Process emissions for 3DCP are 50795.91 kg CO_2ee, and transport emissions are minimal at 1173.84 kg CO_2ee. The total emissions for 3DCP are 804501.75 kg CO_2ee. This highlights 3DCP's potential as the most sustainable option for wall construction due to its lower overall carbon footprint. Compared to Cast-in-Place and Prefabrication, 3DCP shows a reduction of approximately 33% and 28%, respectively, in total carbon emissions. The result of laboratory facilities is illustrated in table 5.1 and figure 5.4.

Table 5.1: Wall Carbon Emissions by construction method of Laboratory Facility

Carbon Emissions	Cast-in-place Concrete	Prefabrication	3DCP
Material Emissions	920,957.45	1,080,954.23	752,532.00
Process Emissions (MasterFormat)	281,359.95	25,942.40	50,795.91
Process Emissions (TCVN)	291,982.84	65,232.72	N/A
Transport Emissions	1,439.16	10,020.84	1,173.84
Total (MasterFormat)	1,203,756.57	1,116,917.47	804,501.75
Total (TCVN)	1,214,379.45	1,156,207.79	N/A

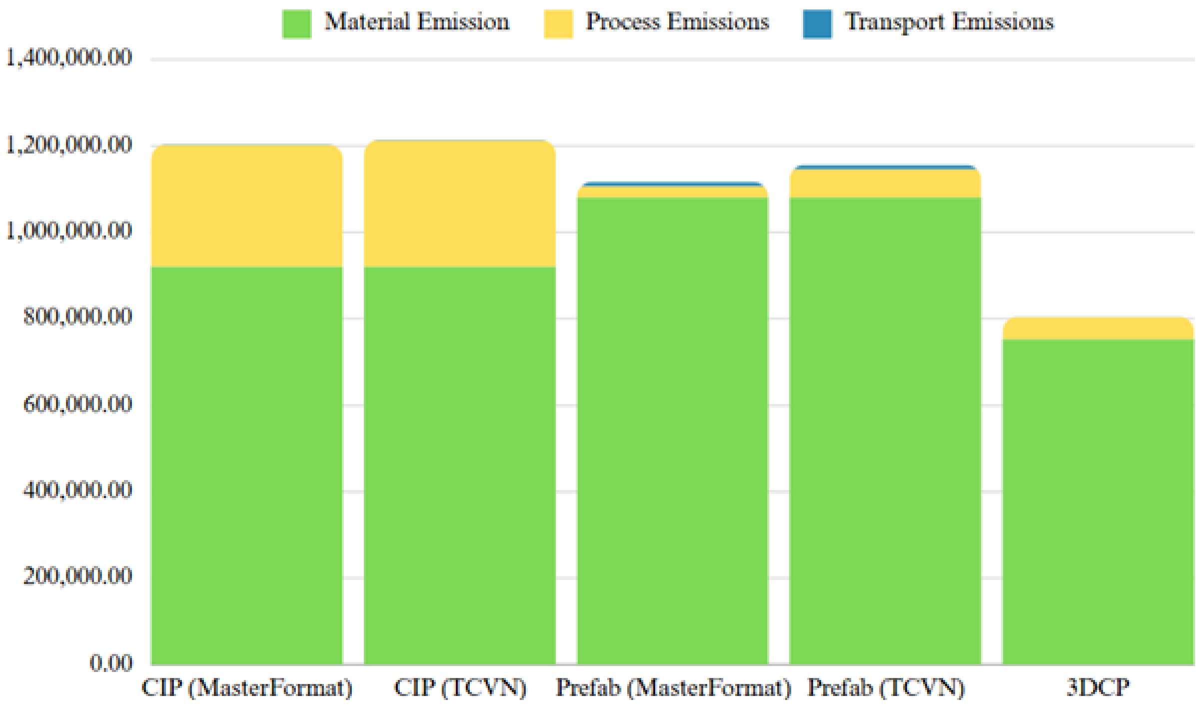

Figure 5.4: Wall Carbon Emissions of Laboratory Facility

doi:10.6342/NTU202403587

For Cast-in-place Concrete (Cast-in-Place), the material emissions are substantial, amounting to 920957.45 kg CO_2ee. Process emissions are also significant, with 281359.95 kg CO_2ee under the MasterFormat standard and 291982.84 kg CO_2ee under the TCVN standard. Transport emissions for Cast-in-Place are relatively low at 1439.16 kg CO_2ee. The total emissions for Cast-in-Place are 1203756.57 kg CO_2ee (MasterFormat) and 1214379.45 kg CO_2ee (TCVN), highlighting the substantial environmental impact of this traditional construction method.

Prefabrication exhibits higher material emissions compared to Cast-in-Place, totaling 1080954.23 kg CO_2ee. However, its process emissions are significantly lower, with 25942.40 kg CO_2ee (MasterFormat) and 65232.72 kg CO_2ee (TCVN). Transport emissions for Prefabrication are higher than Cast-in-Place, at 10020.84 kg CO_2ee, due to the transportation of prefabricated elements from the factory to the construction site. The total emissions for Prefabrication are 1116917.47 kg CO_2ee (MasterFormat) and 1156207.79 kg CO_2ee (TCVN), showing a more efficient but still impactful construction method.

This analysis highlights the efficiency of 3DCP in reducing total emissions, especially in wall construction. Material emissions are the largest contributor across all methods, but 3DCP manages to keep these emissions substantially lower. While Cast-in-Place shows higher process emissions, Prefabrication balances with lower process emissions but higher transport emissions. Overall, the chart and table together effectively illustrate the environmental benefits of adopting 3DCP in construction projects, particularly for wall elements, underscoring its potential for significant carbon footprint reduction.

In the second case study, For Material Emissions, the emissions for Cast-in-Place are 1813006.12 kg CO_2e, constituting approximately 84% of the total emissions under both the MasterFormat and TCVN standards. Prefabrication has higher material emissions at 2127976.55 kg CO_2e, which make up about 98% of the total emissions. In contrast, 3DCP has significantly lower material emissions at 875516.83 kg CO_2e, highlighting its material efficiency. The result of lecture hall is illustrated in table 5.2 and figure 5.5.

Table 5.2: Wall Carbon Emissions by construction method of Lecture Hall

Carbon Emissions	Cast-in-place Concrete	Prefabrication	3DCP
Material Emissions	1,813,006.12	2,127,976.55	875,516.83
Process Emissions (MasterFormat)	338,175.91	31,602.56	59,097.39
Process Emissions (TCVN)	358,898.20	79,391.76	N/A
Transport Emissions	4,261.20	7,107.60	2,001.96
Total (MasterFormat)	2,155,443.23	2,166,686.71	936,616.17
Total (TCVN)	2,176,165.51	2,214,475.91	N/A

In terms of Process Emissions, Cast-in-Place shows significantly higher values with 338175.91 kg CO_2e (MasterFormat) and 358898.20 kg CO_2e (TCVN), accounting for

doi:10.6342/NTU202403587

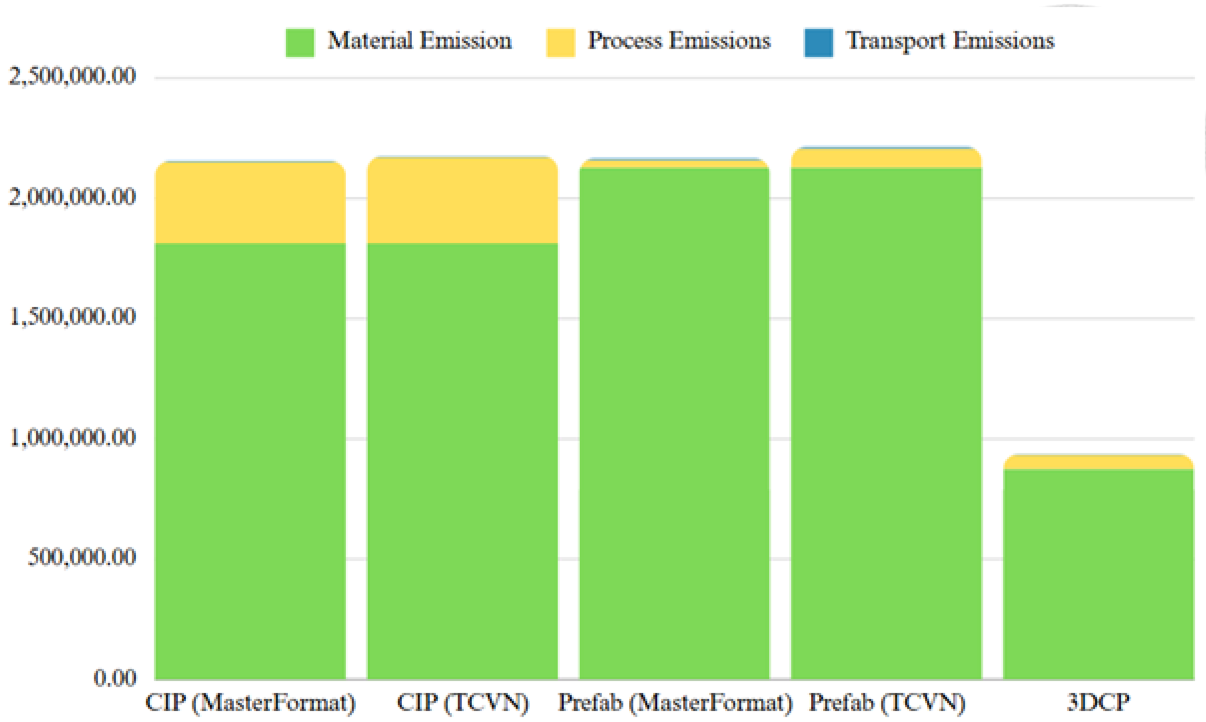

Figure 5.5: Wall Carbon Emissions of Lecture Hall

roughly 16% of the total emissions. Prefabrication's process emissions are much lower at 31602.56 kg CO_2e (MasterFormat) and 79391.76 kg CO_2e (TCVN), representing about 1.5% and 3.6% of the total emissions, respectively. 3DCP has process emissions of 59097.39 kg CO_2e, which is about 6.3% of its total emissions.

Transport Emissions are relatively minor but noteworthy. For Cast-in-Place, transport emissions are 4261.20 kg CO_2e, making up about 0.2% of the total emissions. Prefabrication has higher transport emissions at 7107.60 kg CO_2e, which is around 0.3% of the total emissions. 3DCP, with transport emissions of 2001.96 kg CO_2e, accounts for about 0.2% of its total emissions, reflecting the reduced need for material transportation.

When looking at the Total Emissions, 3DCP stands out with the lowest emissions at 936616.17 kg CO_2e. This is a significant reduction compared to Cast-in-Place, which has total emissions of 2155443.23 kg CO_2e (MasterFormat) and 2176165.51 kg CO_2e (TCVN). Prefabrication, although more efficient in process emissions, still has higher total emissions at 2166686.71 kg CO_2e (MasterFormat) and 2214475.91 kg CO_2e (TCVN). In percentage terms, 3DCP results in approximately 57% lower total emissions compared to Cast-in-Place and 58% lower compared to Prefabrication.

Efficiency in Material Usage

One of the primary benefits of 3DCP is its ability to optimize material usage. Traditional construction methods, including Cast-in-Place and prefabrication, often result in

doi:10.6342/NTU202403587

significant material waste, with Cast-in-Place having a waste percentage of 5% and prefabrication at 1%. In contrast, 3DCP employs precise deposition techniques, using only the necessary amount of material for each structural element. This precision minimizes waste and reduces the overall carbon footprint associated with material production and transportation.

Although the carbon emissions of 3DCP concrete are higher than normal ready-made concrete used in Cast-in-Place (440 kg CO_2e/m^3 vs. 340 kg CO_2e/m^3), the elimination of the need for reinforced rebar results in significantly lower total material emissions. For example, the provided data on the Lecture Hall and Laboratory Facility walls show that material emissions for 3DCP are relatively lower by 50% compared to traditional methods and by 25% compared to prefabrication. By reducing waste and eliminating the need for rebar, 3DCP can significantly lower these material emissions, contributing to more sustainable construction practices.

Reduction in Process Emissions

The automation inherent in 3DCP also leads to a substantial reduction in process emissions. Traditional methods, particularly Cast-in-Place, involve labor-intensive onsite activities that contribute significantly to carbon emissions, including the use of formwork, curing processes, and the movement of materials on the construction site. Prefabrication methods have already shown a reduction in these emissions, but 3DCP can push this reduction even further. By automating the construction process and eliminating the need for extensive formwork and onsite curing, 3DCP minimizes process emissions. For example, the provided data on the Lecture Hall and Laboratory Facility walls indicate that process emissions for 3DCP are approximately 90% lower than Cast-in-Place methods and about 60% lower than prefabrication methods. This significant reduction makes 3DCP a more environmentally friendly option.

Comparative Emissions Data

The provided tables serve as an illustration of how 3DCP can achieve lower carbon emissions compared to traditional methods. In the case of the Lecture Hall and Laboratory Facility walls, material emissions are shown to be the largest contributor to total carbon emissions in both traditional and prefabrication methods. For the Laboratory Facility, traditional construction methods (MasterFormat) result in approximately 84.48 kg CO_2e/m^2, while using the TCVN classification results in about 85.21 kg CO_2e/m^2. Prefabrication methods show a reduction, with emissions of 78.38 kg CO_2e/m^2 (MasterFormat) and 81.12 kg CO_2e/m^2 (TCVN). By leveraging the precision in material usage, 3DCP can further reduce these emissions. 3DCP results in carbon emissions of approximately 56.47 kg CO_2e/m^2.

doi:10.6342/NTU202403587

3DCP offers significant potential for enhancing sustainability, efficiency, and design flexibility in the construction industry. Its ability to reduce material waste, lower labor costs, and accelerate construction timelines makes it a viable alternative to traditional construction methods. However, it is important to note that the current analysis applies specifically to concrete walls. Further studies are needed to explore the application of 3DCP techniques to other structural elements. Additionally, there is a lack of building standards and design manuals for designing and constructing 3DCP structures. Addressing these challenges is essential for the broader adoption of 3DCP and realizing its full potential in reducing the carbon footprint of construction projects.

5.3 Limitation

While this study provides a comprehensive analysis of carbon emissions across different construction methods, several limitations must be acknowledged. These limitations may impact the accuracy, generalizability, and practical implementation of the findings. Understanding these constraints is crucial for interpreting the results within the appropriate context.

Firstly, the scope of construction elements analyzed in this study is specifically limited to concrete structural elements, including columns, beams, slabs, and walls. Other components, such as stairs and finishing layers, are not included in the carbon emissions estimation. Therefore, the results may not fully represent the total emissions for entire buildings or other structural configurations.

The feasibility of 3D Concrete Printing (3DCP) explored in this research is limited to wall elements. Further studies are required to understand the application of 3DCP to other structural elements like columns and beams. Additionally, there is a lack of established building standards and design manuals specific to 3DCP. This limitation affects the ability to standardize and validate the construction processes and structural performance of 3DCP structures. The absence of these guidelines may also hinder the broader adoption of 3DCP in the construction industry.

The study primarily focuses on environmental impacts and does not comprehensively address the economic aspects of adopting different construction methods. Factors such as cost-efficiency, initial investment, and long-term financial benefits are not thoroughly analyzed, which could influence the practicality and attractiveness of these methods in real-world applications. Moreover, the framework assumes the use of current standards and technologies. While these are based on recent databases, they may not reflect the latest advancements or future developments in construction methods. Any technological improvements or changes in construction practices could alter the carbon emissions associated with these methods.

The accuracy of the carbon emissions estimates heavily relies on the quality and avail-

doi:10.6342/NTU202403587

ability of data from construction databases and standards. Inaccurate or incomplete data can affect the reliability of the results. The study uses specific data sources, and any variations in these sources could lead to different outcomes. Additionally, the results of this study may not be fully generalizable to all types of construction projects or geographic locations. Local variations in construction practices, materials, and regulations can influence the carbon emissions of different construction methods. Therefore, the findings should be interpreted with caution when applied to different contexts.

Lastly, the calculation of carbon emissions in this study does not consider the emissions associated with the movement of materials on the construction site. This exclusion simplifies the calculation process but may omit a minor component of the total emissions.

By acknowledging these limitations, the study provides a transparent basis for its findings and highlights areas where further research is needed. Addressing these limitations in future studies will be essential for developing a more comprehensive understanding of the carbon emissions associated with different construction methods and enhancing the developed framework to assist in the process of carbon emissions estimation.

doi:10.6342/NTU202403587

Chapter 6

Conclusion

6.1 Conclusion

This research aimed to develop a comprehensive, BIM-based framework for estimating and comparing the carbon emissions associated with different construction methods, specifically traditional cast-in-place, prefabricated, and 3D concrete printing (3DCP). Through a detailed methodology involving quantity takeoff, material estimation, and carbon emissions calculation, valuable insights were provided into the environmental impacts of these construction methods.

3DCP demonstrated the highest material efficiency with almost no material waste, followed by prefabrication, which also showed significant waste reduction compared to traditional methods. The structural and material usage aspects varied significantly across different construction methods. 3DCP was particularly notable for its ability to minimize material waste, which directly contributes to lower carbon emissions. In contrast, traditional methods resulted in higher material usage and waste, negatively impacting their environmental footprint.

A detailed breakdown of carbon emissions was conducted across different construction methods, focusing on three primary components: material production, transportation, and on-site construction activities. In terms of material production emissions, 3DCP had significantly lower emissions due to precise control over material use and reduced waste during the production process. Despite benefiting from optimized factory conditions that reduce waste, prefabrication showed the most material emissions among the three methods. While the waste percentage of the cast-in-place construction method is the highest, this method showed moderately lower emissions compared to prefabrication methods. This difference is due to the carbon emissions related to forming and curing concrete being included in the material emissions for prefabrication construction methods, whereas these emissions are categorized as process emissions for cast-in-place methods.

On-site construction emissions were lowest for 3DCP, attributable to the reduced need

doi:10.6342/NTU202403587

for heavy machinery and less energy-intensive processes. Prefabrication had moderate on-site emissions, involving the assembly of prefabricated elements. Traditional cast-in-place methods had the highest on-site emissions due to the extensive use of heavy machinery and the emissions related to consumed wooden formwork. Regarding transportation emissions, 3DCP minimized these emissions as the process required fewer materials and less frequent deliveries. Prefabrication had the highest transportation emissions, with factory-produced elements needing to be transported to the site. Despite these differences in construction phases, the comparative analysis revealed that the total carbon emissions for prefabrication and conventional methods were consistent, based on the hypothesis that architectural aesthetics and HVAC utilities remain the same.

The developed BIM-based framework proved to be highly effective in improving the accuracy and reliability of carbon emissions estimation in construction projects. By integrating detailed 3D models with construction standards and databases, the framework enabled precise quantity takeoff, material estimation, and emissions calculation. This comprehensive approach ensured that stakeholders in the construction industry could access reliable data on the carbon emissions of different construction methods, facilitating more informed decision-making for sustainable construction practices.

This research supports the feasibility of 3DCP as a sustainable alternative to traditional and prefabricated construction methods, particularly for wall elements. Its material efficiency and lower carbon emissions make it a promising technology for future construction projects. However, the lack of standardized methods and regulations for 3DCP presents a significant barrier to its widespread adoption. Developing standards and building codes specific to 3DCP is crucial for ensuring its safe and effective implementation. Additionally, the integration of BIM with carbon emissions estimation frameworks proved highly effective in enhancing the accuracy and reliability of the analysis. BIM's capability to provide detailed material and energy simulations is invaluable for sustainable construction practices.

6.2 Future Direction

To build on the findings of this study and address its limitations, several future research directions are recommended. These directions will enhance the understanding of carbon emissions in construction and the feasibility of advanced construction technologies like 3D Concrete Printing (3DCP).

Firstly, future research should focus on refining the current framework for estimating carbon emissions. This includes improving the accuracy of data and addressing any identified gaps. Enhancements in the framework will provide more reliable and comprehensive assessments of carbon emissions in construction.

Expanding the scope of the framework is also crucial. The current framework primar-

doi:10.6342/NTU202403587

ily focuses on concrete structural elements. Including other components, such as stairs and finishing layers, will provide a more comprehensive analysis of the carbon emissions of each construction method. Additionally, 3DCP currently focuses only on walls. Future studies should investigate the carbon emissions, structural integrity, and feasibility of 3DCP for additional elements to provide a more holistic view.

Conducting a detailed economic analysis of different construction methods, including cost-efficiency, initial investment, and long-term financial benefits, will provide valuable insights into their practical viability. Comparative studies between different construction methods in terms of economic factors will help stakeholders make informed decisions.

As construction technologies evolve, it is important to continually update the carbon emissions framework to incorporate the latest advancements. Future research should consider the impact of new materials, construction techniques, and technological innovations on carbon emissions and overall sustainability.

Expanding the scope of carbon emissions analysis to include a full lifecycle assessment (LCA) of buildings will provide a more holistic view of environmental impacts. This should cover all phases, from material extraction and manufacturing to construction, operation, and end-of-life disposal or recycling.

Conducting case studies applying different construction standards will help understand the local variations in carbon emissions. This will improve the generalizability of the findings and provide region-specific insights.

Including the emissions associated with the movement of materials on construction sites in future studies will provide a more accurate estimation of total carbon emissions. This addition will refine the current framework and offer a more detailed analysis.

Long-term studies that monitor the performance, durability, and environmental impact of 3DCP structures over time will provide valuable data on their sustainability and practical application. These studies will help assess the long-term benefits and potential challenges associated with 3DCP.

By pursuing these future directions, researchers can address current gaps, enhance the understanding of 3DCP, and contribute to the development of more sustainable and efficient construction practices. This will ultimately support the transition towards a greener and more innovative construction industry.

doi:10.6342/NTU202403587

References

[1] U.S. Energy Information Administration. Carbon dioxide emissions coefficients. Technical report, U.S. Energy Information Administration, 2023.

[2] Will Arnold. The structural engineer's responsibility in this climate emergency. *The Structural Engineer*, 2020.

[3] Fumin Ren Yanxi Chen Quanze Zhao Shenhao Li Yang Lin Beijia Huang, Jinming Lei. Contribution and obstacle analysis of applying bim in promoting green buildings. *Journal of Cleaner Production*, 2021.

[4] Alain Guiavarch Bruno Peuportier, Stéphane Thiers. Eco-design of buildings using thermal simulation and life cycle assessment. *Journal of Cleaner Production*, 2013.

[5] Tomo Cerovsek. A review and outlook for a 'building information model' (bim): A multi-standpoint framework for technological development. *Advanced Engineering Informatics*, 2011.

[6] PCI Industry Handbook Committee. *PCI Design Handbook Precast and Prestressed Concrete*. PCI, 2010.

[7] Brian H.W. Guo Fatma Abdelaal. Stakeholders' perspectives on bim and lca for green buildings. *Journal of Building Engineering*, 2022.

[8] United Nations Environment Programme Global Alliance for Buildings and Construction. 2022 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. Technical report, United Nations Environment Programme (2022), 2022.

[9] United Nations Environment Programme Global Alliance for Buildings and Construction. Global status report for buildings and construction - beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector. Technical report, United Nations, 2024.

[10] K.M. Fowler and E.M. Raunch. *Sustainable Building Rating Systems Summary.* Pacific Northwest National Laboratory, 2006.

doi:10.6342/NTU202403587

[11] Veronica Soebarto Wassim Jabi Hashem Alhumayani, Mohamed Gomaa. Environmental assessment of large-scale 3d printing in construction: A comparative study between cob and concrete. *Journal of Cleaner Production*, 2020.

[12] Nandini Agarwal Helen Burmeister and Tobias Hausotter. Mastering the transition towards energy efficiency in the buildings sector: The european union's energy performance of buildings directive https://commission.europa.eu/.

[13] Brian Uy Huu-Tai Thai, Tuan Ngo. A review on modular construction for high-rise buildings. *Structure*, 2020.

[14] International Energy Agency: IEA. Co2 emissions in 2023, a new record high, but is there light at the end of the tunnel? Technical report, International Energy Agency: IEA, 2024.

[15] ASTM International. *ASTM F2792-12a, Standard Terminology For Additive Manufacturing Technologies.* ASTM International, 2012.

[16] Roman Putanowicz Izabela Hager, Anna Golonka. 3d printing of buildings and building components as the future of sustainable construction? *Procedia Engineering*, 2016.

[17] Orlando Gibbons John Orr and Will Arnold. A brief guide to calculating embodied carbon. *The Structural Engineer*, 2020.

[18] Kyle W. Williams Greg Sloditskie Julie B. Zimmerman John Quale, Matthew J. Eckelman. Construction matters: Comparing environmental impacts of building modular and conventional homes in the united states. *Journal of Industrial Ecology*, 2012.

[19] Limao Zhang Xianguo Wu Kai Guo, Qing Li. Bim-based green building evaluation and optimization: A case study. *Journal of Cleaner Production*, 2021.

[20] Mohammad Kamali and Kasun Hewage. A framework for comparative evaluation of the life cycle sustainability of modular and conventional buildings. In *Modular and Offsite Construction (MOC) Summit Proceedings*, 2015.

[21] Le Viet Hung Vu Van Linh Nguyen Huy Bien Nguyen Van Tuan Ta Phuong Bao Nguyen Cong Hau Le Trung Thanh, Le Cao Chien. Development of a printer and a high performance concrete for 3d printing technology. In *2nd ACF Webinar, 3D Printing and Construction Automation*, 2022.

[22] Qibo Liu and Zixin Wang. Green bim-based study on the green performance of university buildings in northern china. *Energy, Sustainability and Society*, 2022.

doi:10.6342/NTU202403587

[23] Jack C. McCormac and Russell H. Brown. *Design of Reinforced Concrete*. Wiley, 2013.

[24] Ali Rajabipour Cat Kutay Milad Bazli, Hamed Ashrafi. 3d printing for remote housing: Benefits and challenges. *Automation in Construction*, 2023.

[25] Zubair Ahmed Memon Lokman Hakim Ismail Mohammed F. Al Kazee Qadir Bux alias Imran Latif Nur Izzi Md Yusoff Moad Alosta Mohmed Solla, Ahmed Elmesh and Abdalrhman Milad. Analysis of bim-based digitising of green building index (gbi): Assessment method. *Buildings MDPI*, 2022.

[26] Sameh El-Ashri Musa Alawneh, Motasem Matarneh. The world's first 3d–printed office building in dubai. In *2018 PCI/NBC*, 2018.

[27] Mohamad Yasser Baaj Ibrahim Mousleh Mustafa Batikha, Rahul Jotangia. 3d concrete printing for sustainable and economical construction: A comparative study. *Automation in Construction*, 2022.

[28] C. Bouyssou A. Mallet Ph. Roux M. Zakeri J. Dirrenberger N. Gaudillière, R. Duballet. Building applications using lost formworks obtained through large-scale additive manufacturing of ultra-high-performance concrete. In *3D Concrete Printing Technology*, 2019.

[29] Lu Na. Investigation of the desginers' and general contrators' perceptions of offsite construction techniques in the united states construction industry. Master's thesis, the Graduate School of Clemson University, 2007.

[30] Christine Pasquire Nick Blismas and Alistair Gibb. Benefit evaluation for off-site production in construction. *Construction Management and Economics*, 2007.

[31] Rebekah Bramwell Eirini Karagianni Nikolas Hill, Eugenia Bonifazi and Billy Harris. *2018 GOVERNMENT GHG CONVERSION FACTORS FOR COMPANY REPORTING Methodology paper for emission factors: final report.* Crown, 2018.

[32] Department of Economic and Social Affairs. United nations' sustainable development goals https://sdgs.un.org/goals.

[33] Department of Economic and Social Affairs United Nation. World urbanization prospects the 2018 revision. Technical report, United Nations, 2019.

[34] Changhai Peng. Calculation of a building's life cycle carbon emissions based on ecotect and building information modeling. *Journal of Cleaner Production*, 2016.

[35] O. Pons. Assessing the sustainability of prefabricated buildings. In *Eco-efficient Construction and Building Materials*, 2014.

doi:10.6342/NTU202403587

[36] Frank Schultmann Rebekka Volk, Julian Stengel. Building information modeling (bim) for existing buildings — literature review and future needs. *Automation in Construction*, 2014.

[37] Sara Wilkinson Richard Reed, Anita Bilos and Karl-Werner Schulte. International comparison of sustainable rating tools. *Journal of Sustainable Real Estate*, 2020.

[38] Lavinia Chiara Tagliabue Simona Roggeri1, Paolo Olivari1. Green and transportable modular building: a prefabricated prototype of resilient and efficient house. *IOP Publishing*, 2021.

[39] Magnus Sparrevik and Simon Utstøl. Assessing life cycle greenhouse gas emissions in the norwegian defence sector for climate change mitigation. *Journal of Cleaner Production*, 2020.

[40] International Standard. *ISO 29481-1:2010, Building information modelling — Information delivery manual.* International Standard, 2010.

[41] International Standard. *ISO 17296-2:2015, Additive manufacturing — General principles.* International Standard, 2015.

[42] Sung Joon Suk George Ford Tae Hyoung Kim, Sung Ho Tae and Keun Hyek Yang. An optimization system for concrete life cycle cost and related co2 emissions. *Sustainability MDPI*, 2016.

[43] Ajaz Ahmad Mir Toiba Tabassum. A review of 3d printing technology-the future of sustainable construction. In *Materials Today: Proceedings*, 2023.

[44] UNFCCC. The paris agreement - publication. In *Paris Climate Change Conference - November 2015*, 2018.

[45] Nada Kassim Walaa S.E. Ismaeel. An environmental management plan for construction waste management. *Ain Shams Engineering Journal*, 2023.

[46] Alastair Watson. Digital buildings – challenges and opportunities. *Advanced Engineering Informatics*, 2011.

[47] Wann-Ming Wey and Kuei-Yang Wu. Interdependent urban renewal project selection under the consideration of resource constraints. *Sage Journals*, 2008.

[48] Guiwen Liu Asheem Shrestha Jinxi Jing Yingbo Ji, Kaijian Li. Comparing greenhouse gas emissions of precast in-situ and conventional construction methods. *Journal of Cleaner Production*, 2018.

doi:10.6342/NTU202403587

[49] Vivian W.Y. Tam Yu Bian Shenghan Li I.M. Chethana S.Illankoon Sungkon Moon Zhikun Ding, Ze Fan. Green building evaluation system implementation. *Building and Environment*, 2018.

doi:10.6342/NTU202403587