

ENVIRONMENTAL IMPACTS OF PREFABRICATED CONSTRUCTION:
CO₂ EMISSIONS COMPARISON OF PRECAST AND CAST-IN-PLACE CONCRETE
CASE STUDY

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Abstract

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Construction activities are one of the major contributors to climate change by greenhouse gas emissions. While the use of prefabrication has certain advantages in terms of environmental impacts through material and time efficiency, it is not clear nor has enough data for the quantities and factors comparing the conventional methods. This study aims to review the characteristics of prefabricated construction and to find environmental impacts through the case study. The methodology is the analysis by comparing the carbon emissions of precast concrete which is one of the major prefabricated structures and cast-in-place concrete which is conventional methods. The case study data is based on residential buildings which were built by prefabricated structures in South Korea. The comparison is conducted focused on several scenarios according to the criteria for precast concrete construction such as loss rate of materials, delivery distance, vehicle capacity, equipment types and installation hours. The outcomes are found that the amount of

carbon emissions of precast and cast-in-place concrete for the studied residential buildings. Based on the research findings, it is recommended to adopt precast concrete in building construction in terms of environmental impacts during the product stage and construction stage. However, these averages can be a significant variation among individual projects. The far distance, small vehicle capacity and low efficiency of equipment with a loss of material can adversely affect the environment. The building industry should consider the carbon reduction as a benefit of implementing prefabricated construction after considering the characteristics of the location, distance, transportation method, and installation efficiency.

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CHAPTER 1. INTRODUCTION

1.1 Background

Nowadays, there is no question that public health and environmental system are endangered by climate change. It's impacts have become more apparent, now more than ever.

The earth's climate is changing, due largely to greenhouse gas emissions from human industry. These human-generated gases derive in part from aspects of the built environment such as transportation systems and infrastructure, building construction and operation, and land-use planning (Yonger et al., 2008). However, not many construction management research studies have focused on sustainability and climate change in order to determine the impact and correlation of the environment and construction industry, therefore they require both broad and specialized studies with various perspectives.

Climate change, the most serious threat to human society, is ironically, a threat that human society has created itself. Global atmospheric concentrations of greenhouse gases (GHGs) have increased since 1750, notably carbon dioxide (CO₂) the most predominant greenhouse gas by volume. Emissions of CO₂ from fossil fuel combustion, in conjunction with that emitted from cement manufacture, are responsible for more than 75% of the increase in atmospheric CO₂ since the pre-industrial 18th century (Monahan and Powell, 2011). The CO₂ is generated during construction, that is, during the manufacturing, transportation, production, and installation of the building members, which are used to construct new buildings (Ramesh et al., 2010).

There are many factors to be considered and made decisions for a construction project.

Traditionally, construction activities were designed and developed without considering their

adverse impacts on the environment. However, recently many countries and cities are requiring eco-friendly built environments as the economies develop. One of the environmentally friendly construction methods is prefabricated construction. Prefabricated or modular construction has gradually been replacing the traditional on-site construction due to the benefits provided, a notably faster time, reduced costs, better work quality, and fewer environmental impacts. Also, prefabricated construction guarantees more control over the quality of components and safety of the construction process (Molavi and Barral, 2016).

Modular building is one promising technique to lower the impacts of construction and is utilized for various building types, including single-family homes, multifamily housing, hotels, dormitories, and various commercial and retail structures. Modular construction is a form of prefabrication that involves the creation of discrete volumetric sections of buildings that are transported to a site and assembled into a complete building (Quale et al., 2012).

1.2 Research Purpose and Organization

Although prefabricated construction is generally known as environmentally friendly, there are still various factors affecting the environment which require further study. Especially, the environmental trade-off effects between off-site and on-site construction as they are not investigated thoroughly enough. Therefore, it is part of the effort to find the environmental impacts of building construction to guide decision making. The researcher reviewed the characteristics of prefabricated construction through literature, articles, and cases to find the environmental impacts of prefabricated construction.

This paper has organized a total of 9 Chapters. The definition of terms and typical characteristics

of prefabricated construction are described in Chapter 2, and then the significant characteristics and example cases of prefabricated construction were reviewed and explained from Chapter 3 to Chapter 6. In Chapter 7, in order to analyze the environmental impacts, CO₂ emissions had compared to precast concrete which is presented as the prefabrication process and cast-in-place (CIP) concrete which is presented as the conventional process. The case study was focused on the amounts of CO₂ emissions conducted based on the reviewed existing knowledge and collected data. The research findings and discussions were covered in Chapter 8, and the conclusion was described in Chapter 9.

CHAPTER 2. DEFINITION

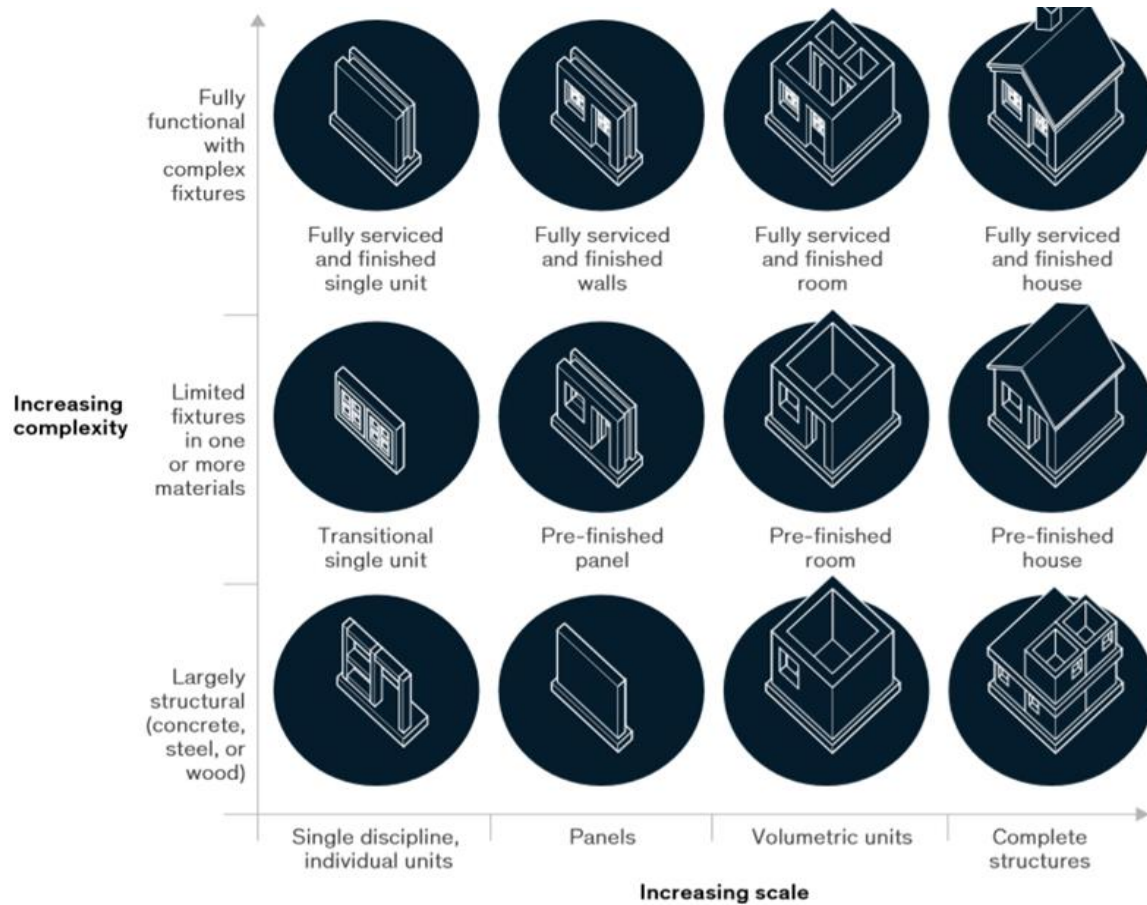
2.1 Prefabricated Construction and Modular Construction

Prefabrication construction can be defined as different words in through situation and approach. There are several definitions used and depend on each construction industry and perspectives on the complexities or characteristics. For instance, prefabrication is defined as a manufacturing process that generally happens at a specialized factory where various materials are combined to form a component in the final installation downstream (Pen et al., 2019; Taum et al., 1987).

Figure 1 shows the complexity and scale degrees of prefabrication according to the components and units. Additional examples of definitions are that Off-Site Construction (OSC), Permanent Modular Construction (PMC), Off-site Prefabrication, and Prefabricated Prefinished Volumetric Construction (PPVC) are some terms used interchangeably in literature to describe prefabricated construction.

In broad terms, modular construction involves producing standardized components of a structure in an offsite factory, then assembling them onsite. Terms such as offsite construction, prefabrication, and modular construction are used interchangeably and cover a range of different approaches and systems. These systems vary depending on the complexity of the elements being brought together. The simplest are single elements that are clipped together using standard connections and interfaces. (Bertram et al., 2019)

In this paper, it is referred to as Prefabricated Construction in general which is in terms of the case including prefabricated structures. Modular Construction also has used the term for the cases including the volumetric modular characteristic especially.



(Source: McKinsey Capital Projects & Infrastructure)

Figure 1. Complexity and Scale of Modular Construction Comparison of Approaches

2.2 Typical Characteristics of Prefabricated Construction

It is well known that prefabricated or modular or construction has gradually replaced the traditional on-site construction due to the benefits provided, a notably faster time, reduced costs, better work quality, and fewer environmental impacts. Prefabricated construction guarantees more control over the quality of components and safety of the construction process. In a precast concrete construction, for instance, precast members require highly skilled workers, more complex techniques, and more complex design. Because the design professionals need to

concentrate on perfecting the modular design, the intensive administrative work may be neglected (Molavi and Barral, 2016). Such complexity and quality control can be likely more efficient through the prefabricated process in the factory than on-site.

In general, the modules or prefabricated components are produced off-site in a factory environment without exposure to weather. Panelized systems are associated with the off-site construction technique, where individual wall sections are manufactured without factory assembly. Unlike in panelized or component-based methods of prefabrication, in modular construction, most of the interior and exterior finishes are put into place by the factory. The modules are transported to the building site 80% to 90% complete, where they are assembled and finished. Because the modules can be constructed while the site and foundation are being prepared, instead of after, modular construction is thought to reduce construction times by 30% to 50% (Quale et al., 2012; Smith, 2010).

In terms of the delivery methods, modular construction is an innovative, sustainable construction delivery method utilizing offsite, lean manufacturing techniques to prefabricate whole building solutions in deliverable module sections. This process permits constructing a building under controlled conditions in a factory, using the same materials and designed to the same building codes and standards as conventionally constructed buildings, but in about half the time. (The Ultimate Guide to Modular Construction, 2019)

Another significant characteristic of prefabricated construction is on the design repeatability. Due to the benefit of the same design and codes, prefabrication or modular buildings are adopting a wide project. In particular, it has further opportunities on healthcare facilities, college buildings and dormitories and manufacturing buildings types that included data centers, prison, power plants, and oil refineries. This characteristic has associated with the scheduling and

productivity of the whole project. According to the article from Smart Market Report by McGraw Hill construction, when deciding whether or not to use prefabrication or modularization, the most important factor is the job site accessibility followed closely by the number of building stories and the type of building exterior (Bernstein, 2011).

CHAPTER 3. TYPES OF PREFABRICATION

3.1 Structural Type of Prefabrication

3.1.1 Steel Frame

- Steel frame modular construction is efficient for a high-rise building. The cost-effectiveness can be enhanced due to the number of repeated modular structures. In terms of the cost and time saving, the steel frame modular can be the appropriate decision by building high-rise. However, the connection and joint methods are complex and remain to solve the on-site process. There are not many buildings built yet a high-rise building, the construction industry is not familiar and confident for high-rise buildings so far. Figure 2 is one of the highest modular buildings in the U.S.
- The steel frame can reuse or recycle with a higher ratio than any other materials. With steel frames, the walls and roof frames typically joined by using fasteners, bolts, and rivets. Therefore, at the end of life, steel can be easily disassembled and be highly recyclable.
- Generally, the weight of a steel modular unit is about 15t to 20t, which is 20 to 35% lighter than a concrete modular unit with a weight of about 20t to 35t. Moreover, the concrete module has generally more constraints for the open space at the structural design than steel structures. Whereas steel modular systems have more flexibility in architectural design owing to the open space framing system and larger modular sizes with beam span ranging from 6m to 12m (Liew et al., 2019).



B2 Pacific Park, Brooklyn (<http://www.fulcro.co.uk/>)

The B2 Pacific Park project in Brooklyn is the world's tallest volumetric modular building, with 32 stories, 363 apartments, and 930 modules. The tower was built by Forest City Ratner Companies, with modules constructed in the Brooklyn Navy Yard, before being shipped to site to be erected.

Figure 2. Steel Frame Modular Building

3.1.2 Wood Frame

- Until the late 1980s, wood-framed buildings with more than two stories were prohibited by building regulations in most European countries, due to the negative perceptions arising from historic city fires. However, driven by the construction Products Directive adopted towards functional criteria, as opposed to prescriptive criteria, thus allowing a larger number of stories with a wooden frame throughout Europe. (Nord et al., 2010; Östman and Källsner, 2011; E. Hurmekoski et al., 2015)
- In general, wood is recognized for its sustainability, overall low environmental impact, natural beauty, and speed of construction than concrete and steel frame. For instance, cross-laminated timber (CLT) which is a new option for construction mass timber building offers advantages including renewability of the raw material and low carbon footprint.
- In the prefabricated process, the wood-frame is automated to the max compared to concrete or steel frame and can be reduced the cost and time for prefabrication and installation because of the lightweight and high machinability.



Student housing with wooden modules in Hamburg, (<https://www.detail-online.com/>)

Prefabricated apartment modules out of cross-laminated timber have found use for student housing in Hamburg's Wilhelmsburg district thanks to intense collaboration between the client, the architects at Sauerbruch Hutton, and Kaufmann Bausysteme, the manufacturer of the modules. A limited number of structural details and restriction to only two module types have brought about a building that is as efficient as it is inexpensive.

Figure 3. Wood Frame Modular Building

3.1.3 Concrete Frame

- Major precast concrete components in building construction are precast facades, staircases, parapets, partitions walls, semi-precast slabs. In the precast concrete construction, precast structural members require more complex design and skilled members for assembly the prefabricated components on the site.
- Concrete modular construction is well known for better fire performance and better

water-tightness, durable, sound-proof and fire-resistance than other material frames. On the other hand, they are required heavy equipment and vehicles to control the modules due to the weight of concrete modular and heavy volume.

- Concrete modular systems are preferable in residential buildings because they are perceived to have better sound and thermal insulation and ease of maintenance. Concrete modules are less stringent in terms of manufacturing and construction tolerances as their joints are made by grouting the gaps between the modules and hence on-site correction can be done during module placement (Liew et al., 2019).



Habitat 67 (Montreal, Quebec), <http://www.metromont.com/>

Designed by architect Moshe Safdie as part of his McGill University master's thesis, Habitat 67 was intended as model housing complex and community building and was constructed to serve as a pavilion during 1967's World's Fair held in Montreal. Habitat 67 utilizes over 350 uniform prefabricated concrete forms put together in a variety of combinations to form the overall 12-story structure. The complex was designed to bring together the benefits of urban and suburban living in one building. Today, Habitat 67 is regarded as an important architectural landmark, and it has become one of Canada's most significant and recognizable buildings.

Figure 4. Concrete Frame Modular Building

3.2 Fabrication Type and Logistics

3.2.1 Panelized Type

- Panelized prefabrication is a construction method where the structural components of a building, such as walls, roofs, and floor systems are constructed off-site in a factory. And then it is delivered to the job site to be incorporated into the building and finished conventionally on-site. Generally, the panels are structural elements and have the very little infrastructure or other components built into them.
- The panels are generally “bare” meaning that they will include the structural members pre-built so that a wall or floor can come off a truck and be placed into the building. Once in place, these panels need to be connected or fastened to other structural components in the field, and generally finished in a conventional way. Wall finishes, plumbing fixtures, electric and other infrastructure are usually not pre-installed, and need to be installed, connected and finished in the field. Panelized buildings, therefore, require a considerable amount of on-site work, but less work than if it were all stick-built in the field. This system works best for buildings that require wide open spaces and high ceilings. (Deluxe Modular, 2019)
- Using panelized exterior walls are more efficient because construction is possible in weather unfavorable to site cast concrete, and because the danger of scaffold work is eliminated. The main disadvantage to these wall panels is the difficulty transporting, connecting, and erecting panels that may be numerous due to structural limitations (Building construction: principles, materials, and systems, 2013; Molavi and Barral, 2016).
- The assembly work onsite of panelized components is much simpler than a conventional

construction, but it is more complex than building together and requires more finishing or assembling activities on the site. On the other hand, it is much easier to transport a panelized type than volumetric. Also, the panelized type can offer greater flexibility than volumetric modules.

3.2.2 Volumetric Type

- Modularization is a construction method where an entire unit of a building is constructed off-site, rather than smaller, structural components as with panelization. Volumetric Modular units require the least amount of on-site construction time, because all plumbing, electrical, and even design finishes have typically already been installed in the facility. This leaves only the task of assembling the modular units together to form a completed building.
- Modular buildings are very versatile and can be designed and built to serve virtually any function. They are particularly well suited, though, for buildings such as hotels, apartments, student housing, and any other types that typically consist of many repetitive units serving similar functions (Deluxe Modular, 2019).
- Volumetric construction encourages high prefabrication rate as the modules are completed with finishes and mechanical, electrical, and plumbing (MEP) in the controlled environment in the factory.

3.2.3 Logistics

The transport method is closely related to the geographical characteristic of project site and the type of structure. The benefit of fabricated construction is greater when the distance between off-

site construction and job site is closer. The owner can save the delivery time and cost from factory to on-site. Depends on the selection of the transport method, the schedule and cost can be affected even though project sites are the same locations.

- **Geographical Characteristic:** The both of distance and location are significant issues for delivering the prefabricated structure. Because many big cities exist and developed near the coast, this geographical characteristic can be the advantage to deliver the volumetric type structure at once. Therefore, in the case the modular manufacturer is located near the coast, the shipping by sea will be the reasonable method to deliver the volumetric modular structures.
- **Prefabrication Size:** According to the panelized and volumetric type and size, transportation efficiency is decided. The panelized type can be reduced the total delivery distance and times, while the volumetric type requires the limited size and weight for delivery efficiency.
- **Storage Capacity:** Delivery method and scheduling should be considered with the storage capacity on-site conditions. If there is not enough storage area when the modules have arrived on site, the advantages of the delivery efficiency of modular construction are invalid.
- **Traffic Rules:** According to the local regulation, the traffic rules on the road and required permits should be reviewed before the planning of modular construction. The road conditions and limitations such as overhead bridges, the narrow width of the road, or road surface can affect the project schedule and cost.



Keetwonen Container Housing project in Holland
(<https://www.keetwonenforsale.com/>)



Panelized module transportation
(<https://www.geo-metrix.ca/>)



Volumetric module transportation and stacking on construction site using a tower crane
(McGraw-Hill Construction, 2011)

Figure 5. Transport Method of Panelized type and Volumetric type

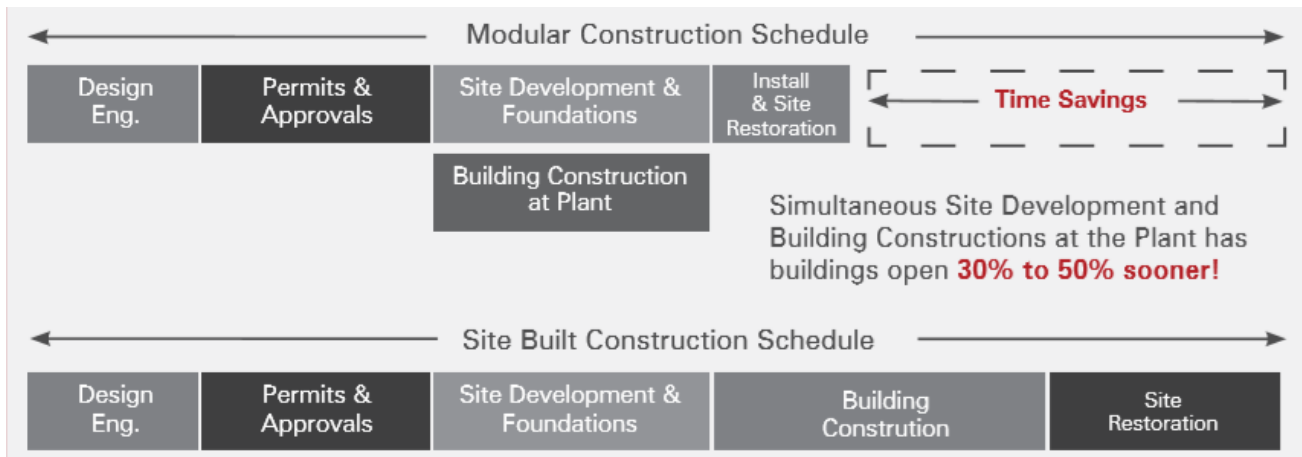
CHAPTER 4. PREFABRICATED CONSTRUCTION CONSIDERATION

Construction management can be demonstrated as construction productivity - how well, how quickly, and at what cost buildings and infrastructure can be constructed - directly affects prices for homes and consumer goods and the robustness of the national economy. Construction productivity will also affect the outcomes of national efforts to renew existing infrastructure systems; to build new infrastructure for power from renewable resources; to develop high-performance “green” buildings; and to remain competitive in the global market. Changes in building design, construction, and renovation, and in building materials and materials recycling, will be essential to the success of national efforts to minimize environmental impacts, reduce overall energy use, and reduce greenhouse gas emissions (NSTC, 2008; MBI, 2010).

4.1 Schedule

The greatest benefit of modularization is in time saved during construction. Modular construction reduces construction time by as much as 50%, which translates to an average of a 9-month construction period as compared to an 18-month construction period, according to the Modular Building Institute (MBI). This is because the modular units can be constructed in the factory all while on-site preparation and construction of the foundation occur. For example, the Hilton Palacio del Rio Hotel in San Antonio, Texas, was built in 1968 for the Texas World’s Exposition of 1968; it is a 500-room deluxe hotel designed, completed, and occupied in 202

working days (Boafo et al., 2016). Quite recently, a Chinese company has built a 57 story, 800 apartment building (called Mini Sky City) in just 19 working days in the Human provincial capital of Changsha. It was roofed in February 2015 (Boafo et al., 2016). Modular construction is less affected by the changeable weather environments, the process can be completed as planned than on-site construction.



(Source: Modular Building Institute)

Figure 6. Streamlined Construction Process

Modular Building Institute describes that there are four stages that make up factory-built construction. First, design approval by the end-user and any regulating authorities; second, assembly of module components in a controlled environment; third, transportation of modules to an ultimate destination; and fourth, erection of modular units to form a finished building (MBI, 2010). The modular construction schedule has benefits for the fast track process. While modules are being assembled in a factory, site work can be accruing at the same time. This permits earlier building occupancy and contributes to a much shorter construction period, reducing financing and supervision costs. In order to reduce the construction schedule, the coordination with subcontractors is required to thoroughly be reviewed and planned in the early stage.

4.2 Cost

The cost of prefabrication can be both an advantage and disadvantage depending on the project conditions and applied components. Cost advantages related to the factory nature of prefabrication include avoidance of construction site hindrances and cheaper labor rates for factory workers as opposed to site workers. Less onsite work contributes to cost savings from project delivery typically provided by modular building systems decrease construction overhead costs and financial liability. Another potential cost advantage is an increase in competition for fabrication and assembly contracts. There are also cost drawbacks to modular construction, which include increases in design engineering, contract administration, and procurement costs. (Molavi and Barral, 2016)

Larger modular manufacturers are able to negotiate lower pricing due to volume and standardization. Many modular manufacturers handle all of their own design work giving them the ability of standardizing systems, components and assemblies, and specifying their standards for fabrication – always using the same systems, components, screws, bolts, fastening modalities and the like. In this way they are able to negotiate better pricing and have the ability to drive down the cost of the building. (Deluxe Modular, 2019)

In terms of financial income, if construction is completed faster than through conventional construction methods, the owner can earn the extra rental income. If it is a commercial building, the financial cost can be increased depends on the use purpose of users. In order to evaluate the cost of prefabricated construction, life cycle costs can be considered important than the initial costs per unit.

4.3 Quality and Safety Control

Quality of the prefabricated structure frames can be identical control due to the manufacturing environments. Because the labor skills and occupational environments are less changeable than the on-site. Panelized and Modular construction is tighter and stronger than conventional construction methods because of the high level of quality control possible in a controlled indoor environment with an experienced labor force. Furthermore, workers familiar with their product can easily integrate materials and techniques into the process when working side-by-side with individuals of other trades backgrounds (Mohamed et al., 2009). Because modular construction occurs in a factory, there is improved supervision, access to tools, and on-time material deliveries. Moreover, most modular manufacturers conduct quality control check and inspection in the factory before the modules are transported to the construction site.

Safety on the site is an important factor for construction activities. Site conditions such as inclement weather or poor natural environment lead to higher accident rates. By using of prefabrication and modularization, the risk from worker accidents and lost time is reduced when construction work is transferred away from the job site and into a controlled manufacturing environment. Especially when the project site is including heavy weather conditions, heights, hazardous operation, congested construction activities, the safety will be more secure and easily controlled in the factory. For example, the risk of workers' mortality and injuries in the factory can be decreased by minimizing fall hazards for installing work needing access to roof areas and controlling the risk of falls from heights during construction activities. Also, the workers in the factory can be more reliable and familiar in the work environments at the factory than on-site environments. New workplaces are even more challenging because they required the anticipation

of hazards, theoretical calculation of the risks, and the determination of acceptable risks in order to specify design interventions. (Dennenberg, 2011)

4.4 Opportunities and Limitations

Numerous opportunities are available for architectures, developers, constructor and manufacturers in prefabricated construction. The latest software and technologies allow greater automation systems for prefabricated construction. When the advanced technology is applied to the construction factories, the construction industry can be changed much faster than conventional construction market. For instance, health care is a sector that is well-suited for prefabrication techniques. The interior layout of hospital rooms allows for efficient use of modulization, and it is a sector highly responsive to strategies that shorten schedule (Bernstein, H. M., 2011). Emerging technologies can offer significant opportunities to improve construction productivity and sustainability. MBI identified five interrelated activities to improve the prefabricated construction from among many suggestions (MBI, 2010). (1) Widespread deployment and use of interoperable technology applications such as BIM (Building Information Modeling). Use of interoperable technologies can help the speed of project related decision making; integrated processes; manage supply chains; reduce time; reduce rework; improve the life-cycle management of buildings. (2) Improved job-site efficiency through more effective interfacing of people, processes, materials, equipment, and information. (3) Greater use of prefabrication, preassembly, modularization, and off-site fabrication techniques and processes. (4) Innovative, widespread use of demonstration installations. (5) Effective performance measurement to drive efficiency and support innovation.

On the other hands, there are some challenges and limitations for conducting the prefabrication construction, even though lots of technical issues are solved and economic benefits are certain in specific conditions. The limitations and risks of modular construction should be defined in the early phase of project management.

- **Early-stage Decisions:** Prefabricated construction required the cost in the early stage comparing to the conventional construction. Because the assembly and coordination with MEP design are completed earlier than on-site construction, the owners have burdens and risks for the overall cost management from the early phase of construction.

In terms of the design, modular construction is based on the concept of repetition of design and the design should be confirmed in advance compared to the conventional method. When the architecture's design does not have a repeated module or component, the advantages of prefabricated construction can be reduced. This limitation should be considered and adjusted the scope and assembly of components in advance for overcoming the drawbacks.

- **Manufacturer Capacity Limitation:** The modular construction market is not yet fully developed and it is still a growing industry. Therefore, the manufacture's lacking capacity can be the obstruction of the productivity, in the case of that a mega project required a large volume of modules in the limited time than feasible capacity.
- **Quality Problems:** The productivity and efficiency of modular construction are not yet fully maximized because there is still much labor work involved in the factory as well as at construction site. This is because the initial investment cost in automation technologies is high and there is a lack of skilled labor in construction. The manufacturing of modular

units sometimes still involves conventional panelized casting, followed by assembly of panels into modular unit. This causes error in verticality and horizontality of the modular that might lead to the uneven surface at the gap between two modules and subsequently lead to water tightness problems (Liew et al., 2019).

CHAPTER 5. SUSTAINABILITY CONSIDERATION

Recently, sustainability in the construction sector has become increasingly important, more than ever before. Prefabricated construction easily incorporates sustainability through the use of recycled materials, high-efficiency mechanical systems, sustainable wood, and low-flow fixtures. Also, it can be easily applied to more energy-efficient designed buildings such as ventilation systems, tight envelopes, and smart lighting to achieve energy savings.

5.1 Needs for Sustainable Construction

Construction of commercial buildings has an environmental impact because of emissions from nonroad equipment. Construction produces 7% of the U.S. greenhouse gas emissions, of which 76% originates from engines. (Marshall et al, 2012). It means that if we reduce the use of equipment and reduce the CO₂ emissions from the equipment or vehicles, there is a lot of potential for reduction of environmental impact by construction activities.

In addition, there are many potential sources in the construction phase with impacts that are discussed. Gangolells and colleagues (2009) found that transportation and construction equipment, waste production, and water consumption all had significant environmental consequences, implying that any improvements in these areas could be priority targets for reducing the overall life cycle impact of the building (Quale et al., 2012). Sustainability is not just about environmental issues, it also encompasses social progress and this is key to the governmental, institutional and executive agencies' strategic responses to the sustainability

agenda. Sustainable development means meeting needs in ways which deliver social progress, protection of the environment, better resource use, economic growth and employment. It requires a stable and competitive economy. Greater resource efficiency lies at the heart of the sustainable development challenge for construction. (DETR, 2000)

In prefabricated construction, consolidating work at a factory can reduce the CO₂ emissions resulting from the transport of materials and laborers as well as from construction operations. Moreover, at the level of site environments, the prefabricated building is able to minimize the environmental impacts of neighboring residents or the surrounding natural environment by reducing the various type of pollutions such as construction noise, dust, and water contamination.

5.2 Three Elements of Construction Sustainability

The strategy for more sustainable construction is a significant milestone on the road to a more socially and environmentally responsible, better-regarded construction industry. It creates a framework within which the industry can make a strong contribution to the better quality of life signaled by our sustainable development strategy (DETR, 2000). Besides, the activities of construction industries are major factors affecting climate change and environmental pollutions in the world. Therefore, the awareness and strategies for sustainable construction are important for all of us. In general, the below three are considered as major elements for sustainability with balance.

- **Environmental Efficiency:** Sustainability in construction needs to minimize environmental damage, pollution, and exhaustion of resources. For example, off site

manufacturing such as precast concrete and increase use of self-compacting concrete on site (no need for vibration compacting) help reduce noise pollution on construction sites.

- **Social Acceptance:** In order to implement sustainability, there are required the social acceptance and awareness of climate change and its impact. Advanced knowledge and scientific data can be helpful for a change of awareness and decision making for sustainable construction.
- **Economic Feasibility:** In the Cambridge dictionary, it means the degree to which the economic advantages of something to be made, done, or achieved are greater than the economic costs. In order to promote sustainable construction, the economic environment should be effectively maintained in business.

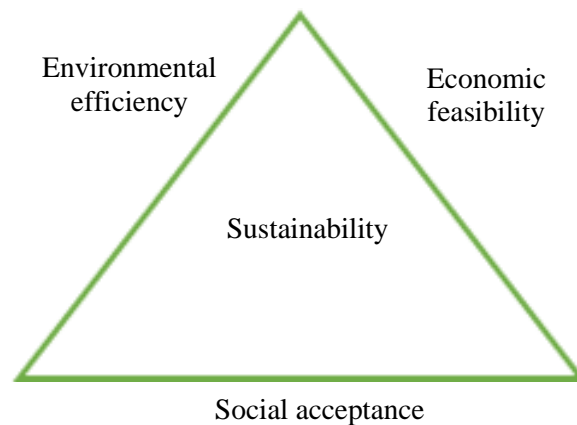


Figure 7. The Three Elements of Sustainable

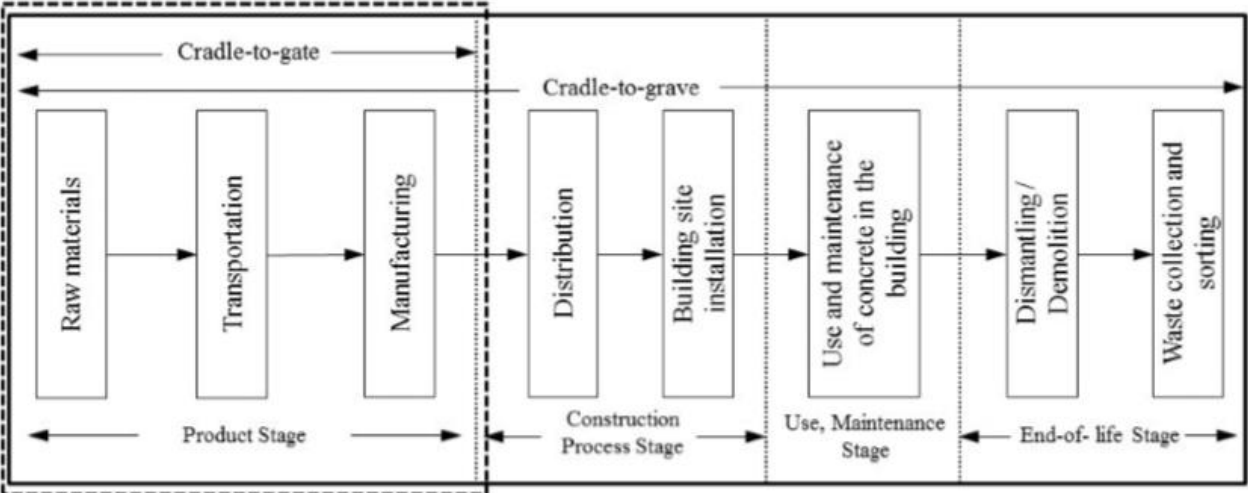
Prefabricated construction is well known a smaller impact on social and environmental impact because project proceed a limited time than conventional construction. Jaillon (2008) conducted research that the sustainable construction aspects of adopting prefabrication in high-rise buildings are examined, and the economic, environmental and social aspects of using

prefabrication are assessed. And the findings revealed that environmental, economic and social benefits of using prefabrication were significant when compared to conventional construction methods. (Jaillon and Poon, 2008)

5.3 Life Cycle Assessment

When looking at the environmental impact of a building, it is important to assess every stage of the environmental life cycle, from material extraction, manufacturing, and construction. The LCA (Life Cycle Assessment) includes building operations and the end-of-life stage where the building is demolished and reused or discarded. However, the process of conducting an LCA is complicated. Applied factors should have information such as site specifications, all the related components or material types, and construction methods, as well as it is difficult to track down the required data and finds meaningful results. Despite the several restrictions, LCA is the most comprehensive approach to determining the environmental life cycle impacts of a building and can be used as a tool to make design decisions that would result in the lower environmental impacts. Therefore, many researchers have used LCAs to examine the potential environmental impacts of building and construction. Considering GHG emissions, which is one of the impact measurements for estimating the LCA results, as well in a study of residential buildings is one of the analyzing methods. In many cases, however, researchers have only conducted partial LCAs and choose to limit the scope of an LCA by excluding certain life cycle stages because of the lack of data or scope of research. Because LCA is still a relatively new science and can be extremely time consuming and expensive to conduct.

In the building, LCA is applied from raw materials extraction to final disposal phase with several stages. There are several types of cycles that can be applied to research such as ‘cradle to grave’, ‘cradle to site’, and ‘cradle to cradle’ of the closed-loop life cycle. Figure 8 shows an example of the LCA boundary system. This case study is adopted the partial LCA concept of ‘cradle to gate’ among the whole concept of ‘cradle to grave’ for boundaries. The prefabricated building of the case study has been conducted the partial LCA focused on the main structural materials such as steel and concrete. The detailed description has been explained in Chapter 7.



Source: An optimization system for concrete life cycle cost and related CO₂ emissions [sustainability 2006]

Figure 8. System Boundary of Concrete Life Cycle Assessment (LCA)

CHAPTER 6. CASE STUDY OF ENVIRONMENTAL IMPACTS

6.1 Case Study Objective

The researcher determined that conducting a case study was crucial for identifying and understanding the areas in which environmental decision-making would be useful. In this research, the objectives of the study to find the environmental impacts of prefabricated construction included the following.

- to identify and quantify the amount of carbon dioxide emissions in precast and the CIP concrete method by collecting data
- to quantify and assess the carbon dioxide emissions in precast and CIP concrete which factors may be affected and how they may be affected
- to find a way to promote positive or mitigate adverse environmental impacts through comparison of the case study with a CIP concrete method

6.2 Methodology

6.2.1 Process of Case Study

The research for the calculation of CO₂ emissions was conducted in two ways. Firstly, the primary method was through a survey on literature and data inventories for CO₂ emissions of construction. In addition, equipment use hours or material quantities for analysis were estimated based on professional's interviews, collected data, and drawings provided by the precast concrete

manufacturer. Secondly, the analysis of CO₂ emissions was comparing between precast and CIP concrete as variable criteria of scenarios. In order to demonstrate how the prefabricated module differs from the conventional method as an environmental perspective, that methodology had been set up. Figure 9 shows the methodology process for this case study.

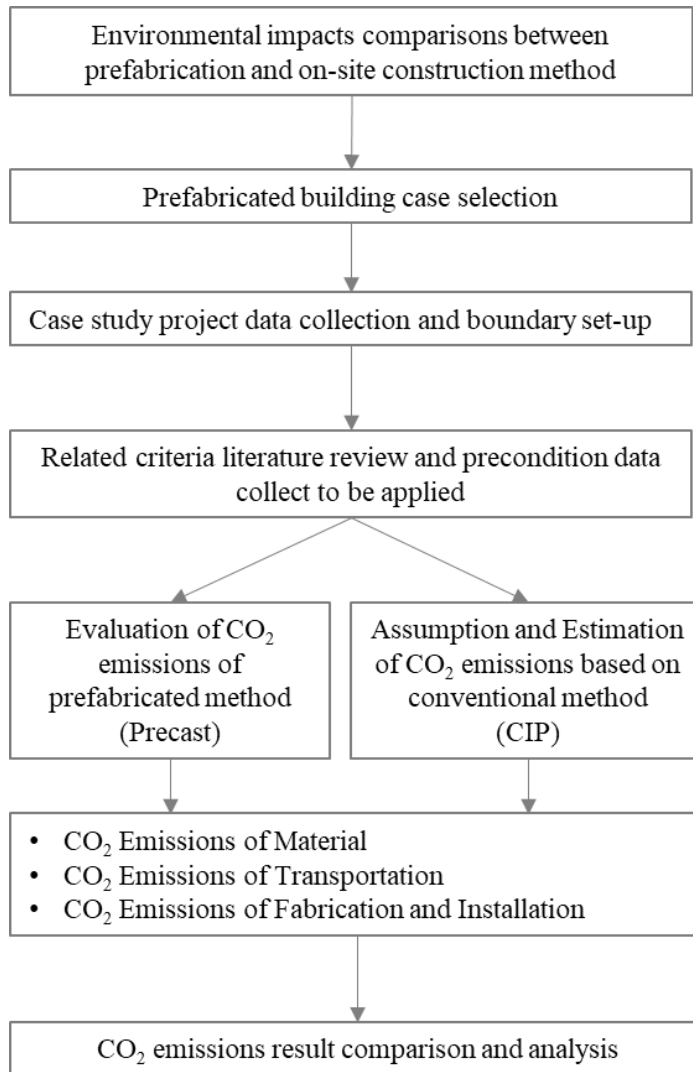


Figure 9. Case Study Methodology Process

6.2.2 Scenario Analysis Methodology

The scenario basis of various criteria such as distance, material, delivery vehicle size, and equipment type had used for the case study project's evaluation conditions in order to quantify the amount of CO₂ emissions. In this case study, the purpose of scenarios was not to make accurate predictions or confirm expectations. The primary aim is that the scenarios and criteria are to find determinants for future consideration of environmental impacts on prefabricated construction. The scenario overview and conditions are described in section 7.5.

6.3 Case Study Project Information

- **Location and Layout:** The project of the case study has located in the urban area of South Korea where is 80km away from the precast concrete factory. The project consists of separated two blocks. Figure 11 shows the layout of Block A (153 units). One building has been attached and comprised of two to eleven units of residential housing. The information on the building is indicated in Table 1.
- **Housing Units:** A total of 203 housing units which are assembled by Precast panelized modules are residential buildings of 84 m² (904 ft²) area. All units are three floors having six types of plans. The structures of prefabricated concrete had designed modules of a type of wall, column, girder, stairs, HCS (hollow core slab), reinforced concrete slab and solid slab. Figure 10 shows the typical type of housing unit.
- **Construction Schedule:** The schedule from production to installation on-site was completed within eleven (11) months. The installation on-site schedule has been considered six (6) months in this case study.

Unit Type	Unit Area (m ²)	Unit Area (ft ²)	A Block (17 buildings)	B Block (11 buildings)	Total Unit
A ~ F type	84m ²	904 ft ²	153	50	203

Table 1. Case Study Residential Housing Units



Figure 10. Typical Type Images of Case Study Residential Building



Figure 11. Case Study Block A (153 units) Layout Image

6.4 Case Study Boundary

Regarding the quantification of CO₂ emissions, the basic groups of case studies are confined as the precast and CIP concrete construction methods. The boundary of CO₂ emissions of each method can be divided as two-stage of 'Product Stage' and 'Construction Stage'. The estimation of CO₂ emissions on a case study is including components, fabrication, transportation, and installation process of precast and CIP concrete. The evaluated values of the product stage have used the concept of LCA (cradle to gate). The CO₂ emissions values as precondition data are based on the existing data inventories or related literature. CO₂ evaluations of precast concrete including prefabrication, transportation, and on-site installation process are determined by the provided actual data of this project by the manufacturer, while all CO₂ emissions of CIP concrete are estimated by the scenarios.

The general LCA process includes four stages as described in Chapter 6. However, the researcher has only selected the product stage and construction stage for this case study because of the following reasons. Firstly, after the construction stage, the utility usage and operation method can be various due to numerous additional factors. Also, it is difficult to track data in a limited time to compare the difference. The comparison results after the construction stage may be affected not only by the characteristic of precast and CIP concrete but also by the other materials, design, location, and construction methods. Secondly, in the event that the comparison scope is narrow and specific, the comparison data accuracy can be greater than in the wide scope. If there are combine all related data, the analysis outcomes of comparison and correlations of precast and CIP may be devalued. The researcher has determined and designed the case study boundary in order to enhance the accuracy and convince the outcomes as focused on the product stage and installation of precast and CIP concrete.

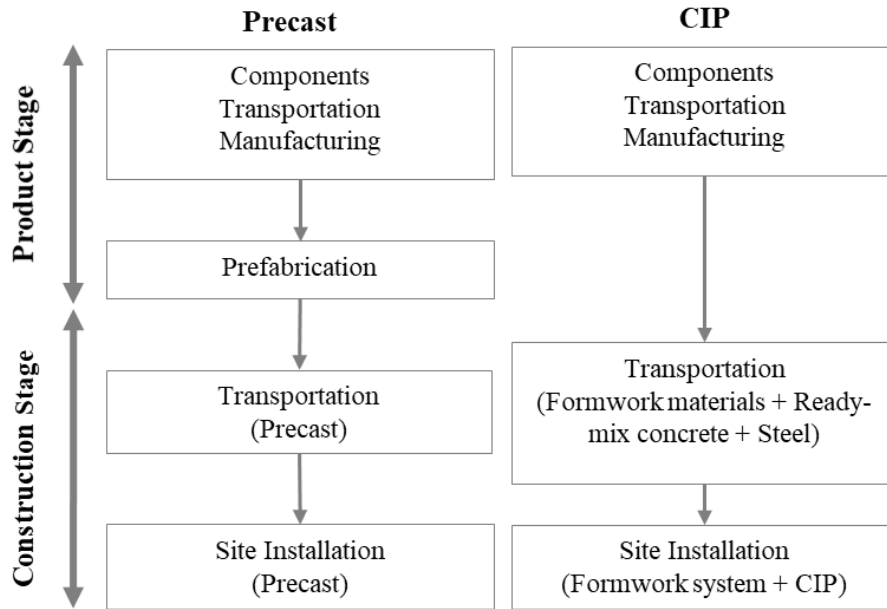


Figure 12. Boundary System for CO₂ Emissions Comparison

6.5 Case Study Scenarios Overview

The scenarios have focused on three major criteria of differences between prefabricated construction and conventional construction. First of all, the difference of loss rate in the precast concrete and CIP concrete has been set up differently, and the material amount is used the base data for whole case analysis. Secondly, distance and transportation capacity has been analyzed for comparison. Thirdly, the comparison based on the energy or equipment usage amount during precast or CIP concrete's construction stage has been conducted for the calculation of CO₂ emissions. Table 2 presents the scenario description list for an overview of the case study. The detailed explanation for each scenario is described in Section 7.7.

Process	Variation	Scenario Classification	Description of Scenario	
Material	Loss	Precast	Precast concrete 3% material loss	
		CIP	Concrete 5%, Steel bar 10% material loss	
Transport	Distance	A1	Precast	Precast factory to Site 80km
			CIP	Manufacturer to Site 80km, temporary materials 160km
		A2	Precast	Precast factory to Site 50km
			CIP	Manufacturer to Site 50km, temporary materials 100km
		A3	Precast	Precast factory to Site 20km
			CIP	Manufacturer to Site 20km, temporary materials 40km
	Vehicle Capacity	B1	Precast	Vehicle capacity 25ton
			CIP	Vehicle capacity 25ton, Ready Mix Concrete truck 14ton
B2		Precast	Vehicle capacity 10ton	
		CIP	Vehicle capacity 10ton, Ready Mix Concrete truck 14ton	
Fabrication & Installation	Equipment	Precast	Equipment energy use for Precast concrete in Factory	
	Equipment Use hour	Precast	Equipment energy use for Installation of Precast concrete on-site for 6 months	
		CIP	Equipment energy use for CIP on-site installation for 9 months	

Table 2. Scenario for CO₂ Emissions Comparison

6.6 Data Collection for Preconditions

The first step of the case study assessment was data collection for CO₂ emissions of the product stage and construction stage on precast and CIP concrete. A wide and varied range of factors and data were required in order to calculate the CO₂ emissions of the case project. Even though there are some LCA data inventories and software tools that are directly applicable, the researcher has selected the CO₂ emissions values in several databases. The researcher has considered that this method can find and apply more accurate figures for estimation.

Especially, through a wide range of published information sources such as research papers and institution's data inventories had been reviewed to assess CO₂ emissions of concrete, steel, and

vehicles' fuels. The following (Table 3) is showing the preconditions for calculation of the CO₂ emission which is applied to this research. In the case of CO₂ emissions of the equipment has been converted from data of the amount of diesel or electricity usage.

6.6.1 CO₂ Emissions of Concrete and Steel

- **Concrete:** The amount of CO₂ emission from the concrete production stage has calculated by the sum of the quantity of each ingredient used for producing per 1 m³ of concrete. The base units of the CO₂ emission for cement, aggregate, and water had been based on the Korea LCI (Life Cycle Inventory) database (DB). In addition, blast furnace slag, fly ash, and chemical admixtures which are not database units in Korea, were applied to the overseas LCI database (Kim, 2016). Kim focused on developing an optimization system, dubbed the concrete life cycle assessment system, to recommend options to help minimize CO₂ emissions and the cost incurred at every stage of the concrete production process. In Kim's research, applying the optimized design, the concrete CO₂ emissions could be reduced by 34%, 225.7 kg- CO₂/ m³ from 340.9 kg- CO₂/ m³. In this case study, 340.9 kg- CO₂/ m³ has been applied to concrete CO₂ emission calculations as a common condition of construction.
- **Steel (Rebar):** The basic unit of CO₂ emissions of steel was used as the type of rebar for residential construction. The residential rebar is used for the girder, column, slab, and wall from 10mm to 22mm size. Lee (2012) use 4,002.04 kg- CO₂/ton for his research for a comparison of the CO₂ emissions of the enhanced GF (Green Frame) and existing GF design for an apartment building in South Korea (Lee et al., 2012).

6.6.2 CO₂ Emissions of Transportation

The transportation sector is one of the largest contributors to anthropogenic U.S. greenhouse gas (GHG) emissions. According to the *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017* (the national inventory that the U.S. prepares annually under the United Nations Framework Convention on Climate Change), transportation accounted for the largest portion (29%) of total U.S. GHG emissions in 2017. Cars, trucks, commercial aircraft, and railroads, among other sources, all contribute to transportation end-use sector emissions (EPA, 2019). Reduction in carbon emissions in transportation can play an important role in energy conservation and environmental impact reduction.

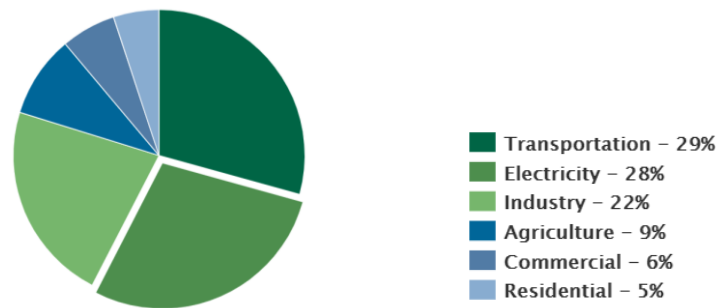


Figure 13. 2017 U.S. GHG Emissions by Sector

(<https://www.epa.gov/greenvehicles>)

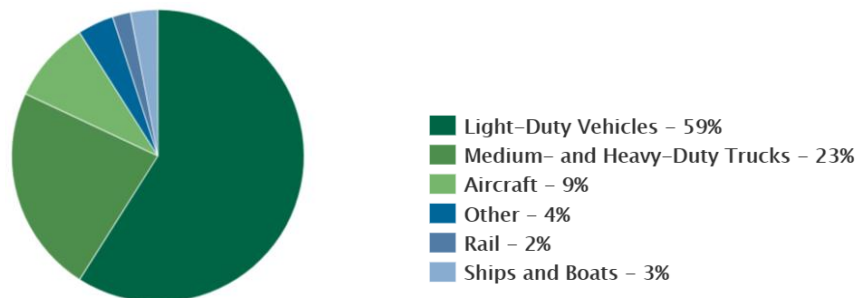


Figure 14. 2017 U.S. Transportation Sector GHG Emissions by Source

(<https://www.epa.gov/greenvehicles>)

- **Heavy Duty Truck:** According to the EPA's data source, heavy duty trucks had contributed the second portion (23%) of transportation GHG emissions in 2017 (See Figure 14). For this case study, CO₂ emissions of heavy-duty trucks (rigid type) data has based on the TRACCS database (<https://tracccs.emisia.com/index.php>) of vehicle model year 2010 in UK. The database of road transport has fuel consumption, fuel consumption factors and CO₂ emissions according to vehicle capacity.
- **Ready Mix Concrete Truck:** The RMC trucks weigh 20,000 to 30,000 pounds (9,070 to 13,600 kg) and can carry roughly 40,000 pounds (18,100 kg) of concrete although many varying sizes of mixer trucks are currently in use. The most common truck capacity is 8 cubic yards (6.1 m³) (https://en.wikipedia.org/wiki/Concrete_mixer). In this study, ready mix concrete vehicle capacity has considered as 8 cubic yards (6.1 m³). Therefore, the CO₂ emissions of the RMC truck have considered as the scope of heavy-duty trucks (Rigid 12-14t) and calculated to 0.465 kg CO₂ per km.

6.6.3 CO₂ Emissions of Equipment and Utilities

- **On-site placement activities (fuel, pumping, vibration):** Due to the limitation of the case study, the activities for onsite placement used to existing data from the literature. It has including the power and energy consumptions for pumping and vibration for concrete placement. The on-site placement activity has contributed to the CO₂ emissions 9.0 kg-CO₂ per m³. The equipment for erecting, temporary materials installation, materials moving on-site has not been considered here.
- **Equipment on-site installation:** CO₂ emissions for installation have considered tower

crane and forklifts as major energy consumption of installation on-site. Other activities or factors have not added for the calculation due to the wide range of uncertainty and limitation for measurement.

- **Fuel and Electricity:** The basic precondition units for diesel (2.68 kg CO₂/liter) and electricity (1.35kg CO₂/kWh) have been used from the database of U.S. Energy Information Administration Estimates. These units are also applied to equipment calculation after transformed computation.

Phase	Description	CO ₂ emission	Author/s or References	CO ₂ emission used in this study	Applied Method
Material	Production of Ready-mix Concrete	340.9 kg-CO ₂ /m ³ 330 kg-CO ₂ /m ³	(Kim et al., 2016) (Flower and Sanjayan, 2007)	340.9 kg-CO ₂ /m ³	Precast, CIP
	Production of steel bar	4002.04 kgCO ₂ /ton	(Lee et al., 2012)	4002.04 kgCO ₂ /ton	Precast, CIP
Transportation (Vehicle)	Heavy Duty Trucks (Rigid 7.5-12t)	0.440 kg CO ₂ /km	TRACCS (Model year 2010) Fuel consumption factors 140 (g/km)	0.465 kg CO ₂ /km	Precast, CIP
	Heavy Duty Trucks (Rigid 12-14t)	0.465 kg CO ₂ /km	TRACCS (Model year 2010) Fuel consumption factors 148 (g/km)	0.465 kg CO ₂ /km	Precast, CIP
	Heavy Duty Trucks (Rigid 14-20t)	0.543 kg CO ₂ /km	TRACCS (Model year 2010) Fuel consumption factors 173 (g/km)	0.543 kg CO ₂ /km	Precast, CIP
	Heavy Duty Trucks (Rigid 20-26t)	0.656 kg CO ₂ /km	TRACCS (Model year 2010) Fuel consumption factors 209 (g/km)	0.656 kg CO ₂ /km	Precast, CIP
Concrete and Rebar Prefabrication Activities for concrete and rebar (factory use)	Fuel (Diesel)	10.16 kg CO ₂ /gallon (2.68 kg CO ₂ /liter) 3.0 kg CO ₂ /liter	U.S. Energy Information Administration estimates (Flower and Sanjayan, 2007)	2.68 kg CO ₂ /liter	Precast
	Electricity factor	(0.52114-0.74884) kg CO ₂ /kwh 1.35 kgCO ₂ /kWh	(Brander et al., 2011) U.S. Energy Information Administration Estimates	1.35kgCO ₂ /kWh	Precast
On-site placement activities	Onsite placement activities (fuel, pumping, vibration)	9.0 kg-CO ₂ /m ³	(Ghayeb et al., 2020; Flower and Sanjayan, 2007)	9.0 kg-CO ₂ /m ³	CIP
Equipment on-site installation	Folk lift (75<HP≤100, Diesel)	29.8 kgCO ₂ /Hour	(Marshall et al.,2012)	29.8 kgCO ₂ /Hour	CIP
	Crane 25t (9.6 L/h, Diesel)	25.7 kgCO ₂ / Hour	(Lim et al., 2015)	25.7 kgCO ₂ / Hour	CIP
	Crane 50t (15.5 L/h, Diesel)	41.5 kgCO ₂ / Hour	(Lim et al., 2015)	41.5 kgCO ₂ / Hour	Precast

Table 3. Preconditions of CO₂ Emissions for Scenario Criteria

6.7 Data Analysis

6.7.1 Material Loss and CO₂ Emissions

The total materials (concrete and steel bar) weight of the project which is design-based quantities was obtained by the precast manufacturer. For comparing the weight of precast and CIP, it was assumed that the designed quantities are identical, but the loss rate is different. The loss rate for precast concrete including steel is 3%, whereas the loss rate for CIP concrete is 5% and the steel bar is 10%. Because the prefabricated component is easier to control the waste materials by fabrication and less damaged compared to on-site materials. In addition, the loss rate of the CIP concrete has estimated including not only for fabrication but also for the waste from the job site. Because the extra materials of concrete and collected leftovers of steel bars from job sites are eventually discarded. There may be other possibilities that depend on the detailed design and construction method, the materials can use more for modular construction due to the overlapped slab or wall design. Therefore, the quantities of materials should be compared and considered to construct a green building in advance. Table 4 shows the amounts of materials quantities and CO₂ emissions.

Material	Designed Quantity	CO ₂ Emissions Unit	CO ₂ Emissions kg-CO ₂	
			Precast concrete based on case study (loss 3%)	CIP concrete (loss 5% for concrete, loss 10% for steel bar)
Concrete	17,925 m ³	340.9 kg-CO ₂ /m ³	6,293,951	6,416,164
Steel bar	2,410 ton	4002.04 kg-CO ₂ /ton	9,934,264	10,609,408
Total CO ₂ Emissions		-	16,228,215	17,025,572

Table 4. Concrete and Steel Bar Quantities and CO₂ Emissions Calculation

As a result of the calculation of the CO₂ emissions of materials in this case study, steel materials consist of 61% of the total CO₂ emissions of precast and concrete components consist of 39%. Therefore, it can be found that the steel materials' impact of CO₂ emissions had been larger than the concrete materials (See Figure 15). Moreover, since the impact of the material loss rate of steel (10%) has higher than precast (3%) when the materials are fabricated on-site, CIP may be more affected by the steel materials than precast.

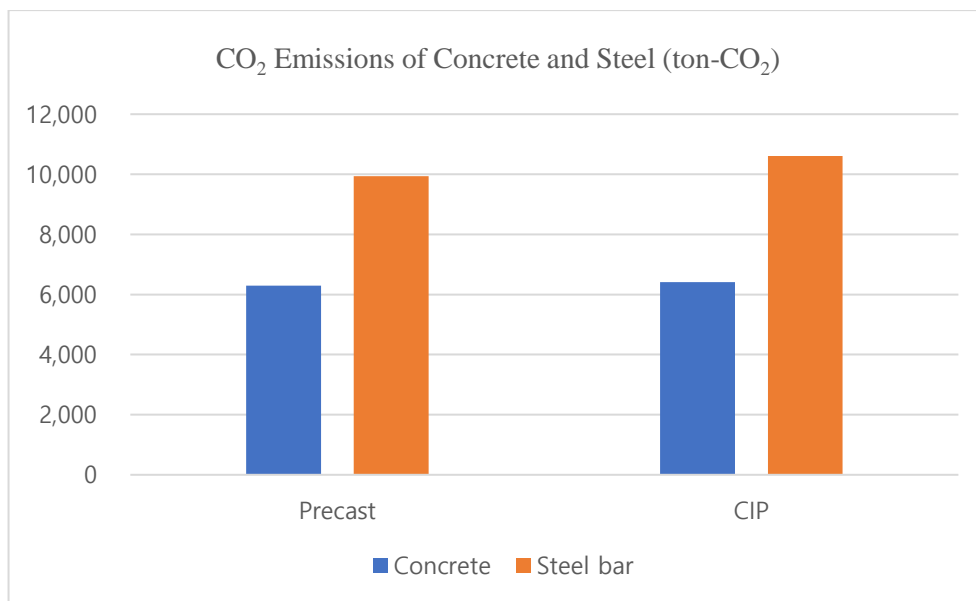


Figure 15. Comparison of CO₂ Emissions of Concrete and Steel bar

6.7.2 Transportation (Distance)

In the prefabricated construction, transportation distance which is the distance of the factory to the site may be one of the most significant determinants to select the prefabrication method. In the case of the distance or location is not suitable for the deliver the prefabricated modules, the project productivity can be reduced. Also, the

transportation distance should be considered not only for the impact on time or cost but also for CO₂ emissions as a significant impact. The heavy-duty trucks are causing the most CO₂ emissions as the second of the transport sector.

Scenario A1, A2, and A3 have performed to compare the impact of materials transportation distance between the panelized precast and CIP concrete method. In the precast concrete, 80km is the actual distance from the factory to on-site. When the distance between the prefabrication factory and the construction site is getting closer, the environmental impact can decrease and the productivity may increase. **Scenario A1** has been estimated with the amount of CO₂ emissions based on distance 80 km, **Scenario A2** was based on 50 km, and **Scenario A3** was based on 30 km. Through scenario A1, A2, and A3, the researcher has compared how much difference and degree of the environmental impact through estimating CO₂ emissions of both precast and CIP concrete.

Regarding the materials to be delivered, scenarios about transportation have added the temporary materials for CIP such as Euro-form panels, scaffoldings, and pipes. In order to estimate the weight of temporary materials, there are several preconditions.

(a) *Building Layout*: The amounts of temporary materials have been calculated based on one building that is attached in a row with seven housings. It means that the overlapped wall has not been calculated for the temporary materials. (b) *Form use cycle*: It has assumed that Euro-form panels which may be used on-site, the recycle times of wood panels of Euro-form are limited as five reuse-cycle times. Also, it has been considered that a total of four sets may be used on-site at the same time. The detail calculation data table of the temporary materials is attached to the Appendix.

Precast Concrete Case study	Material Amount (ton) loss 3%	Vehicle Capacity (ton)	CO ₂ Emissions kg CO ₂ /km	Vehicle Q'ty	Scenario A1		Scenario A2		Scenario A3	
					Distance to site (km)	CO ₂ Emission kg CO ₂ /km	Distance to site (km)	CO ₂ Emission kg CO ₂ /km	Distance to site (km)	CO ₂ Emission kg CO ₂ /km
Heavy Duty Truck (Precast)	44,947	25	0.656	1,798	80	94,535	50	58,970	20	23,588

Table 5. CO₂ Emissions for Transport (Scenario A-Distance) of Precast

CIP	Material Amount	Vehicle Unit	CO ₂ Emissions /vehicle	Vehicle Q'ty	Scenario A1		Scenario A2		Scenario A3	
					Distance to site (km)	CO ₂ Emission (kg CO ₂)	Distance to site (km)	CO ₂ Emission (kg CO ₂)	Distance to site (km)	CO ₂ Emission (kg CO ₂)
Ready-Mix concrete (5% loss)	18,822 m ³	6m ³ per Vehicle	0.543 kg CO ₂ /km	3,137	80	136,271	50	85,170	20	34,068
Steel Bar (10% loss)	2,651 ton	25 ton	0.656 kg CO ₂ /km	107	80	5,615	50	3,510	20	1,404
Placement Formwork materials	132 ton	25 ton	0.656 kg CO ₂ /km	6	160	630	100	394	40	157
Scaffolding Materials	334 ton	25 ton	0.656 kg CO ₂ /km	14	160	1,469	100	918	40	367
Total (CIP Transport Scenario)					-	143,986	-	89,991	-	35,996

Table 6. CO₂ Emissions for Transport (Scenario A-Distance) of CIP

As a result of this scenario study, the interval of the difference in CO₂ emission of precast and CIP is getting smaller when the distance is getting closer. Figure 16 presents the result of the CO₂ emissions for transportation distance of 20km, 50km, and 80km. There are two different slopes in the graph and the CIP's slope has more slant than precast. For instance, in the case of the distance is far more than 80km, which is the actual distance from the factory to site, the difference of both CO₂ emissions will be getting larger than close distance.

The difference between precast and CIP in the graph is the sensitivity for environmental impacts level about the distance. Therefore, we can determine that CIP has more environmental impact sensitivity than precast according to distance from factory to site. Regarding the sensitivity of the CO₂ emission by distance, Figure 17 shows the CO₂ emissions of precast and CIP based on the CO₂ emissions baseline of 80km.

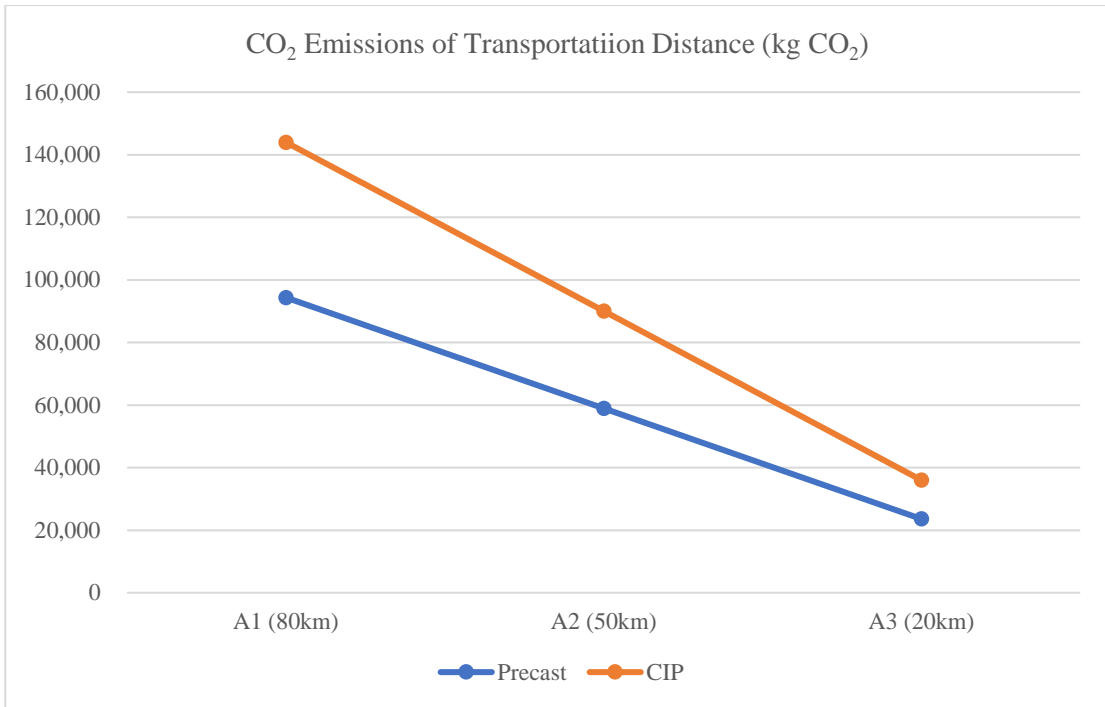


Figure 16. CO₂ Emissions of Transportation Distance

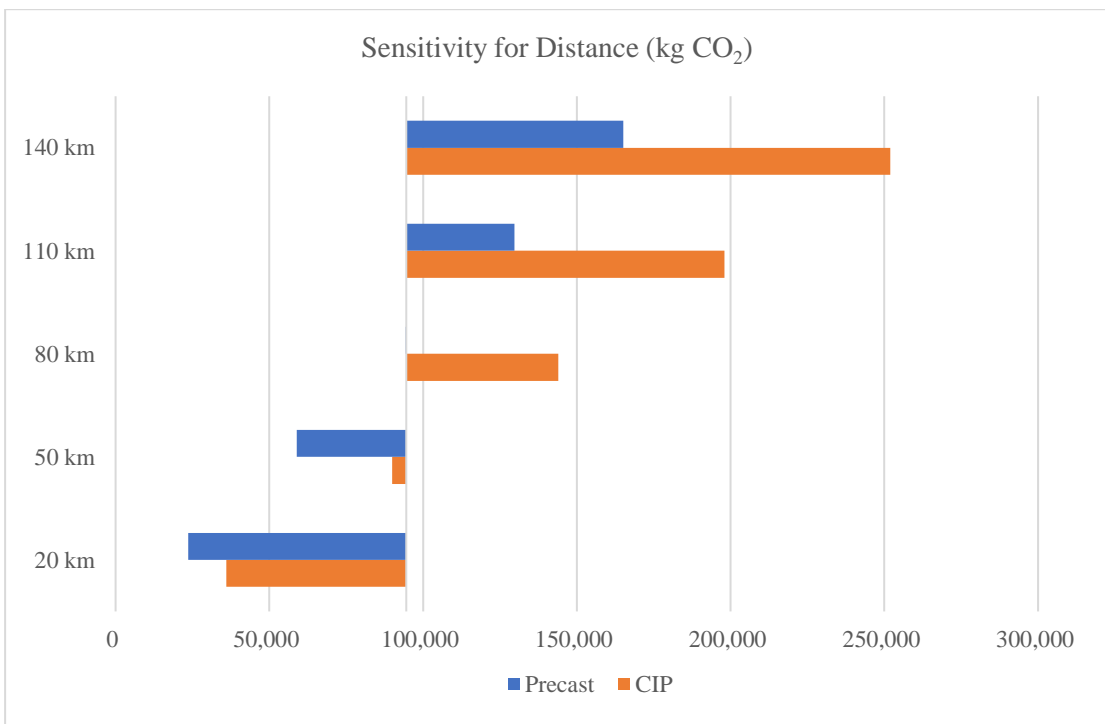


Figure 17. CO₂ Emissions Sensitivity for Distance

6.7.3 Transportation (Vehicle Capacity)

Scenario B1 and B2 are for comparison of the correlation and impact between vehicle capacity and CO₂ emissions amount of precast and CIP respectively. In order to compare the CO₂ emissions of precast and CIP concrete, the two types of truck capacity have been considered. **Scenario B1** has evaluated for 25t vehicle capacity and **Scenario B2** is evaluated for 10t vehicle capacity.

In this project, most of the precast concrete is panelized type structures for wall, column, girder, and slab. Therefore, in order to select a type of heavy-duty truck, weight is the primary factor rather than the volume of precast. In the case study, trailers and cargo trucks of 25t capacity have been mainly used for panelized precast concrete delivery (Figure 18).



Figure 18. Transportation Type for Panelized Module of Case Study

Precast Concrete Case study	Material Amount (ton) loss 3%	Distance to site (km)	Scenario B1				Scenario B2			
			Vehicle Capacity (ton)	Vehicle Q'ty	CO ₂ Emissions /vehicle	CO ₂ Emission (kg CO ₂)	Vehicle Capacity (ton)	Vehicle Q'ty	CO ₂ Emissions /vehicle	CO ₂ Emission (kg CO ₂)
Heavy Duty Truck (Panelized Precast)	44,947	80	25 ton	1,798	0.656 kg CO ₂ /km	94,353	10 ton	0.440 kg CO ₂ /km	4,495	158,213

Table 7. CO₂ Emissions for Transport (Scenario B-Vehicle) of Precast

CIP	Material Amount	Distance to site (km)	Scenario B1				Scenario B2			
			Vehicle Unit	Vehicle Q'ty	CO ₂ Emissions /vehicle	CO ₂ Emission (kg CO ₂)	Vehicle Unit	Vehicle Q'ty	CO ₂ Emissions /vehicle	CO ₂ Emission (kg CO ₂)
Ready-Mix concrete (5% loss)	18,822 m ³	80	6m ³ per Vehicle	3,137	0.543 kg CO ₂ /km	136,271	6m ³ per Vehicle	3,137	0.543 kg CO ₂ /km	136,271
Steel Bar (10% loss)	2,651 ton	80	25 ton	107	0.656 kg CO ₂ /km	5,615	10 ton	266	0.440 kg CO ₂ /km	9,363
Placement Formwork materials	132 ton	160	25 ton	6	0.656 kg CO ₂ /km	630	10 ton	14	0.440 kg CO ₂ /km	986
Scaffolding Materials	334 ton	160	25 ton	14	0.656 kg CO ₂ /km	1,469	10 ton	34	0.440 kg CO ₂ /km	2,394
Total						143,986				149,014

Table 8. CO₂ Emissions for Transport (Scenario B-Vehicle) of CIP

As a result of the scenario about vehicle capacity, in the event of the required materials has delivered by trucks of 10t capacity, there was no benefit for the precast than CIP in terms of transportation. However, when the vehicle capacity has 25t for material delivery, CO₂ emissions can be reduced by 45% compared to the CIP concrete process. In this case study, the manufacturer has actually used 25t capacity trucks for the delivery of precast concrete from the factory to the construction site. But, the weight of the temporary materials such as pipes, euro-forms, and scaffolding materials can be increased or decreased depends on the on-site scheduling and construction method, the impacts of CO₂ emissions may be varying based on the conditions.

The weight of precast concrete is a decisive factor for delivery rather than the volume since the shape of most of the precast was by panelized type. In Figure 19, the reason why the graph has a gentle slope for CIP than precast is that the vehicle capacity of RMC (ready-mix concrete) is the fixed figure as the weight for 6 m³ volume of concrete. That volume is a concrete batching capacity installed in the vehicle, and then the capacity of the vehicle has been considered as the type of heavy-duty trucks (Rigid 12t-14t). Therefore, when the CIP concrete method has a fixed delivery capacity for RMC, only the weight of the steel bar has been evaluated to the variable factors in the scenarios. As a result, there is a finding that precast has more sensitive for vehicle capacity.

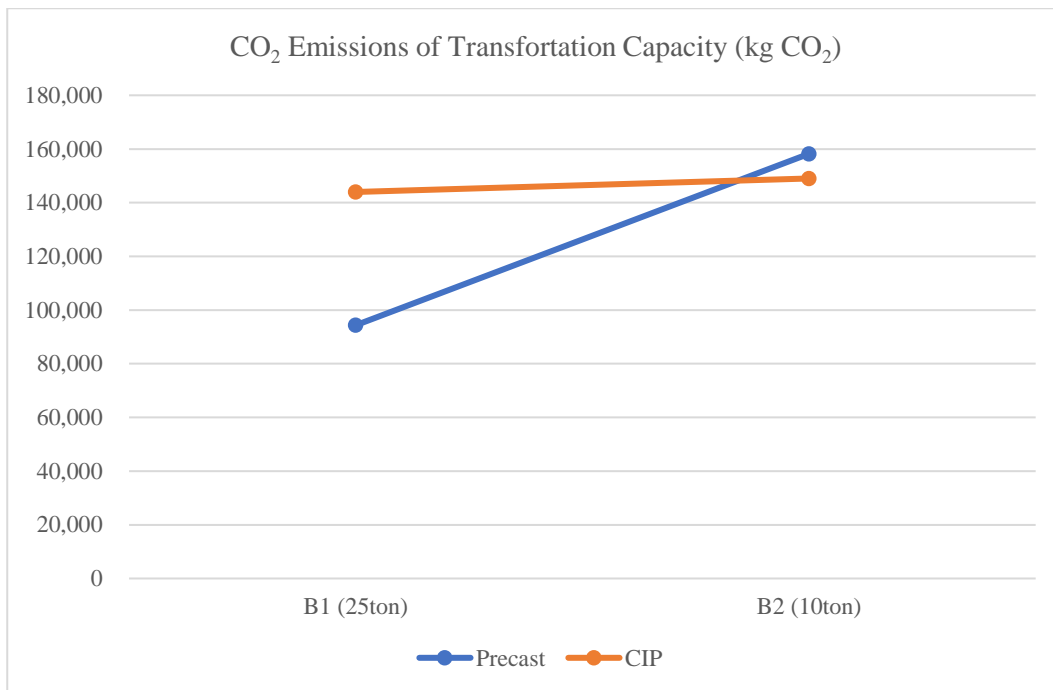


Figure 19. Comparison of CO₂ Emissions of Transport Vehicle between Precast and CIP

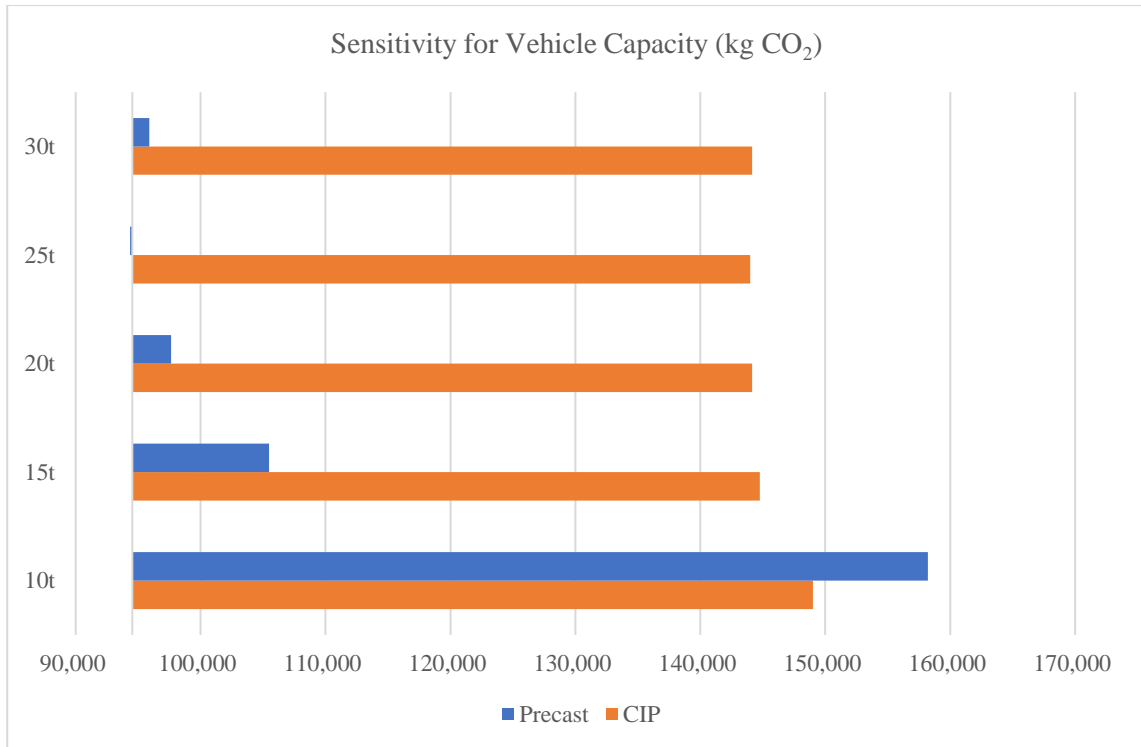


Figure 20. CO₂ Emissions Sensitivity for Vehicle Capacity

Figure 20 shows more obvious figures related to the sensitivity of the CO₂ emission for the vehicle capacity of precast concrete. The graph bars illustrating as CO₂ emissions show the difference between precast and CIP results. The baseline has based on the 25t vehicle capacity in the event of the distance 80km. This is equal to the actual condition of the precast delivery condition of the case study.

CIP method has almost similar CO₂ emissions from 15t to 30t, while CO₂ emissions of precast have a sharp drop compared to CIP when the vehicle capacity has changed from 10t to 25t. Also, when they use 25t vehicle capacity for precast delivery, it is expected that the CO₂ emissions may the lowest degree.

6.7.4 Fabrication and Installation

Comparison of CO₂ emissions by fabrication and installation activities of precast and CIP concrete has been evaluated based on several assumptions which include equipment use-hour and major equipment types. In regards to the prefabrication process of precast, however, the data such as usage of the fuel, electricity, and equipment of precast has based on the actual data provided by the manufacturer.

The reflected utility usage is the data from the bills presented during June of 2019. In June, the operation of the factory capacity was approximately 99% of the productivity of the factory, and it produced a total of 35,983 tons of precast concrete. As a result of the calculation (see Table 9). CO₂ emissions for prefabrication activity in the factory have evaluated as 11.3 kg CO₂ per ton.

In order to compare CO₂ emissions of installation activity, preconditions and baseline for calculation are under the distance 80km from the factory to site, crane capacity of 50t (8ea) for precast, crane capacity of 25t (4ea) for CIP, and 1.5 times longer schedule of CIP than precast concrete.

For on-site installation of CIP concrete, the construction schedule has 9 months which is considered as 3 months longer than the precast concrete on-site installation schedule.

Additionally, temporary structures (formwork, supporters, scaffolding) are estimated retrospectively with varying degrees of assumptions for CIP concrete. The detail assumptions and calculation are described in Table 9 and Table 10.

Activity	Evaluation	CO ₂	CO ₂ Emission (kg CO ₂)	Reference/ Assumption
Off-Site Prefabrication (energy use for concrete and rebar)	44,947 ton (3% loss for precast)	^[b] 11.3 kg-CO ₂ /ton	507,901	Based on total utility usage at factory equipment and operation (June 2019, 99% operation)
On-Site Installation (Crane)	^[a] 7,680 hours	41.5 kg CO ₂ /hour (50t)	318,720	6 months for precast installation
Total			826,621	

^[a] (8 hour/day * 20 day * 6 month) * 8 Crane =7,680 hours

^[b] (1) + (2) =11.3 kg-CO₂/ton

(1) Diesel: (12,197 Liter) x (2.68 kg CO₂/liter) / (35,983 ton) =0.908 kg CO₂/ton

(2) Electricity: (279,049 kwh) x (1.35kgCO₂ per kWh) / (35,983 ton) = 10.469 kg CO₂/ton

Table 9. CO₂ Emissions for Fabrication and Installation of Precast

Activity	Evaluation	CO ₂	CO ₂ Emission (kg CO ₂)	Reference/ Assumption
On-Site Fabrication (Energy use for concrete and rebar)	45,940 ton (5% loss for concrete, 10% loss for steel)	9.0 kg-CO ₂ /m ³ (20.7 kg-CO ₂ /ton)	950,958	Including pump, vibration and fuel
On-Site Installation (Crane)	^[c] 5,760 hours	25.7 kg CO ₂ /hour (25t)	148,032	Concrete placement 9 months
On-Site Installation (Forklift)	^[d] 2,880 hours	29.7 kg CO ₂ /hour (75<HP<100)	85,536	Concrete placement 9 months
Total			1,184,526	

^[c] (8 hour/day * 20 day * 9 month) * 4 Crane = 5,760 hours

^[d] (4 hour/day * 20 day * 9 month) * 4 Forklift = 2,880 hours

Table 10. CO₂ Emissions for Fabrication and Installation of CIP

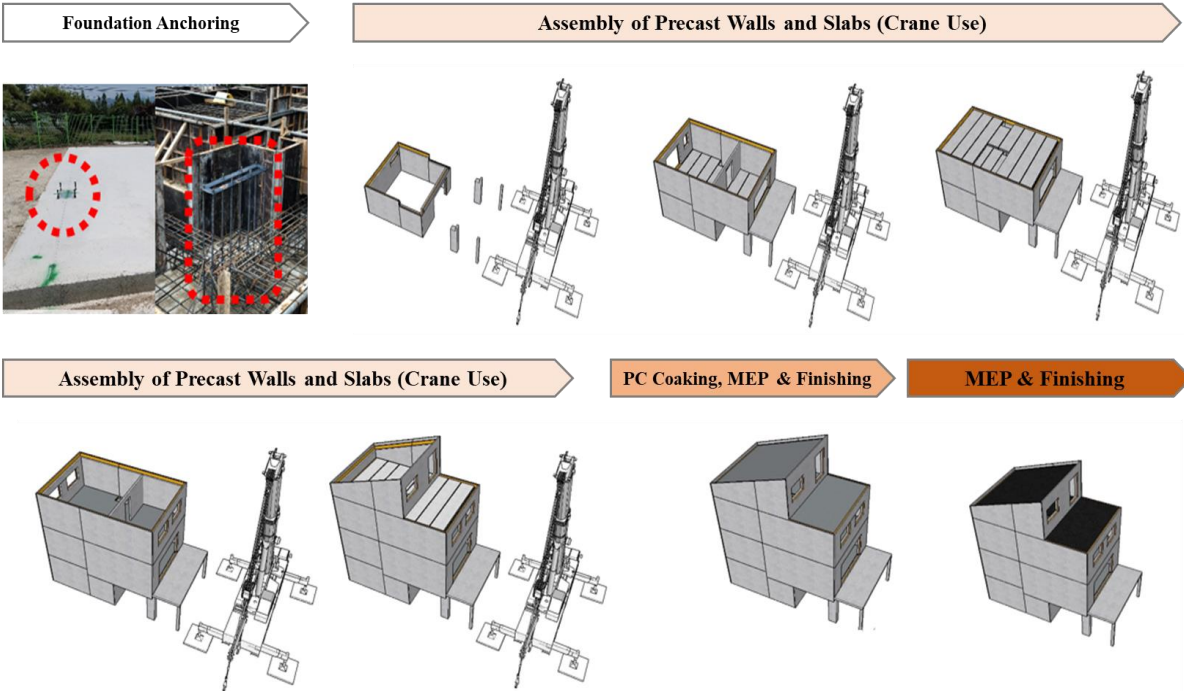


Figure 21. Precast Concrete Assembly Simulation

As a result of the calculation under the assumed data scenarios, the fabrication and installation of the CIP method have 43% more CO₂ emissions than precast. There can be estimated several reasons.

Firstly, the reason is that the quantities of materials to be fabricated are different. The CIP has larger material loss than precast in the scenario's baseline.

Secondly, the usage of energy including equipment operation for the fabrication has calculated as a different condition that one is off-site (factory) and the other is on-site.

The CO₂ emissions data for calculation of the off-site (factory) is based on the actual bill from the factory which was 11.3 kg- CO₂ /ton. Whereas, the data for CO₂ emission for concrete placement on-site was based on the data collected from other literature which was 20.7 kg- CO₂ /ton which are included uncertainty according to the design and characteristic of the researched on-site.

Thirdly, the CO₂ emissions are associated with the total construction schedule and process of activities. In the case study, the CIP installation schedule on-site has considered 3 months longer than precast. the estimation for the schedule and activities management can be changeable and diversified under the site conditions. In general, on-site placement can be determined more likely to spend energy on fabrication and time, even though there are remained the limitation on the degree of accuracy.

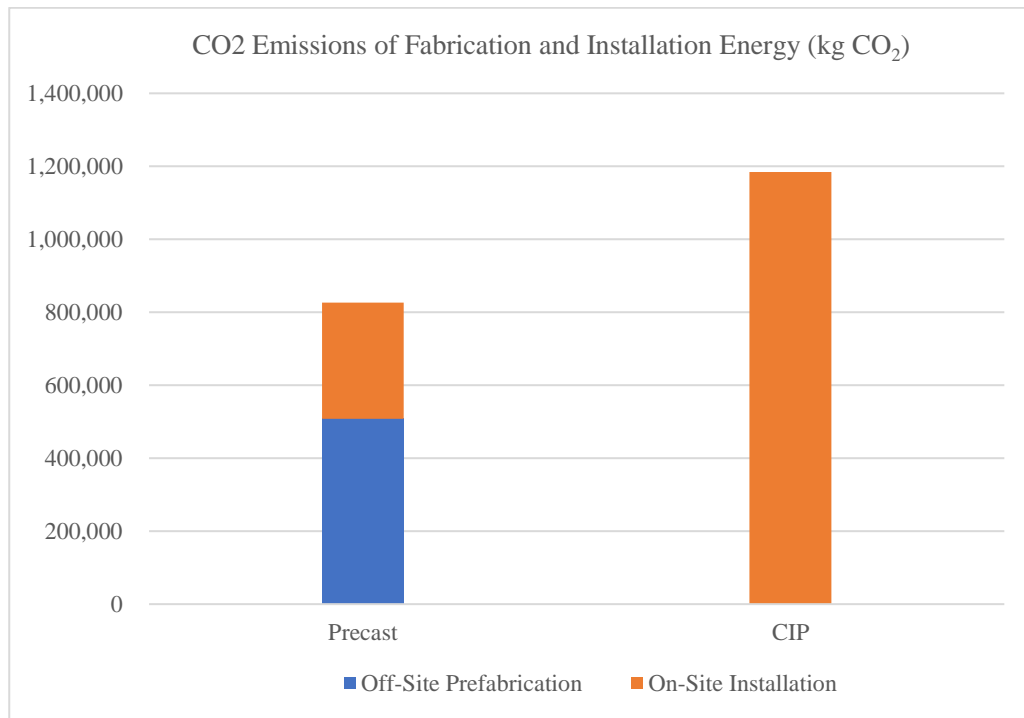


Figure 22. Comparison of CO₂ Emissions for Fabrication and Installation Energy

6.7.5 Total Amount and Ratio Comparison

The total amount of CO₂ emissions of the case study has been compared as below Figure 23. The results have been evaluated according to the criteria which are including material loss rate, delivery distance (80km), vehicle capacity (25 ton), off- or on-site fabrication, and installation.

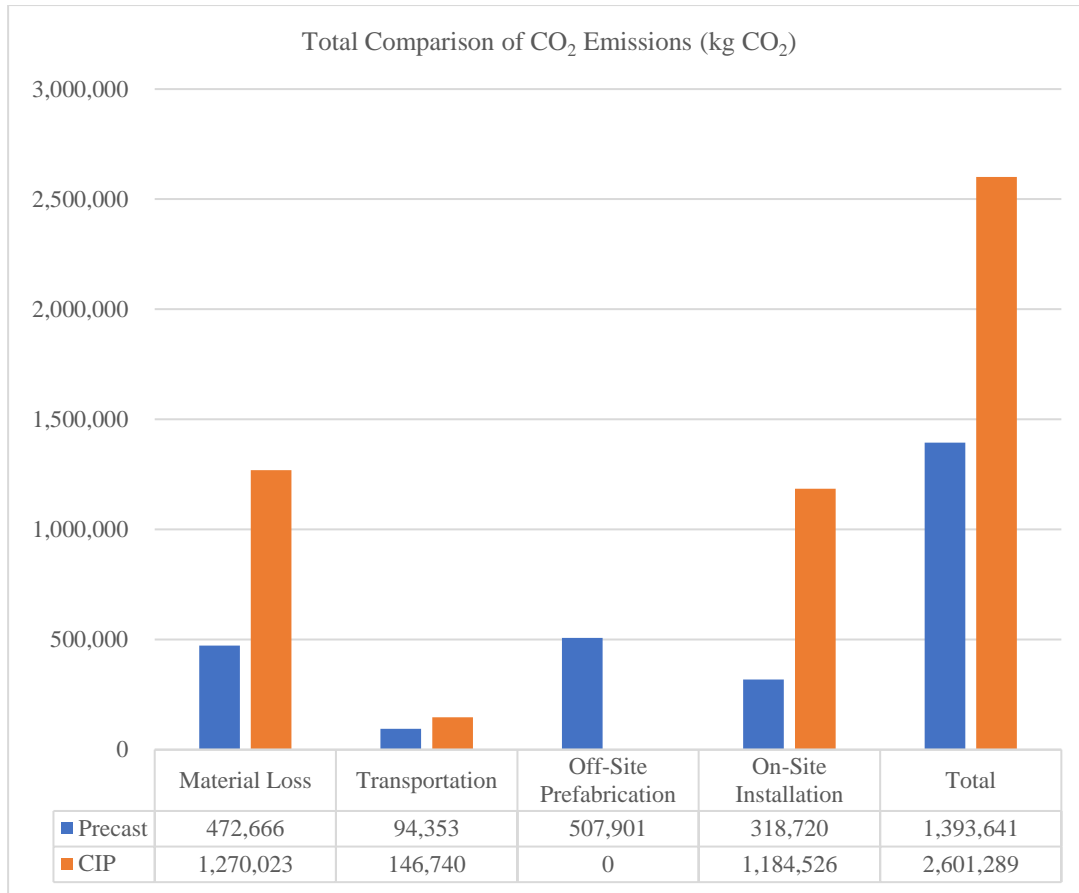


Figure 23. Comparison of Total CO₂ Emissions of Precast and CIP

As a result of the case study based on scenarios, the total CO₂ emissions of the difference figures between precast and CIP concrete is almost twice. Figure 23 shows the comparison number and graph.

The largest determinants of the different figures have a material loss and on-site installation activities. Since the CIP method does not have off-site prefabrication activities, all the related fabrication activities are done on-site. This reason brings the difference in CO₂ emissions to the on-site installation. In transportation, there is a lower difference in terms of total CO₂ emissions. However, this does not mean the transportation and installation impacts are less important. Because all processes still have

numerous possibilities to increase the negative impact and positive potential to eliminate or reduce CO₂ emissions. The point to be focused on is that we should find solutions to reduce the environmental impacts at each factor based on a scientific basis.

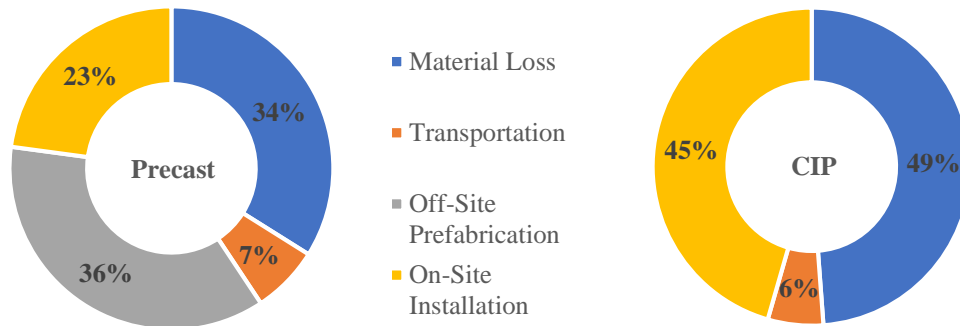


Figure 24. Ratio Comparison of CO₂ Emissions of Precast and CIP

The comparison results of the CO₂ emissions' ratio for the precast and CIP based on the scenarios, CO₂ emissions of the off-site prefabrication process affect the precast method as the largest portion as 36%. The portion of CO₂ emissions of the material loss which is 34% has almost similar to the first one. Whereas, CO₂ emissions of material loss in CIP concrete have affected the largest portion at 49%. This is because the material loss rate of on-site construction had been higher than factory fabrication. (See Figure 24)

The transportation from the factory to the site was respectively 7% and 6% of precast and CIP concrete which is the smallest portion and impacts of CO₂ emissions of the process ratio. One of the major reasons may be that the transportation of materials is only a one-time event and contributes the shortest time for energy use compared to the other processes for calculation.

During the construction stage of CIP, CO₂ emissions of on-site installation have in charge of 45% ratio of the whole process. This is because CIP concrete has required more intensive work on-site all related activities including the fabrication, assembly, and placement. On the other hand, the precast method has only the erection and arrangement work on-site with prefabricated concrete.

Therefore, during the on-site installation phase, in the case of increasing the number of tower cranes or delaying the schedule may be increased energy consumption and CO₂ emissions. However, there are various possible ways in order to reduce CO₂ emissions during installation. For instance, by building up a reliable schedule for delivery and installation can lead to lower environmental impacts. When material loss and waste are managed effectively or when the manufacturers use their energy sources from renewable or green energy, the difference in CO₂ emissions can be a lot.

CHAPTER 7. DISCUSSION

7.1 Findings and Recommendations

The most important aspect of sustainable construction and a healthy built environment is to not create pollution. However, since this is difficult by modern technology, sustainable construction can be normally defined as to minimize or eliminate emissions of impacts on the environment. Based on this perspective, the analysis of the case study shows several findings that we can positively consider the prefabricated construction method in the decision-making process for a sustainable environment.

First of all, the best way is to reduce the loss of materials during the production and construction stages. Since the loss of the materials has in charge of the largest portion of CO₂ emissions in the CIP and the second-largest portion in the precast. Generally, prefabrication techniques can have more efficient and less wasteful than conventional construction methods by controlling the process at the off-site factory. Another way to reduce environmental impacts from materials in prefabrication is that we adopt eco-friendly materials instead of traditional materials. If the prefabricated components made with alternative materials such as green concrete or recycled steel, the environmental impacts may be significantly reduced and it can be the more sustainable construction method.

Secondly, the outcome of transportation analysis shows the different sensitivity about materials delivery distance and vehicle capacity between precast and CIP. For instance, the CIP concrete

method is more sensitive to transportation distance than precast concrete's when it is far away from 80km distance. The common result is that it can reduce considerable CO₂ emissions amounts in both precast and CIP when the distance between the prefabrication factory and on-site is close.

In terms of the vehicle capacity, the CIP method has less sensitivity to change of the vehicle capacity for material delivery than precast. This is because the number of RMC trucks required in the CIP method cannot be changed to the other vehicle capacity, also, it has a fixed number. In addition, about 40% of the material weight is concrete components required to be delivered from RMC trucks. In the precast method, it has the lowest emissions when the vehicle capacity is 25t. But, in the case that the vehicle capacity is 10t, the environmental impact may be greater rather than CIP and be the worst adverse decision for the constructors in terms of cost, schedule, and environment.

Figure 25 and Figure 26 can illustrate the difference and sensitivity of CO₂ emissions according to the distance and vehicle capacity by applying the expanded scope from the case study.

Thirdly, it is one of the determinants of environmental impacts that the heavy-duty cranes and use hours of equipment when considering 'on-site installation'. The outcomes of the precast concrete method bring to increased energy consumption and CO₂ emissions compared to CIP on-site installation process. Therefore, it requires the constructor's efforts to reduce the CO₂ emissions from the installation process by improving the equipment efficiency, work schedule, and productive time of the prefabricated building.

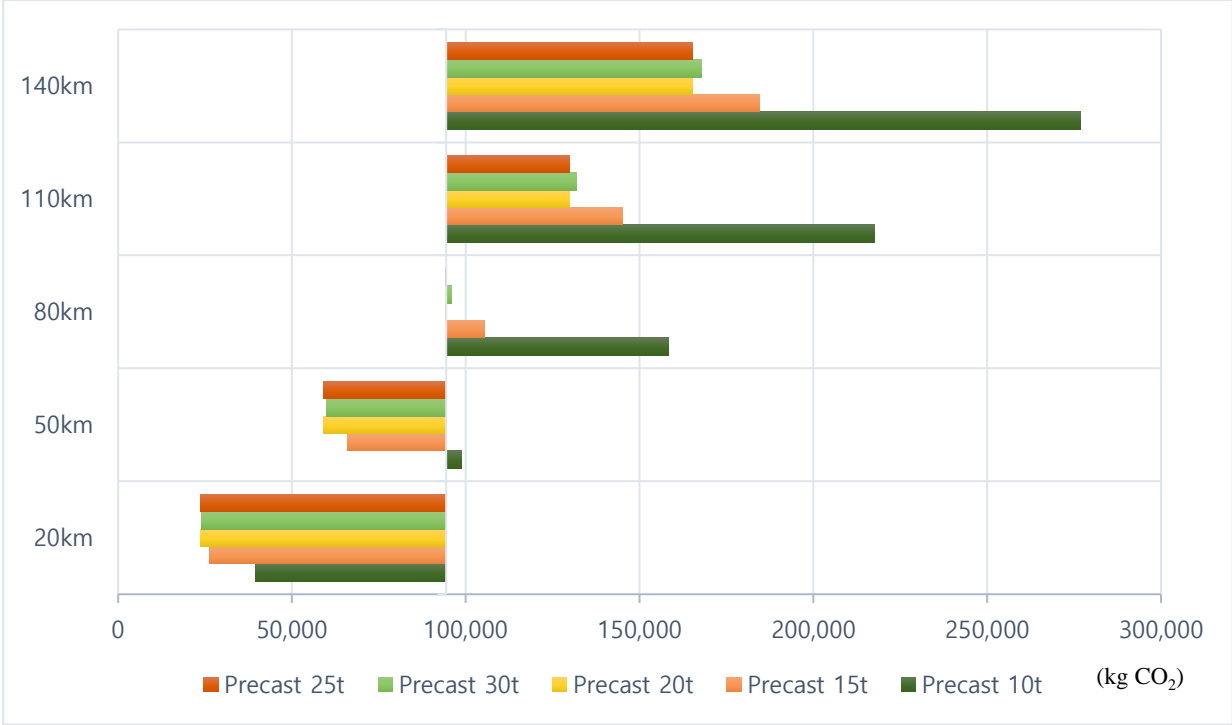


Figure 25. Sensitivity of Precast Concrete for Distance-Vehicle Capacity

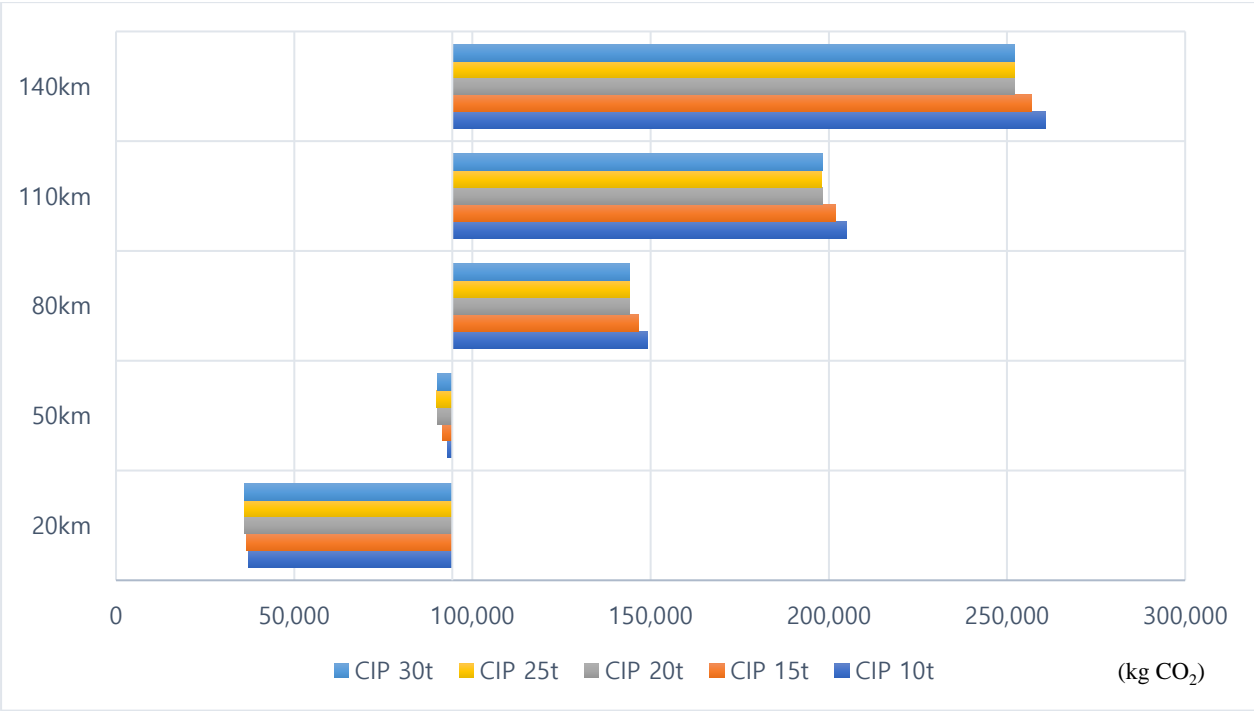


Figure 26. Sensitivity of CIP Concrete for Distance-Vehicle Capacity

Lastly, during the fabrication and installation process, CO₂ emissions of the precast method have been more affected than CIP. In the case study scenario, the fabrication and installation of precast have a portion of 59% of its total, while the CIP method has 45% of its total. Therefore, it can be considered that the efficiency of equipment and assembly productivity of precast at the factory can be significant factors not only to save the schedule but also to reduce the environmental impacts. The decision-makers can use the technology of prefabricated construction as one of the alternatives. And, it can be efficiently improved for mitigating environmental impacts based on the case study outcomes and further research on the correlation to productivity and environmental impacts.

7.2 Limitations

This study has limitations in several ways. There has been only one project's case study for precast concrete and comparing the conventional construction method. In addition, the conditions of every construction project have their own unique characteristics and complexities in the real world. Therefore, even though the building's structural design and construction methods are equal, they cannot have identical conditions such as the project site condition, the schedule, the location, and labor skills. The outcomes of this analysis could be changed depending on the different conditions and complexities of the project.

Moreover, the scenarios have included a few assumed conditions such as material loss rate, schedule, energy use hours, temporary materials' quantities, and so on to estimate the CO₂ emissions of the conventional construction methods. Even though the assumptions may be in the scope of general project characteristics, the outcomes can be changed depending on how to set

the baseline conditions of assumption. The accurate assumption is often difficult because most environmental impacts have multiple factors over the scenario criteria.

To validate the results presented in this case study, which were based on a single residential project, it is important to perform the analysis on other various projects. Because the projects are varied by the type and size and more advanced methodology and data collections are required to be studied to provide the information and data accurately. Also, in order to draw a meaningful and widespread outcome and framework of prefabrication construction and environmental impact, researchers will need further numerous experimental data and evaluations.

CHAPTER 8. CONCLUSION

Decision making based on a single issue, such as carbon dioxide emissions, may not be the answer for construction methods in real life as overall and numerous impacts can be dependent upon the project characteristics. However, the analysis of the assessment of the environmental impact should be one of the major considerations in order to make environmentally friendly buildings. Prefabricated construction can be utilized as one of the options for mitigating environmental problems in the construction industry. The adoption of prefabrication offers significant advantages through the development of technology and changing the management. However, appropriate criteria for applicable assessments widely are still deficient. In most cases, the decision to use prefabricated construction has been based on cost evaluation.

In this research paper, the collected data and scenarios have constraints and limitations of applying it in general. However, we could find and discuss a feasible solution through the review of one specific case in detail. Also, this discussion can provide improvements to the methods of thinking and decision-making for the next project. As described in advance, the primary purpose of this case study and scenarios was not to calculate accurate figures but to find the meaning and direction for decision making in terms of environmental impacts. In order to contribute to reducing environmental impacts by construction activities, further studies are required with multiple perspectives by researchers.

References

- Al-Husseini, M., Manrique, J. D., & Mah, D. (2009). *North Ridge CO2 Analysis Report: Comparison between Modular and On-Site Construction*. Integrated Management & Realty Ltd.
- Bernstein, H. M. (2011). *Prefabrication and Modularization: Increasing Productivity in the Construction Industry*. McGraw-Hill Construction.
- Bertram, N., Fuchs, S., Mischke, J., Patter, R., Strube, G., & Woetzel, J. (2019). *Modular construction: From projects to products*. McKinsey & Company.
- Boafo, E.B., Kim, J.H., & Kim, J.T. (2016). Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways. *Sustainability*.
- Building construction: principles, materials, and systems. 2nd edition.* (2013). Pearson Education Inc.
- Chen, Y., Okudan, G.E., & Riley D.R. (2010). Sustainable performance criteria for construction method selection in concrete buildings. *Automation Construction*, pp. 235-244.
- Deluxe Modular.* (2019). Retrieved from Modular Construction: www.deluxemodular.com
- Dennenberg, A. L., Frumkin H., & Jackson R. J. (2011). *Making Health Places: Designing and Building for Health, Well-being, and Sustainability*. Washington, Covelo, London: ISLAND PRESS.
- DETR. (2000). *Building a Better Quality of Life: A Strategy for more Sustainable Construction*. London: Department of the Environment, Transport and the Regions.
- Fast Facts on Transportation Greenhouse Gas Emissions.* (2019). Retrieved from EPA (Environmental Protection Agency): <https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions>
- Flower, D. J. M., & Sanjayan, J. G. (2007). Green House Gas Emissions due to Concrete Manufacture. *Int J LCA* 12 (5), pp. 282-288.
- Ghayeb, H. H., Razak, H.A., & Sulong, N.H.R. (2020). Evaluation of the CO2 emissions of an

- innovative composite precast concrete structure building frame. *Journal of Cleaner Production* 242.
- Hurmekoski, E., Jonsson, R., & Nord, T. (2015). Context, drivers, and future potential for wood-frame multi-story construction in Europe. *Technological Forecasting & Social Change*, pp. 181-196.
- Jaillon, L and Poon, C.S. (2008). Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study. *Construction Management and Economics* 26, pp. 953-966.
- Kim, T.H., Sung, H.T., Sung, J.S., George, F., & Keun, H.Y. (2016). An Optimisation System for Concrete Life Cycle Cost and Related CO2 Emissions. *Sustainability*.
- Lee S., Joo J., Kim, J.T., & Kim S. (2012). An Analysis of the CO2 Reduction Effect of a Column-Beam Structure Using Composite Precast Concrete Members. *Indoor and Built Environment*, pp. 150-162.
- Liew, J.Y.R., Chua, Y.S., & Dai, Z. (2019). Steel concrete composite systems for modular construction of high-rise buildings. *Structures*, pp. 135-149.
- Lim T.K., Gwak, H. S., Kim, B. S., & Lee, D.E. (2015). Integrated Carbon Emission Estimation Method for Construction Operation and Project Scheduling. *KSCE Journal of Civil Engineering*, pp. 1211-1220.
- Marshall, S. K., Rasdorf, W., Lewis, P., & Frey, H. C. (2012). Methodology for Estimating Emissions Inventories for Commercial Building Projects. *Journal of Architectural Engineering*, pp. 251-260.
- MBI. (2010). *Improving Construction Efficiency & Productivity with Modular Construction*. Retrieved from Modular Building Institute: www.modular.org
- Molavi, J. & Barral, D.L. (2016). A Construction Procurement Method To Achieve Sustainability In Modular Construction. *Procedia Engineering*, pp. 1362-1369.
- Monahan, J., & Powell, J.C. (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, pp. 179-188.

- Pen, W., Li, K., & Teng, Y. (2019). Briefing: Life-cycle carbon assessment fo prefabricated buildings: challenges and solutions. *Engineering Sustainability* 172(1), pp. 3-8.
- Quale, J. E. (2012). Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*, pp. 243-253.
- Ramesh, T., Prakash, R., & Shukla, K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, pp. 1592-1600.
- Reducing your Transportation Footprint*. (2019). Retrieved from C2ES:
<https://www.c2es.org/content/reducing-your-transportation-footprint/>
- Smith, R. (2010). Prefab architecture: A guide to modular design and construction. *New York: Wiley*.
- Taum, C., Venegas, J. A., & Willians J. (1987). *Constructability Improvement Using Prefabrication, Preassembly, and Modularization*. Austin, TX, USA: Bureau of Engineering Research, University of Texas at Austin.
- The Ultimate Guide to Modular Construction*. (2019). Retrieved from Deluxe Modular:
www.deluxemodular.com
- TRACCS. (2019). Retrieved from TRACCS: <http://traccs.emisia.com/download.php>
- Yonger, M., Morrow-Almeida, H. R., Vindigni, S. M., & Dannenberg, A. L. (2008). The Built Environment, Climate Change, and Health Opportunities for Co-Benefitis. *American Journal of Preventive Medicine*, pp. 517-526.

Appendix. Supplementary Data

(1) Heavy Duty Trucks (TRACCS, 2019)

Vehicle	Type	Fuel Consumption Factors (g/km), Model year 2010	From Fuel Consumption to CO ₂
Heavy Duty Trucks	Rigid 12-14t	148	3.140 g CO ₂ per g of fuel
Heavy Duty Trucks	Rigid 14-20t	173	3.140 g CO ₂ per g of fuel
Heavy Duty Trucks	Rigid 20-26t	209	3.140 g CO ₂ per g of fuel
Heavy Duty Trucks	Rigid 26-28t	221	3.140 g CO ₂ per g of fuel
Heavy Duty Trucks	Rigid 28-32t	255	3.140 g CO ₂ per g of fuel

(2) Utility Usage Data from Precast Concrete Factory and CO₂ Emission Units

Type	Unit	Usage (June 2019)	Usage/ton	CO ₂ Emissions Criteria
Diesel	Liter	12,197	0.339	10.16 kg CO ₂ /gallon 2.68 kg CO ₂ /liter
Electricity	kwh	279,049	7.755	1.35kgCO ₂ per kWh
Ground Water	Ton	5,271	0.146	Groundwater depletion and CO ₂ emission due to bicarbonate extraction and pumping *Not compared

(Factory Bill of June 2019, based on Precast Product Amount 53,983 ton)

(3) Precast concrete amount of case study

Structure Type	Precast Concrete (m³)	Steel Bar (kg)
Wall	10,177	1,483,037
Column	236	14,987
Girder	367	39,879
Stairs	776	126,836
HCS (Hollow core slab)	1,737	0
Reinforced Concrete Slab	2,677	745,758
Solid Slab	1,955	0
Total	17,925	2,410,497

(4) A Type Unit Form Work Area Estimation

Floor	Area	Area (m²)
1floor	Matt footing	11.5
	Wall	127.4
	Interior wall	74.1
	Stairs	4.5
2nd floor	Slab	78
	Wall (exterior)	237.7
	wall (interior)	65.1
	Stairs	4.5
3rd floor	Slab	78
	Wall (exterior)	237.7
	wall (interior)	65.1
	Stairs	4.5
Top floor	Slab	27.3
	Wall	60
	Roof	30
Total		1,105.4

(5) Calculation for A type Unit Scaffolding System Weight

Type		Size (mm)	Weight (ton)	EA	Sum (ton)
A	Vertical	3,450	16	156	2,496
B	Horizontal (standard)	3,450	16	288	4,608
	Horizontal (for plank)	1,291	6.2	38	236
C	Bracing	3,450	16	168	2,688
D	Steel plank	500 x 1829	17	248	4,216
E	Accessories and Stairs (A+B+C) x 10%	-	-	-	1,003
Total Amount					15,246

[1] Seven (7) Units combined for one building (11.4 *6) + 15.2 = 83.6 ton

[2] Four (4) Buildings (7 unit/building) Scaffolding Weight = 83.6 ton * 4 building =333.4 ton

(6) Units

- a) One square foot (ft²) ≈ 0.093 square meter (m², SI).
- b) One pound per square foot (lb/ft²) ≈ 4.88 kilograms per square meter (kg/m²).
- c) One mile (mi) ≈ 1.609 kilometers (km, SI).
- d) One metric ton (t) = 103 kilograms (kg, SI) ≈1.102 short tons.
- e) CO₂-eq: Carbon dioxide equivalent (CO₂-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount to of carbon dioxide as the reference.