Developments in the Built Environment 20 (2024) 100550

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

Embodied carbon of BIM bridge models according to the application of off-site prefabrication: Precast concrete applied to superstructure and substructure

Hyunsik Kim [a], Seungjun Roh [b,*], Jeonghwan Kim [a]

[a] Department of Civil Engineering, Korea National University of Transportation, Chungju, 27469, South Korea
[b] School of Architecture, Kumoh National Institute of Technology, Gumi, 39177, South Korea

ARTICLE INFO

Keywords:
Off-site construction
Precast concrete
Carbon footprint
Embodied carbon
Building information modeling
Bridge lifecycle assessment

ABSTRACT

Embodied carbon (EC) changes of bridges using PC and RC, were analyzed using BIM and One-Click LCA. Identically shaped, concrete bridges (RC, PC, superstructure-only PC, and substructure-only PC) were modeled; the bills of quantity were extracted and input into the LCA software for EC comparison. As a result, it was found that applying PC instead of RC is not necessarily a guaranteed method to reduce the EC of bridges. Sensitivity analysis on the EC according to concrete waste and material transportation distances of all models were conducted. References from a carbon perspective were presented for applying PC separately to superstructure and substructure. As a result, solutions for the application of PC were derived considering the changes in concrete waste and transportation distance of concrete inputs. Conclusively, it was analyzed that substructure-only PC is effective in reducing EC overall, regardless of the amount of concrete waste and transportation distance of inputs.

1. Introduction

The construction industry contributes hugely to carbon emissions; therefore, it is necessary to develop technologies can reduce emissions (Wang et al., 2023) and provide a better understanding of carbon emissions from a lifecycle perspective. Off-site construction (OSC) is drawing attention as a crucial construction technology owing to its multiple benefits (Wang et al., 2019; Arslan et al., 2023; Jayawardana et al., 2023; Lee et al., 2024). Prefabrication technologies like OSC are gaining importance in the construction sector owing to their sustainability, energy efficiency, embodied carbon (EC) (greenhouse gas emissions associated with the whole life cycle, cradle to grave, of a product or building), and waste reduction, and productivity improvement (Wang et al., 2019; Arslan et al., 2023; Jayawardana et al., 2023; Lee et al., 2024; Teng et al., 2018; Kim et al., 2023a). However, from a structure lifecycle perspective, OSC technology cannot universally guarantee EC reduction (Teng et al., 2018; Kim et al., 2023a). Unlike reinforced concrete (RC) which is fabricated on-site, precast concrete (PC) is prefabricated in a factory and moved to the construction site – facilitating the consideration of embodied global warming potential (GWP) of the manufacturing process (Kim et al., 2023a). From an entire lifecycle perspective, such an approach could potentially result in higher EC emissions than even on-site construction.

Lifecycle assessment (LCA) has been used to evaluate and analyze environmental performance from this perspective. Several industry sectors have selected the LCA methodology to assess their carbon footprints. Carbon footprint is a measure that converts all the emitted greenhouse gases (GHGs) into CO_2 equivalents and is expressed in of weight (Li and Zheng, 2020); it has also been used to include carbon dioxide emissions from all the materials or energy consumed in a process (Li and Zheng, 2020; Liu et al., 2011; Yu et al., 2011). Thus, carbon footprints make it possible to evaluate the EC of entire structures including material and energy consumption in all lifecycle processes of construction structures.

Recent studies have combined LCA techniques with building information modelling (BIM) technology because BIM of its additional benefits relative to traditional, structural modeling methods (Ranathungage et al., 2018; Bueno et al., 2018; Migilinskas et al., 2013; Al-Ashmori et al., 2020; Musa et al., 2018); therefore, the construction sector has explored various methods for LCA–BIM combined utilization. The utilization of LCA–BIM methodologies at initial stages of construction projects can become critical for decision making even at later stages of the project. Designs with the lowest carbon impact must be selected for structure, materials, and design methods (Guignone et al., 2023).

This study utilized a BIM bridge model as a representative structure

* Corresponding author.
E-mail address: roh@kumoh.ac.kr (S. Roh).

https://doi.org/10.1016/j.dibe.2024.100550
Received 28 February 2024; Received in revised form 11 September 2024; Accepted 25 September 2024
Available online 1 October 2024

Abbreviations

BIM	building information modelling
BoQ	bill of quantity
EC	embodied carbon
EPD	environmental product declaration
GHG	greenhouse gases
GWP	global warming potential
LCA	life cycle assessment
LCI	lifecycle inventory
LCIA	lifecycle impact assessment
PC	precast concrete
RC	reinforced concrete
RMC	ready mixed concrete

in civil engineering, for carbon footprint assessment and analysis, to identify the conditions under which the lifecycle EC of PC structures can be reduced. This study extracted the bill of quantity (BoQ) of each of four models of identically shaped, concrete bridge structures (i.e., all RC, all PC, PC for superstructure, and PC for substructure) and input them to the LCA tool for comparing the lifecycle global warming potential (GWP) of each model. Additionally, based on the sensitivity analysis of the change in the concrete waste and material transportation distance from the fabrication to bridge construction site, this study compared the GWPs of bridges entirely constructed using RC with those using complete or partial PC. In conclusion, this study suggests the conditions that should be considered when replacing RC with PC bridge structures to reduce EC. This study is significant in the extension of LCA–BIM, from buildings to bridges; it is expected to provide solutions for alternative PC and RC applications beyond a simple comparison of GWP of PC and RC structures, in the early stages of bridge projects. In particular, this study is the first to present references for the sustainable application of prefabricated concrete in bridges by demonstrating changes in EC when PC is separately applied to bridge superstructure and substructure. Additionally, this study features a distinctive approach from previous LCA studies on PC bridges by considering the changes in concrete waste generated during the construction stage and the transportation distance of inputs when applying PC and RC to the bridge superstructure and substructure.

2. Literature review

2.1. Lifecycle carbon footprint

LCA is one of the internationally standardized, environmental assessment methods and is defined by ISO 14040 as the compilation and evaluation of all inputs, outputs, and potential environmental impacts of a product system throughout its lifecycle (Kloepffer, 2008; Iso, 2006; Vasishta et al., 2023). LCA has been widely utilized, globally, to analyze the cradle-to-grave environmental impacts of various products or services, that is, from raw material acquisition to end-of-life (Finnveden et al., 2009; Joshi, 1999). LCA is generally conducted in four phases: (1) goal and scope definition, (2) lifecycle inventory (LCI), (3) lifecycle impact assessment (LCIA), and (4) interpretation. As for goal and scope definition, it is possible to establish all research prerequisites including functional units, system boundaries, life periods, data requirements, assumptions, and limitations, as well as setting the application of the research, and the intended audience. At the LCI phase, it is possible to quantitatively measure the inputs and outputs of the established system, and it is a crucial process that is repeatedly supplemented to meet research objectives (Joshi, 1999). The LCIA phase is to consider potentially relevant environmental impacts and select appropriate impact assessment methods and relevant impact categories depending on the goal and scope definition (Vasishta et al., 2023; Finnveden et al., 2009). The impact categories are highly diverse including global warming potential, eutrophication potential, ozone layer depletion, acidification potential, photochemical oxidation, land use, and water use effects. LCA studies often focus on GWP due to worsening global warming.

Green building certificate systems mandate GWP evaluation in LCAs related to the construction sector. There are various green building certificate systems such as: leadership in energy and environmental design in the U.S.; building research establishment environmental assessment method in the U.K.; green standard for energy and environmental design in South Korea (Pai and Elzarka, 2021; Ferreira et al., 2023; Kim et al., 2023b, 2023c). LCAs have been conducted on construction materials like ready mixed concrete and concrete structural products such as PC, pre-stressed concrete, and piles, as per the environmental product declarations of several countries; similarly, GWP has been adopted as the main impact category of carbon footprint assessment of each construction product (AzariJafari et al., 2023; Witte and Garg, 2024; Rangelov et al., 2021; Novakova et al., 2023). This is the standard practice in various studies on the environmental impacts of bridge structures, and GWP impact analysis has been conducted in diverse bridge LCA studies, as shown in Table 1 (Hammervold et al., 2013; Du and Karoumi, 2013; Penadés-Plà et al., 2018; Du et al., 2014, 2018; O'Born, 2018; Khorgade et al., 2022). Therefore, it is crucial to consider carbon footprint in construction, and more studies are warranted with precise insights from the GWP perspective.

2.2. LCA–BIM integration

BIM has been integrated with LCA and utilized to optimize construction planning and design and to improve the environmental performance of construction structures. Several types of LCA–BIM integrations have been studied with an analysis of their advantages and disadvantages (Ranathungage et al., 2018; Bueno et al., 2018). According to some reviews, LCA–BIM integrations can be categorized into five types: (1) exporting BoQ from the BIM environment to LCA tools; (2) exporting to the LCA tool using the industry foundation classes (IFC) format; (3) processing in a BIM viewer tool before being sent to the LCA tool; (4) using BIM plugins in BIM software, such as Tally; (5) developing secondary tools in BIM environment, in which the information is added to the BIM model (Obrecht et al., 2020; Cheng et al., 2022; Wastiels and Decuypere). Braholli classified the LCA–BIM integrations into three types: (1) the conventional method; (2) the static method with BIM tools; and (3) the dynamic BIM integrated method (Braholli, 2020). In particular, among several LCA–BIM types, the conventional method

Table 1
Impact categories considered in previous, bridge LCA studies.

Reference	※ Environmental impact categories	Study focus
Hammervold et al. (2013)	ADP, AP, EP, GWP, ODP, POCP	LCA study of three superstructure types
Du and Karoumi (2013)	ADP, AP, EP, GWP, ODP, POCP	LCA of two railway bridges with different superstructure designs
Penadés-Plà et al. (2018)	18 categories including GWP, ODP, POCP	LCA of a prestressed concrete precast bridge
Du et al. (2018)	13 categories including GWP, ODP, POCP	LCA comparison between concrete frame and soil steel short span bridges
Du et al. (2014)	12 categories including GWP, ODP, POCP	LCA of five types of bridges with different superstructure designs
O'Born, 2018	ADP, ADP (fossil fuels), AP, EP, GWP, ODP, POCP	LCA study of a large-scale timber bridge
Khorgade et al. (2022)	11 categories including ADP, AP, EP, GWP, ODP, POCP	LCA comparison between carbon fiber reinforced polymer and steel reinforced bridges

※ Notes: abbreviations of major impact categories.
ADP: Abiotic depletion, AP: Acidification, EP: Eutrophication, GWP: Global warming, ODP: Ozone layer depletion, POCP: Photochemical oxidation.

(exporting the BoQ from the BIM environment to LCA tools) is the most commonly utilized (Guignone et al., 2023; Obrecht et al., 2020; Cheng et al., 2022; Wastiels and Decuypere; Braholli, 2020).

The conventional method, as shown in Fig. 1, can be broadly divided into two steps: (Step 1) automatically or manually extracting BoQ from the BIM model; (Step 2) Inputting the extracted values into the LCA tool to generate LCA results by connecting these values with the environmental impact indicators.

This type of LCA–BIM has several disadvantages compared to other types owing to the separated steps. First, the assessment is time consuming, and the manual data input is error prone. LCA results are not directly linked to the model, which can make the decision-making process difficult and complicated. Also, specialized knowledge is needed to perform separate LCA procedures and calculations (Guignone et al., 2023).

But the conventional method has the following advantages: there is no need to purchase plug-ins to the modeling platform to perform LCA or to have in-depth knowledge of specific BIM segments such as visual programming and IFC data processing (Guignone et al., 2023). There are a few limitations in utilizing other LCA–BIM methodologies. Areas to be improved include tool complexity, the data linkage difficulties in these programs, data interoperability concerns between different software programs, and the data exchange and implementation problems of LCA tools and BIM software (Ajayi et al., 2015). The LCA process sometimes requires professional interpretation and judgment; if other LCA–BIM methodologies are utilized, it may be difficult to compare the results of similar designs (Diaz and Anton, 2014; Iris et al., 2011). Therefore, most studies implement LCA–BIM using the conventional method (Guignone et al., 2023; Cheng et al., 2022). Although there are several options for LCA–BIM, there is no consensus on which type is the most appropriate (Ajayi et al., 2015). In the end, it is assumed that a method should be selected in line with the purpose and target of LCA.

2.3. *LCA of concrete structures prefabricated off-site*

Off-site prefabrication of construction structures is more advantageous in carbon reduction than traditional construction methods are. However, according to a review study by Teng et al., prefabrication does not always guarantee EC reduction in construction structures (Teng et al., 2018). In steel, prefabricated structures, high EC saving is possible through steel reuse; concrete based prefabricated structures are difficult to reuse, so there may not be a dramatical advantage in terms of EC reduction (Teng et al., 2018; Aye et al., 2012). Kim et al. calculated embodied lifecycle GWP of PC and concrete pile factory production, which are representative prefabricated concrete products; both concrete products were found to have values similar to high strength RC for general on-site placement (Kim et al., 2023a). Therefore, it is necessary to examine prefabricated concrete structure conditions to achieve EC reduction.

Meanwhile, previous carbon footprint studies focusing on buildings have conducted in-depth research on the carbon emission impacts associated with the use of factory-made prefabricated concrete products. In the case of Li et al. (2021a), the carbon footprint during the materialization stage of PC stairs was assessed (Li et al., 2021a). A detailed assessment was conducted on the production, transportation, and construction substages of PC stairs within the system boundary of the study. Moreover, by conducting a case study on prefabricated stairs in five buildings in China, the study revealed a linear relationship between carbon emissions and building height, cubic quantity, and unit cost. Thus, by analyzing not only the EC from the production of prefabricated concrete products but also their application from a whole building structure perspective, it is possible to identify factors that influence the carbon emissions resulting from the use of prefabricated concrete. Several studies have analyzed the carbon footprint of whole building structures based on prefabricated components or prefabrication rates across multiple buildings to provide valuable references for the application of prefabricated concrete in buildings (Li et al., 2021b, 2022). In particular, by utilizing BIM in the research process, it was possible to efficiently assess the carbon footprint of various building models and compare them across different models. Li et al. (2023) also utilized BIM models of five buildings to analyze carbon emissions associated with the application of prefabricated concrete composite plates (Li et al., 2023). Furthermore, Geographic Information System (GIS) technology was additionally employed for analyzing the spatial distribution of carbon emissions along transport routes from the factory to the construction site. Thus, research on the carbon footprint of prefabricated concrete has primarily been conducted in depth with a focus on buildings. In contrast, research on the carbon emissions associated with the application of prefabrication in concrete bridges is still lacking. It is necessary to analyze the impacts of prefabrication across various bridge models to sustainably apply prefabricated concrete to bridges. Additionally, cases where technologies such as BIM are utilized to efficiently conduct bridge LCA analyses will provide valuable references for future research on various bridge environmental assessments.

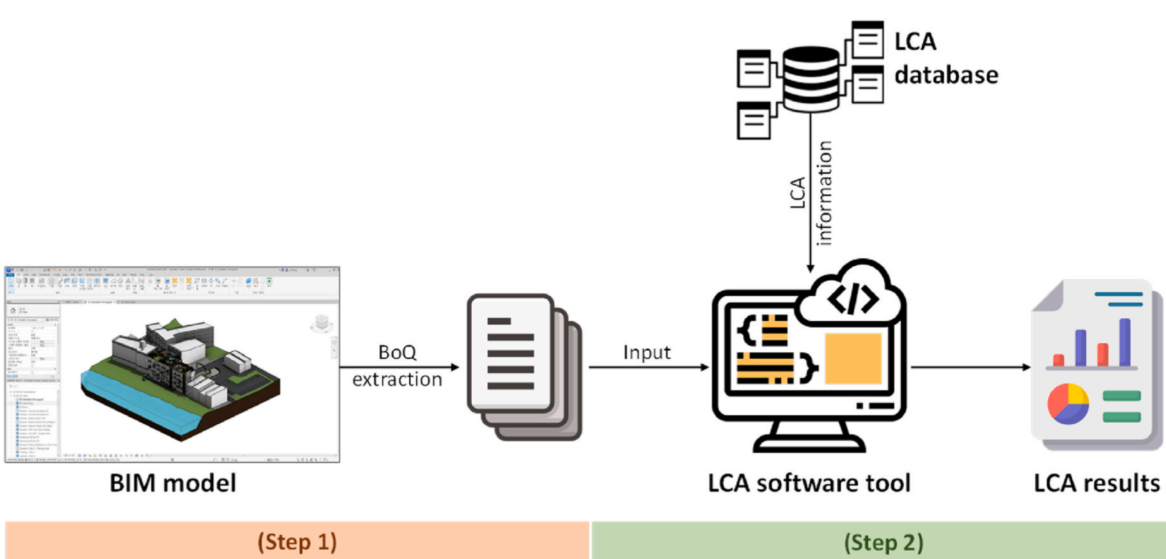

Fig. 1. The conventional method of LCA using BIM (Guignone et al., 2023).

2.4. Research direction according to literature review

In the construction sector, it is essential to estimate and analyze the GWP of structures through life cycle carbon assessments. Therefore, research on the whole life cycle embodied carbon of bridge structures is also necessary. However, while numerous studies have been conducted on the carbon emissions associated with off-site prefabrication in buildings, research focused on concrete bridges remains insufficient. Therefore, this study aims to address this research gap by utilizing the LCA methodology to investigate the changes in life cycle EC resulting from the application of prefabrication in concrete bridges. In performing LCA for structures, extracting the BoQ information is crucial, and with the increased use of BIM in structural designs, various methods for integrating BoQ information into LCA tools have been proposed. Among these methods, when professional interpretation and judgment from an LCA perspective are required, the conventional method for extracting BoQ is considered the most suitable approach. Therefore, this study intends to use the conventional method to analyze trends in EC across various bridge models.

3. Materials and methods

This study first used a BIM tool to model four RC and PC bridge structures, extract BoQ information for each model, input the information into the LCA tool, and assess their EC by carbon footprint assessment. Then, the GWP indices of each model were compared, and sensitivity analysis was performed with respect to changes in concrete waste and transportation distance. The brief framework of this study can be found in Fig. 2.

3.1. Modeling and BoQ information extraction

3.1.1. BIM bridge model

This study targeted concrete bridge structures as shown in Fig. 3. Autodesk's Revit program was utilized for modeling concrete structures, and the modeling process was performed after dividing structures into superstructure and substructure.

The concrete structure of the superstructure comprises a box girder, whereas that of the substructure comprises two piers and abutments. Here, the pier is composed of pier foundation (F_pier), pier column (pier_column), and pier cap (pier_cap), whereas the abutment consists of the main abutment structure (abutment_main), wingwalls (abutment_wing), and abutment foundation (F_abutment) including the abutment stem and backwall.

3.1.2. BoQ extraction

To perform a multifaceted analysis of the BoQ and LCA results of such a structure, a conventional LCA–BIM method was used. As shown in Fig. 4, four cases were modeled and BoQ was extracted to analyze ECs for the cases where RC or PC were applied to the entire concrete structure of the bridge and RC or PC were separately applied to the superstructure and substructure, respectively. In Case 1 (RC-RC), superstructure and substructure were all constructed on-site. In Case 2 (PC-PC), the superstructure and substructure were all prefabricated off-site. In Case 3 (PC-RC), only the superstructure was prefabricated off-site. In Case 4 (RC-PC), only the substructure was prefabricated off-site. However, in all cases, the foundation of the pier and abutment was modeled as RC fabricated on-site.

The RC quantity should include waste; this study used the concrete waste review (eight studies) by Kazaz et al. (2015) – concrete waste generation ranges from 1% to 13.2% of the designed quantity in construction projects. Thus, this study set the premium rate of RC to the median – 7.1%, and the RC input reflecting the extra amount was calculated using Equation (01). Here, V_input (m^3) is the input volume of concrete, V_model (m^3) is the measured volume of concrete (from the project model), and W_model (%) is the ratio of concrete waste to V_model. BoQ for the four cases is summarized in Table 2.

$$W\_model = (V\_input - V\_model) / V\_model$$

$$V\_input = V\_model \times (1 + W\_model) \qquad \text{(Equation 01)}$$

3.2. Carbon footprint assessment

This study used the One-Click LCA software, which enables the utilization of environmental product declaration (EPD) data to perform LCA of structures. One-click LCA classifies lifecycle stages into production, transportation, construction, and end-of-life stages to evaluate the EC and GWP of the bridge per stage. The system boundary for the carbon footprint assessment in this study can be found in Fig. 5.

3.2.1. Production stage

The production stage in this study evaluates the EC emissions from the process of collecting natural resources to the process of manufacturing construction materials. In this stage, as for RC, the process of producing reinforcement steel (rebar) and ready mixed concrete (RMC) is evaluated; for PC, the process is assessed from the input of reinforcement and RMC to the production of PC structures in a factory. This study utilized the EPD database of Norway, which provides EPD data for various concrete products, as unit GWP values for the production of RC materials used on-site and unit GWP values for the production of PC products (The Norwegian EPD Foundation). Unlike RC, the EPD data for PC products already reflect construction waste in the prefabrication process and do not need adjustment. The EPD data utilized in this study to calculate GWP in the production stage is shown in Table 3.

3.2.2. Transportation stage

The transportation stage in this study evaluates the carbon emissions of transporting construction materials manufactured in the production

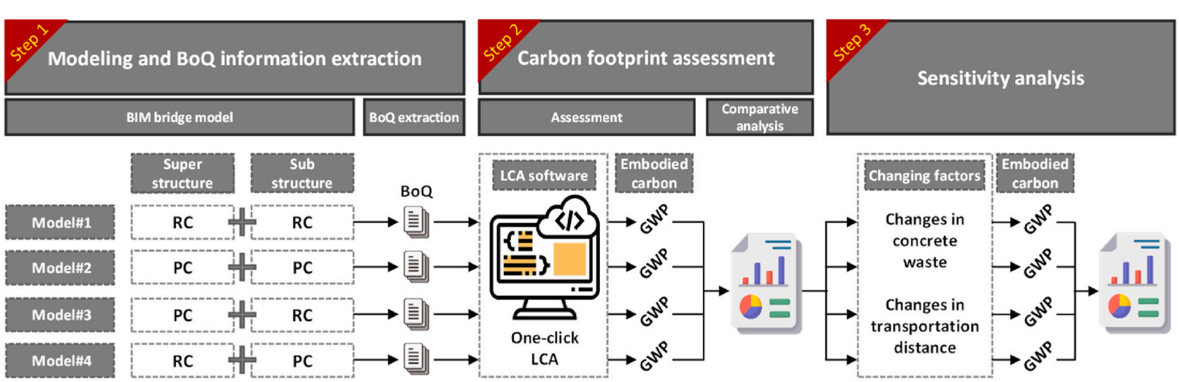

Fig. 2. Brief framework of this study.

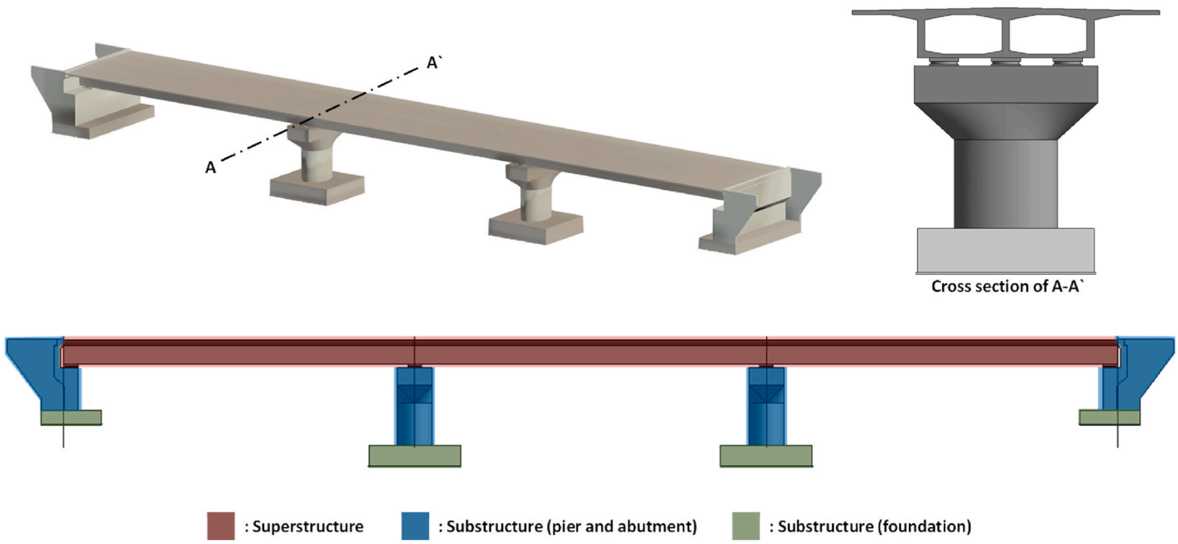

Fig. 3. Composition of the research target – concrete structures of the bridge.

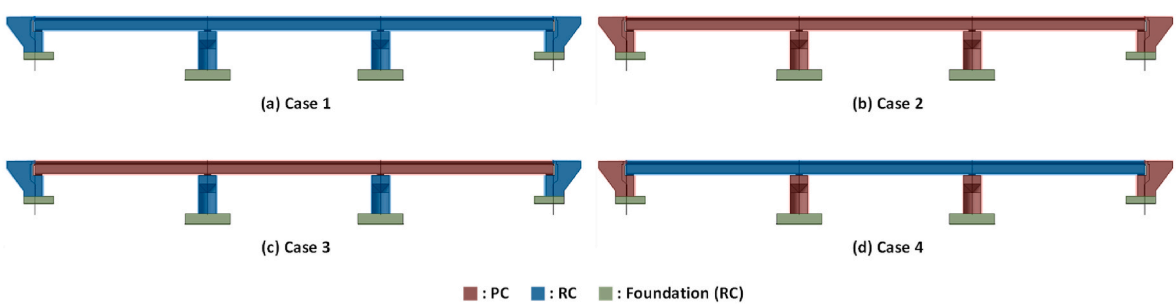

Fig. 4. Modelling cases.

stage to the construction site. In this stage, for RC, the process of transporting reinforcement steel (rebar) and RMC to the construction site is evaluated, and for PC, the process of transporting prefabricated structures from the factory to the site is assessed. This study assumes that a concrete mixer truck is utilized to transport RMC and a trailer is used to transport rebar and PC for the assessments, as shown in Table 4 (Ecoinvent. Ecoinvent v3, 2016). The transportation distance of each material is set to 60 km for RMC and PC, and 370 km for rebar, reflecting the default value set in the One-Click LCA program. As the GWP changes are expected to be considerable owing to the transportation distances of RMC and PC, the main materials used in concrete structures; more analysis was conducted through sensitivity analysis.

3.2.3. Construction stage

In the construction stage, carbon emissions from on-site construction, installation processes, and transportation and disposal of construction waste were evaluated. For construction waste, the GWP value in the construction stage was calculated through One-Click LCA by assuming that most of the extra amount of RC was waste. One-Click LCA is set to input the extra amount of concrete compared to V_input, not the extra amount of concrete compared to V_model, when entering the ratio of construction waste; as shown in Equation (02), W_input (%), which represents the ratio of concrete waste to V_input, was calculated and input.

$$W\_input = (V\_input - V\_model) / V\_input \qquad \text{(Equation 02)}$$

3.2.4. End-of-life stage

In the end-of-life stage in this study, carbon emissions from the transport and disposal of waste generated after the end of the bridge's lifespan were evaluated. However, for PC, waste is generated during prefabrication, and for RC, the waste generated is added into the equation. Since carbon emissions from the waste of PC and RC were already included at the production stage and construction stage, respectively, they were excluded at the end-of-life stage to avoid duplication of GWP values.

3.3. Sensitivity analysis

This study analyzed changes in EC in Cases 1, 2, 3, and 4 through two sensitivity analyses: GWP according to changes in concrete waste (Analysis 1); GWP according to changes in transportation distance (Analysis 2). Here, Analysis 1 was performed to confirm the decreasing tendency of EC with less on-site concrete waste when applying PC to the bridge. To this end, the percentage of concrete waste (W_model) was changed from 0 to 15% in 1% increments to calculate GWP of all cases. Meanwhile, Analysis 2 was conducted to examine the change in total EC according to the differences in the RMC and PC transportation distances to the construction site. To this end, the transportation distance was changed from 0 to 100 km in 10 km increments to calculate the total GWP of all cases.

Table 2
Quantity of all cases.

Case	Concrete structure classification		Material type	Input quantity	Unit
	Group	Family name			
Case 1	Superstructure	box girder	RMC	2734.09	m^3
			Reinforcement	326,841.20	kg
	Substructure	pier_column 1	RMC	103.46	m^3
			Reinforcement	25,118.64	kg
		pier_column 2	RMC	103.46	m^3
			Reinforcement	25,118.64	kg
		pier_cap 1	RMC	272.60	m^3
			Reinforcement	66,182.66	kg
		pier_cap 2	RMC	272.60	m^3
			Reinforcement	66,182.66	kg
		abutment_main 1	RMC	398.28	m^3
			Reinforcement	96,696.30	kg
		abutment_main 2	RMC	398.28	m^3
			Reinforcement	96,696.30	kg
		abutment_wing 1	RMC	46.71	m^3
			Reinforcement	11,339.83	kg
		abutment_wing 2	RMC	46.71	m^3
			Reinforcement	11,339.83	kg
Case 2	Superstructure	box girder	PC	2591.71	m^3
	Substructure	pier_column 1	PC	99.59	m^3
		pier_column 2	PC	99.59	m^3
		pier_cap 1	PC	262.40	m^3
		pier_cap 2	PC	262.40	m^3
		abutment_main 1	PC	383.38	m^3
		abutment_main 2	PC	383.38	m^3
		abutment_wing 1	PC	44.96	m^3
		abutment_wing 2	PC	44.96	m^3
Case 3	Superstructure	box girder	PC	2591.71	m^3
	Substructure	pier_column 1	RMC	103.46	m^3
			Reinforcement	25,118.64	kg
		pier_column 2	RMC	103.46	m^3
			Reinforcement	25,118.64	kg
		pier_cap 1	RMC	272.60	m^3
			Reinforcement	66,182.66	kg
		pier_cap 2	RMC	272.60	m^3
			Reinforcement	66,182.66	kg
		abutment_main 1	RMC	398.28	m^3
			Reinforcement	96,696.30	kg
		abutment_main 2	RMC	398.28	m^3
			Reinforcement	96,696.30	kg
		abutment_wing 1	RMC	46.71	m^3
			Reinforcement	11,339.83	kg
		abutment_wing 2	RMC	46.71	m^3
			Reinforcement	11,339.83	kg
Case 4	Superstructure	box girder	RMC	2734.09	m^3
			Reinforcement	326,841.20	kg
	Substructure	pier_column 1	PC	99.59	m^3
		pier_column 2	PC	99.59	m^3
		pier_cap 1	PC	262.40	m^3
		pier_cap 2	PC	262.40	m^3
		abutment_main 1	PC	383.38	m^3
		abutment_main 2	PC	383.38	m^3
		abutment_wing 1	PC	44.96	m^3
		abutment_wing 2	PC	44.96	m^3
Cases 1, 2, 3, 4	Substructure (Foundation)	F_pier 1	RMC	514.71	m^3
			Reinforcement	29,509.80	kg
		F_pier 2	RMC	514.71	m^3
			Reinforcement	29,509.80	kg
		F_abutment 1	RMC	397.34	m^3
			Reinforcement	22,403.49	kg
		F_abutment 2	RMC	397.34	m^3
			Reinforcement	22,403.49	kg

4. Results and discussions

4.1. Carbon footprint assessment and analysis

Fig. 6 shows the result of the carbon footprint assessment for the four bridge model cases. The total GWP of Cases 1 and 2 was 2606.64 tonCO2-eq and 2631.46 tonCO2-eq, respectively. However, GWP in the production stage in Cases 1 and 2 was 2240.21 tonCO2-eq and 2482.16 tonCO2-eq, respectively, indicating that the value of Case 2 was found to be 241.95 tonCO2-eq larger than Case 1 (9.28% compared to the total GWP of Case 1). This outcome originates from the GWP reflected in the production stage in the off-site production process of PC. Unlike Case 1 in which RMC and reinforcement are directly used in the construction site, it was found that Case 2, where concrete materials and reinforcement are transported to the factory before use for prefabricating, had higher GWP. The GWP of Case 2 was lower than that of Case 1 in the

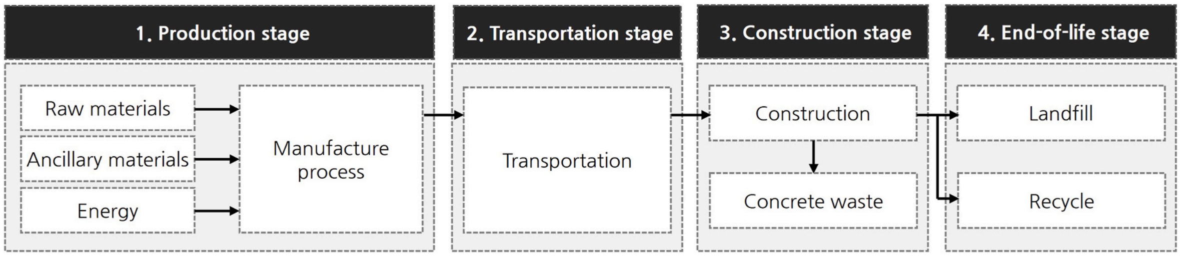

Fig. 5. System boundary of assessment.

Table 3
Data utilized for calculating GWP at the production stage (The Norwegian EPD Foundation).

Structure	Material type	Extra data information	Unit
RC	Ready mix concrete (for structure)	Excluding rebar, C45/55	kgCO2-eq/m^3
	Ready mix concrete (for foundation)	Excluding rebar, C20/25	kgCO2-eq/m^3
	Reinforcement steel (Rebar)	7850 kg/m3	kgCO2-eq/kg
PC	Precast concrete (for superstructure)	PC beam, reinforced, C45/55, 2,500 kg/m^3	kgCO2-eq/kg
	Precast concrete (for substructure)	PC column, C45/55, 2,400 kg/m^3	kgCO2-eq/kg

Table 4
Data utilized for calculating GWP at the transportation stage (Ecoinvent. Ecoinvent v3, 2016).

Transportation type	Extra data information	Unit
Concrete mixer truck (for RMC)	8 m^3, 100% fill rate	kgCO2-eq/ton·km
Trailer combination (for reinforcement, PC)	40 ton, 100% fill rate	kgCO2-eq/ton·km

transportation and construction stages by 68.60 tonCO2-eq (2.63% compared to the total GWP of Case 1), and 123.69 tonCO2-eq (4.75% compared to the total GWP of Case 1), respectively. Such results indicate that the EC reduction in prefabrication is highly influenced by transportation and construction stages. Additionally, although the difference in GWP values between the two cases was not large in the end-of-life stage, GWP of Case 2 was found to be 24.82 tonCO2-eq lower than that of Case 1 (0.95% compared to the total GWP of Case 1). This result demonstrates that applying PC instead of RC is not necessarily a guaranteed method to reduce carbon emissions. Meanwhile, the total GWP in Case 3 was 2736.53 tonCO2-eq, which was 129.89 tonCO2-eq higher than in Case 1 (4.98% compared to the total GWP of Case 1), whereas that of Case 4 was 2501.57 tonCO2-eq, which was 105.07 tonCO2-eq lower than Case 1 (4.03% compared to the total GWP of Case 1). This means that when a prefabricated PC structure is applied to the substructure of the bridge analyzed in this study, the EC is the lowest; when applying PC only to the superstructure, the EC may be higher than when constructing the entire concrete structure of the bridge on-site. As such, this study found that replacing concrete structures with prefabricated concrete does not always guarantee advantages in terms of carbon emission.

In addition, Fig. 7 indicates the outcomes of calculating the GWP contribution rate per lifecycle stage of four cases. The GWP contribution rate in all cases was found to be highest at the production stage, and the more PC was applied, the higher the rate (85.94%, 94.33%, 91.07%, and 89.16%, respectively, from Cases 1–4). This is the result that reflects GWP generated in the process of producing PC in a factory; it was confirmed that GWP reduction through the efficiency of the production process is crucial in reducing EC of the bridge in line with the application of PC structures.

4.2. *Sensitivity analysis of changes in construction concrete waste (analysis 1)*

Fig. 8 shows the changes in GWP in Cases 1, 2, 3, and 4 according to changes in concrete waste generated on-site through Analysis 1. The increase in the total GWP in line with the higher percentage of concrete waste was confirmed to be significantly larger in Case 1 than in Case 2; the change particularly came from the production stage or the construction stage. Additionally, the increase in the total GWP resulting from the rise in the percentage of concrete waste in Case 3 and Case 4 was smaller compared to Case 1, but larger compared to Case 2. As for Case 1, as the concrete waste increased from 0 to 15%, the total GWP increased by 663.32 tonCO2-eq (28.93% compared to when concrete waste was 0%); as for Case 2, it increased by 140.75 tonCO2-eq (5.49% compared to when concrete waste was 0%). Additionally, as for Case 3 and 4, the total GWP increased by 364.61 tonCO2-eq (14.23% compared to when concrete waste was 0%) and 439.12 tonCO2-eq (19.15% compared to when concrete waste was 0%), respectively. In particular, the combined GWP increase from the production and construction stages was 645.42 tonCO2-eq (97.30% of the total GWP increase) for Case 1, 135.76 tonCO2-eq (96.45% of the total GWP increase) for Case 2, 354.53 tonCO2-eq (97.24% of the total GWP increase) for Case 3, and 426.32 tonCO2-eq (97.09% of the total GWP increase) for Case 4, respectively, confirming that there was an enormous influence of concrete waste in the two stages. This finding is attributable to the greater production of concrete and reinforcement at the production stage in proportion to the extra amounts, and larger quantities of construction waste to be transported. In Case 1, the increase in GWP becomes larger as the concrete waste increases throughout the bridge as compared to Case 2, 3, and 4. As for the bridge model utilized in this study, it was confirmed that the percentage of concrete waste exceeded 7.81% and the EC in Case 2 became lower than that in Case 1. Additionally, it was observed that the EC of Case 1 surpasses that of Case 3 when the percentage of concrete waste exceeds 13.56%, and similarly, the EC of Case 4 surpasses that of Case 2 when the percentage of concrete waste exceeds 13.67%. Thus, when the percentage of concrete waste reaches 15%, the EC is highest in the following order: Case 1, Case 3, Case 4, and Case 2.

Furthermore, to examine the trend of carbon reduction achieved by using PC compared to RC structures, the percentage of GWP reduction for Case 2, Case 3, and Case 4 relative to Case 1 was calculated based on the increase in concrete waste (as in Fig. 9). As a result, the change in the percentage of GWP reduction was analyzed as per the higher percent of concrete waste and found to increase in a negative quadratic curve. Especially, when the concrete waste generated from the construction site is 0%, GWP in Cases 2 and 3 was found to increase by 11.87% and 11.78%, respectively, compared to Case 1; when the concrete waste is 15%, GWP can be reduced up to 8.47%, 0.97%, respectively. When constructing an RC structure on-site, waste generated at the site can be reduced, thereby reducing the EC emissions of the bridge, when compared to the case of using a PC structure. The EC of the bridge can be

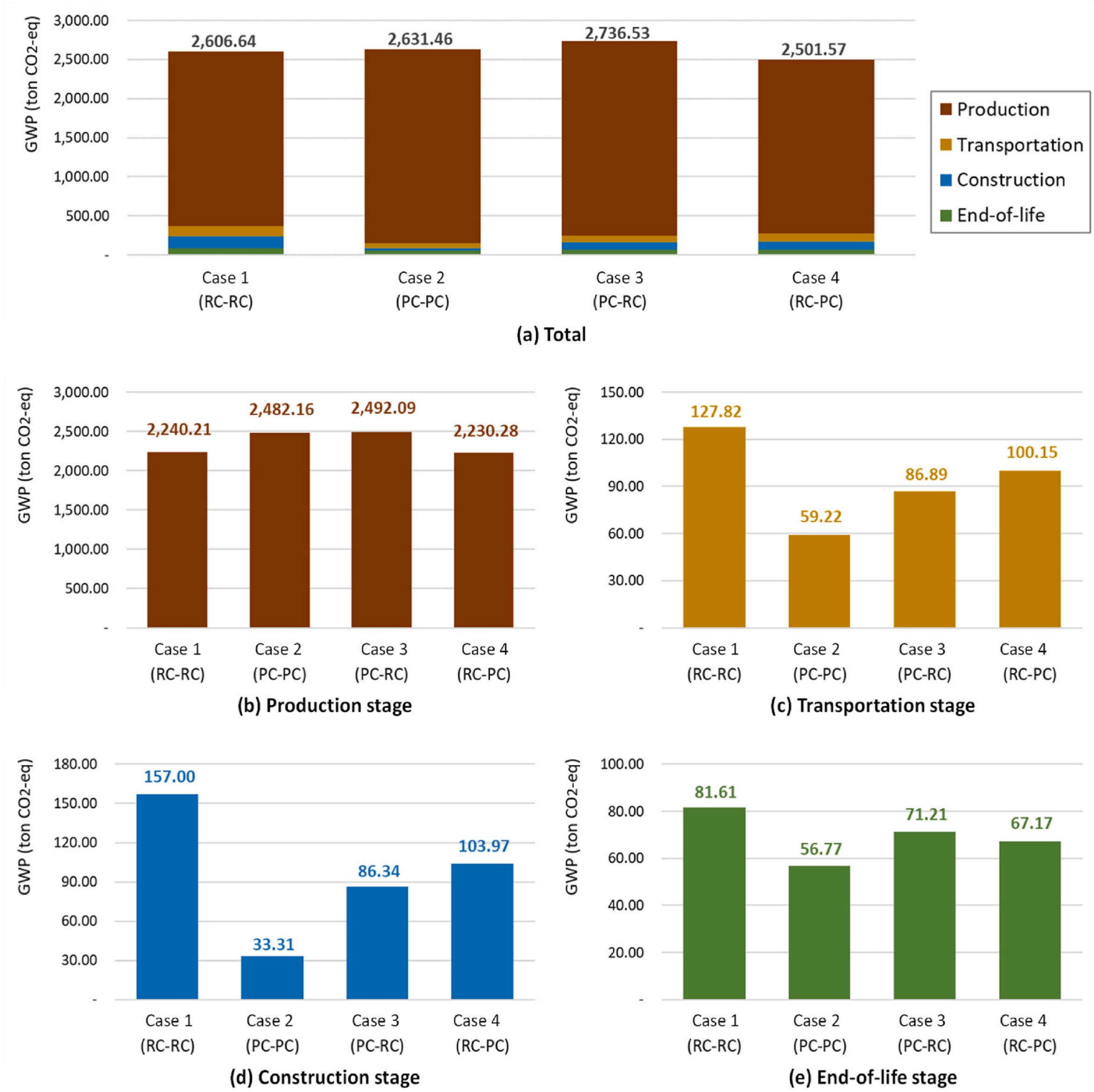

Fig. 6. Results of carbon footprint assessment for Cases 1, 2, 3, and 4.

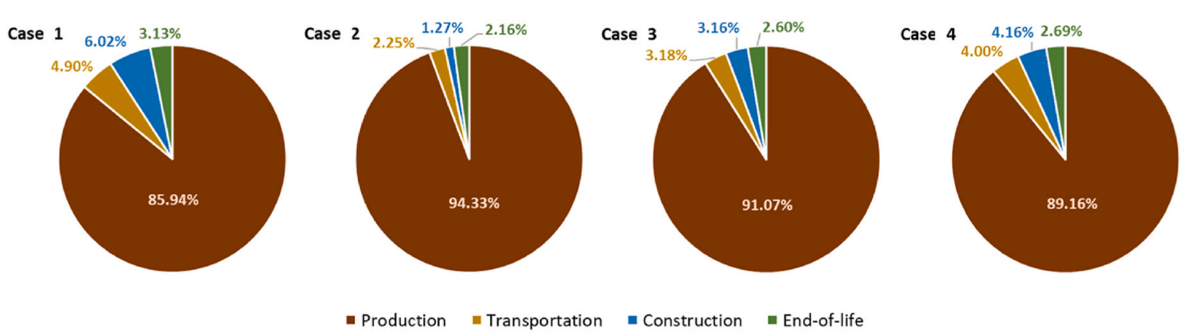

Fig. 7. GWP contribution rate per lifecycle stage.

reduced by applying PC structures to the overall bridge or superstructure construction where a great amount of waste is expected to be generated. Meanwhile, the EC in Case 4 was only 0.01% higher compared to Case 1 when concrete waste was 0% while the EC in Case 4 was 7.58% lower compared to Case 1 when concrete waste increased to 15%. This indicates that Case 4 is generally effective in reducing EC, regardless of the amount of concrete waste generated.

4.3. Sensitivity analysis of changes in transportation distance (analysis 2)

Furthermore, based on Analysis 2, which was performed to examine the change in total EC between Cases 1, 2, 3, and 4 in line with the

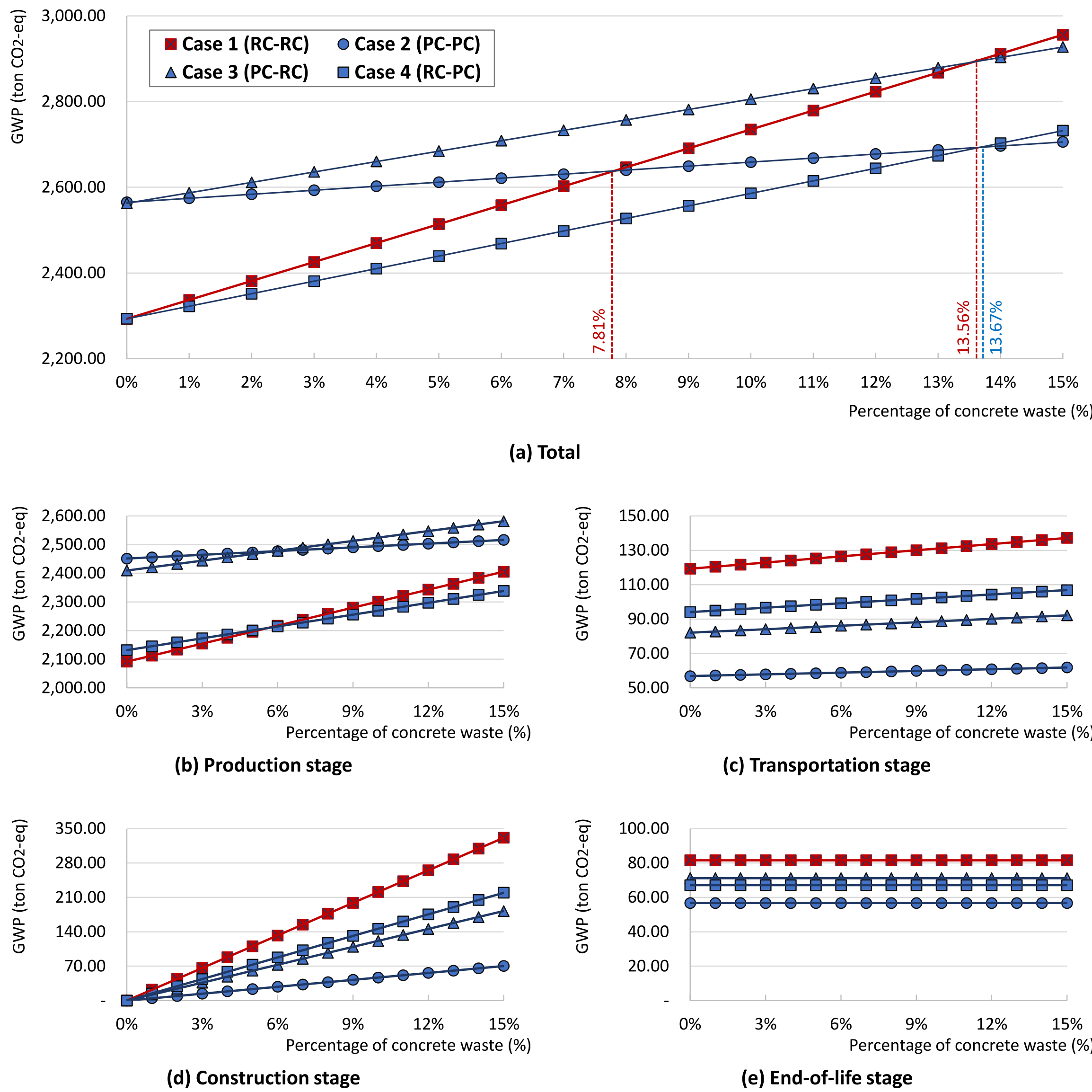

Fig. 8. Changes in GWP of Cases 1, 2, 3, and 4 in line with changes in concrete waste on-site (Analysis 1).

change in the distance of transporting the RMC and PC to the construction site, the changes in total GWP in all four cases according to transportation distance were derived as shown in Fig. 10. As a result, the increase in GWP in line with the longer transportation distance was found to be significantly larger in Case 1 than in Case 2, which is similar to the trend in Analysis 1. As for Case 1, as the transportation distance increased from 0 to 100 km, the total GWP increased by 193.45 tonCO2-eq (7.77% compared to when the transportation distance was 0 km); in terms of Case 2, it increased by 39.35 tonCO2-eq (1.51% compared to when the transportation distance was 0 km). This result was derived from the fact that the GWP per ton·km of the concrete mixer truck used to transport RMC was larger than that of the trailer. However, considering that concrete should transported by a concrete mixer truck within a maximum of 2 h, and generally within 1 h or 1 h and 30 min, it is expected that the actual transport distance of RMC is unlikely to exceed 100 km (British standard institution (BSI), 2023; Vruno, 2011). This implies that there is a certain limit to the increase in GWP as the transportation distance of RMC increases. Considering the nature of PC structures that have nearly constant GWP with transportation distance, the reduction of EC through the reduced distance is negligible. RC structures that are constructed on-site can benefit in carbon reduction from the reduction of RMC transportation distance. Meanwhile, in Cases 3 and 4, the total GWP increased by 132.96 tonCO2-eq (5.00% compared to when the transportation distance was 0 km) and 156.74 tonCO2-eq (6.51% compared to when the transportation distance was 0 km), respectively, as the transportation distance increased from 0 km to 100 km. Since the increasing rates of both cases are similar to Case 1, the result shows that the EC remains highest in the following order within a 100 km transportation distance: Case 3, Case 1, and Case 4. This indicates that there is no significant impact on the ranking of EC among Cases 1, 3, and 4 due to changes in the transportation distance of major structural materials. Case 4 is generally the most effective model in reducing EC.

4.4. Discussions

This study utilized BIM generated models and an LCA tool to examine how RC structures, constructed on-site, and PC structures, prefabricated off-site, affected the EC of concrete bridges. As shown in Table 5, PC structures have been generally considered more environmentally friendly than RC structures, but this study found that RC structures can also contribute to EC reduction under diverse conditions. In construction

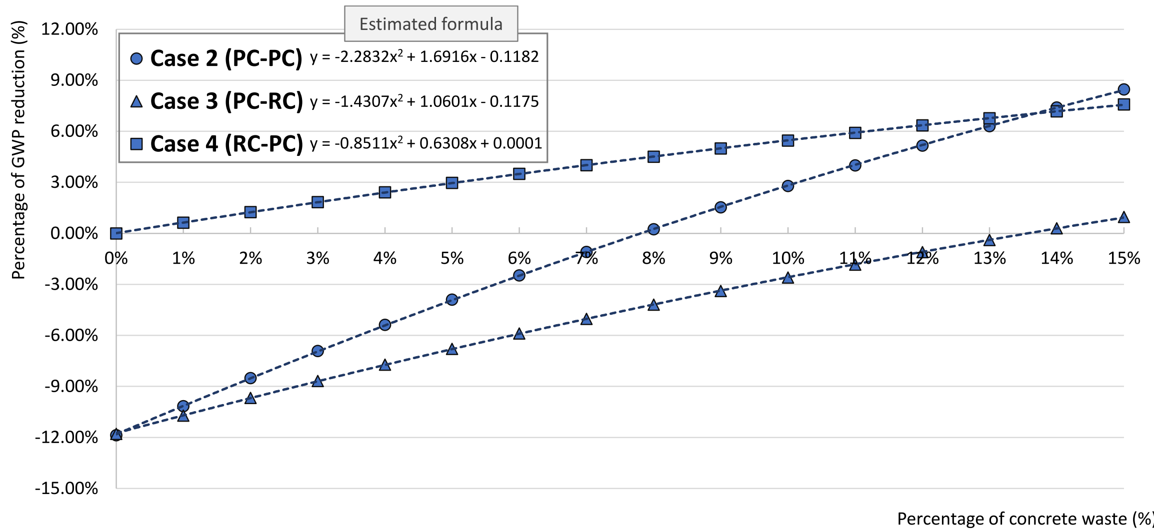

Fig. 9. Changes in percentage of GWP reduction of Cases 2, 3, and 4 compared to Case 1 in line with increases in concrete waste (Analysis 1).

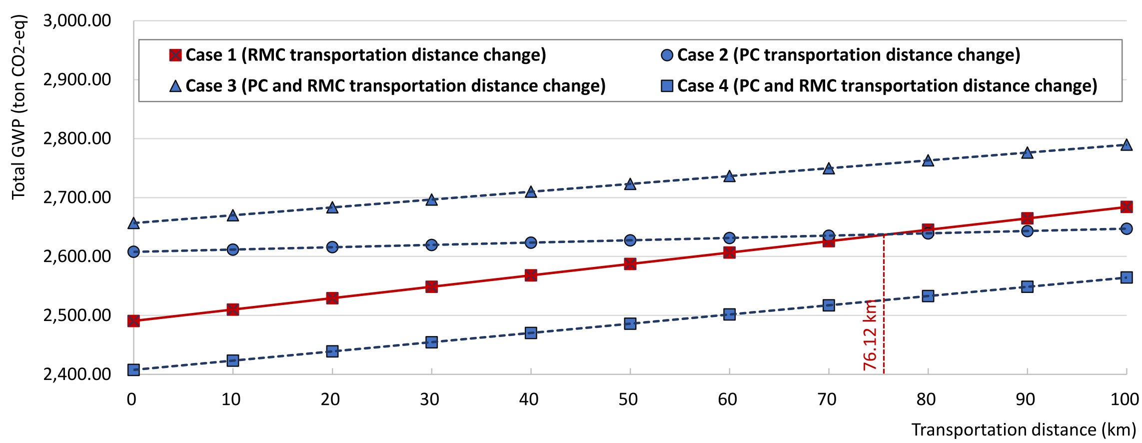

Fig. 10. Changes in total GWP of Cases 1, 2, 3, and 4 according to changes in transportation distance of RMC and PC (Analysis 2).

Table 5
RC and PC application conditions for embodied carbon reduction in concrete bridge structures.

Structure	Summary of embodied carbon reduction conditions
RC	- Reduce the transportation distance of materials - Apply RC to the superstructure - Reduce the extra amount of input concrete, and construction concrete waste
PC	- Increase off-site prefabrication process efficiency - Apply PC to substructure - Utilize PC for projects with high concrete excess and waste

projects that are expected to generate a great amount of construction waste (7.81% in this study), PC-structure application combined with efficient PC-production processes may reduce carbon in bridge construction and production stages. This study found that the application of PC only to substructure can derive the most environmentally friendly results. As the OSC technology utilization in the construction field is set to increase in the future (Jang et al., 2019; Jung and Yu, 2021), the findings of this study are expected to play an important role in establishing sustainable OSC application methods. Particularly, by simultaneously considering the application of prefabrication to both the superstructure and substructure of bridges, it is expected that this approach can support sustainable design and construction from a comprehensive perspective for bridges.

The limitations of this study are that only one type of bridge model was selected and analyzed as a sample and the EPD data of a specific concrete product was applied to the production stage. There are diverse types of bridges, composed of irregular structures, and the characteristics of each structure can influence its EC. In addition, for the EPD data of each material, GWP values can change depending on changes in production volume, regional features, composition of raw materials, and factory equipment. Therefore, follow-up studies should define bridge types, assess ECs in consideration of structural features per type, and generalize the unit GWP values of RMC, reinforcement steel, and PC to be used in the carbon footprint assessment process. However, this study has significance in that it targeted concrete bridge structures, suggested carbon footprint assessment methods using BIM and an LCA tool, and analyzed changes in the EC of bridges in line with the application of PC and RC structures. The methodology and findings of this study are expected to serve as the basis for follow-up studies.

5. Conclusions

This study targeted concrete bridge structures, and utilized the BIM model with LCA software to suggest solutions for how the conditions under which PC structures should be applied to reduce the EC of bridges.

Accordingly, it conducted carbon footprint assessment and analysis on four bridge model cases (Case 1: the entire RC, Case 2: the entire PC, Case 3: PC for superstructure, Case 4: PC for substructure), and arrived at the following conclusions:

1. The total GWP of Cases 1, 2, 3, and 4 was 2606.64 tonCO2-eq, 2631.46 tonCO2-eq, 2736.53 tonCO2-eq, and 2501.57 tonCO2-eq, respectively. This result demonstrated that applying PC instead of RC is not necessarily a guarantee for reducing EC of bridges. The EC was found to be the lowest when PC was applied only to the substructure.
2. In particular, when applying PC, GWP was found to be the highest at the production stage among the lifecycle stages of a bridge, whereas the EC reduction is mainly influenced by transportation and construction stages; therefore, the reduction of GWP through efficient off-site prefabrication processes was analyzed to be crucial for reducing EC of bridges for the application of PC structures.
3. Sensitivity analysis was conducted on the change in GWP with construction concrete waste for Cases 1, 2, 3, and 4. As concrete waste increased from 0 to 15%, the total GWP was found to increase by 28.93% in Case 1, 5.49% in Case 2, 14.23% in Case 3, and 19.15% in Case 4. For the bridge model used in this study, it was confirmed that the EC in Case 2 became significantly lower than that in Case 1 when the percentage of concrete waste exceeded 7.81%. It was analyzed that Case 4 is effective in reducing EC overall, regardless of the amount of concrete waste generated.
4. A sensitivity analysis was conducted on the change in GWP with transportation distance (RMC and PC input distance) for Cases 1, 2, 3, and 4. When the transportation distance increased from 0 to 100 km, the total GWP was found to increase by 7.77% for Case 1 and 1.51% for Case 2. However, in general, it is expected that the transportation distance of RMC is unlikely to exceed 100 km; considering the nature of PC structures with negligible changes in GWP with transportation distance, it is difficult to secure EC reduction benefits through shortening the distance, when compared to RC. Meanwhile, there was no significant impact on the ranking of EC among Case 1, 3, and 4 due to changes in the transportation distance of major structural materials. Case 4 was generally the most effective in reducing EC overall.
5. Summarizing the EC reduction conditions of bridges with the application of RC and PC structures based on the analysis, shortening the transportation distance of materials, application of RC to the superstructure, and reducing the extra amount of input concrete and construction concrete waste were found to be important for RC. The efficiency of off-site prefabrication processes, application of PC to the substructure, and utilization of PC in projects with a high amount of extra concrete and construction concrete waste were the main conditions for PC.

The findings of this study are expected to be widely applied in the future to establish sustainable application methods for OSC. However, this study has limitations in that it selected and analyzed only one type of bridge model as a sample and applied EPD data of a specific concrete product to the production stage. The methodology and results of this study are expected to be utilized as an important foundation for follow-up studies to overcome these limitations.

Funding

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (grant number RS-2023-00246508).

CRediT authorship contribution statement

Hyunsik Kim: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Seungjun Roh:** Supervision, Methodology. **Jeonghwan Kim:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Ajayi, S.O., Oyedele, L.O., Ceranic, B., Gallanagh, M., Kadiri, K.O., 2015. Lifecycle environmental performance of material specification: a BIM-enhanced comparative assessment. Int. J. Sustain. Build. Technol. Urban Dev. 6, 14–24. https://doi.org/10.1080/2093761X.2015.1006708.

Al-Ashmori, Y.Y., Othman, I., Rahmawati, Y., Amran, Y.H.M., Abo Sabah, S.H., Rafindadi, A.D., Mikić, M., 2020. BIM benefits and its influence on the BIM implementation in Malaysia. Ain Shams Eng. J. 11 (4), 1013–1019. https://doi.org/10.1016/j.asej.2020.02.002.

Arslan, D., Sharples, S., Mohammadpourkarbasi, H., Khan-Fitzgerald, R., 2023. Carbon analysis, lifecycle assessment, and prefabrication: a case study of a high-rise residential built-to rent development in the UK. Energies 16, 973. https://doi.org/10.3390/en16020973.

Aye, L., Ngo, T., Crawford, R., Gammampila, R., Mendis, P., 2012. Lifecycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy Build. 47, 159–168. https://doi.org/10.1016/j.enbuild.2011.11.049.

AzariJafari, H., Rangelov, M., Gregory, J., Kirchain, R., 2023. Suitability of EPDs for supporting lifecycle and comparative analysis of concrete mixtures. Environ. Sci. Technol. 57 (19), 7321–7327. https://doi.org/10.1021/acs.est.2c05697.

Braholli, O., 2020. Automated Procedures for LCA Analysis on a BIM Project, Master in Building Information Modelling. Politecnico Di Milano.

British standard institution (BSI), 2023. BS 8500-1:2023 concrete. Complementary British standard to BS EN 206. BSI. https://knowledge.bsigroup.com/products/concrete-complementary-british-standard-to-bs-en-206-specification-for-constituent-materials-and-concrete-1?version=standard&tab=preview. (Accessed 31 December 2023).

Bueno, C., Pereira, L.M., Fabricio, M.M., 2018. Lifecycle assessment and environmental-based choices at the early design stages: an application using building information modelling. Architect. Eng. Des. Manag. 14, 332–346. https://doi.org/10.1080/17452007.2018.1458593.

Cheng, B., Lu, K., Li, J., Chen, H., Luo, X., Shafique, M., 2022. Comprehensive assessment of embodied environmental impacts of buildings using normalized environmental impact factors. J. Clean. Prod. 334, 130083. https://doi.org/10.1016/j.jclepro.2021.130083.

Diaz, J., Anton, L.A., 2014. Sustainable construction approach through integration of LCA and BIM tools. In: Computing in Civil and Building Engineering, pp. 283–290. https://doi.org/10.1061/9780784413616.036.

Du, G., Karoumi, R., 2013. Lifecycle assessment of a railway bridge: comparison of two superstructure designs, maintenance, management, life-cycle design and performance. Struct. Infrastruct. Eng. 9 (11), 1149–1160. https://www.diva-portal.org/smash/get/diva2:793949/fulltext03.pdf.

Du, G., Safi, M., Pettersson, L., Karoumi, R., 2014. Lifecycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs. Int. J. LCA. 19 (12), 1948–1964. https://link.springer.com/article/10.1007/s11367-014-0797-z.

Du, G., Pettersson, L., Karoumi, R., 2018. Soil-steel composite bridge: an alternative design solution for short spans considering LCA. J. Clean. Prod. 189, 647–661. https://doi.org/10.1016/j.jclepro.2018.04.097.

Ecoinvent. Ecoinvent v3.3 ecoinvent: zürich, Switzerland. https://support.ecoinvent.org/database#releases, 2016–. (Accessed 1 December 2022).

Ferreira, A., Pinheiro, M.D., de Brito, J., Mateus, R., 2023. A critical analysis of LEED, BREEAM and DGNB as sustainability assessment methods for retail buildings. J. Build. Eng. 66, 105825. https://doi.org/10.1016/j.jobe.2023.105825.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Suh, S., 2009. Recent developments in lifecycle assessment. J. Environ. Manag. 91 (1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Guignone, G., Calmon, J.L., Vieira, D., Bravo, A., 2023. BIM and LCA integration methodologies: a critical analysis and proposed guidelines. J. Build. Eng. 73, 106780. https://doi.org/10.1016/j.jobe.2023.106780.

Hammervold, J., Reenaas, M., Brattebø, H., 2013. Environmental lifecycle assessment of bridges. J. Bridge Eng. 18 (2), 153–161. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000328.

Iris, X., Zhou, W., Tang, L., 2011. BIM-based lifecycle cost and assessment tool for sustainable building design decision. In: 4th International Conference on Construction Engineering and Project Management (ICCEPM-20011), p. 8. Sidney, Australia.

Iso, I., 2006. Environmental management-lifecycle assessment-principles and framework. Br.Stand. Inst., 14040. London. (Accessed 1 December 2020).

Jang, J., Chen, H., Lee, C., Kim, T., 2019. Research trends in off-site construction management : review of literature at the operation level. Kor. J. Construct. Eng. Manag. 20 (4), 114–125. https://doi.org/10.6106/KJCEM.2019.20.4.114.

Jayawardana, J., Sandanayake, M., Jayasinghe, J.A.S.C., Kulatunga, A.K., Zhang, G., 2023. A comparative lifecycle assessment of prefabricated and traditional construction – a case of a developing country. J. Build. Eng. 72, 106550. https://doi.org/10.1016/j.jobe.2023.106550.

Joshi, S., 1999. Product environmental life-cycle assessment using input-output techniques. J. Ind. Ecol. 3 (2–3), 95–120. https://doi.org/10.1162/108819899569449.

Jung, S., Yu, J., 2021. A study on the critical success factors of off-site construction through keyword frequency analysis - a literature review of overseas research -. Kor. J. Construct. Eng. Manag. 22 (1), 13–26. https://doi.org/10.6106/KJCEM.2021.22.1.013.

Kazaz, A., Ulubeyli, S., Er, B., Arslan, V., Arslan, A., Atici, M., 2015. Fresh ready-mixed concrete waste in construction projects: a planning approach. Procedia Eng. 123, 268–275. https://doi.org/10.1016/j.proeng.2015.10.088.

Khorgade, P., Rettinger, M., Burghartz, A., Schlaich, M., 2022. A comparative cradle-to-gate lifecycle assessment of carbon fiber-reinforced polymer and steel-reinforced bridges. Struct. Concr. 24, 1737–1750. https://doi.org/10.1002/suco.202200229.

Kim, H., Kim, J., Roh, S., 2023a. The embodied lifecycle global warming potential of offsite prefabricated concrete products: precast concrete and concrete pile production in Korea. Buildings 13, 2590. https://doi.org/10.3390/buildings13102590.

Kim, J., Lee, D., Nam, S., 2023b. Potential for environmental impact reduction through building LCA (Lifecycle Assessment) of school facilities in material production stage. Build. Environ. 238, 110329. https://doi.org/10.1016/j.buildenv.2023.110329.

Kim, H., Lim, H., Kim, J., Roh, S., 2023c. Propriety assessment model for lifecycle operational global warming potential of apartment buildings in Korea using energy efficiency and energy effective area data. Sci. Rep. 13, 2420. https://doi.org/10.1038/s41598-023-29142-6.

Kloepffer, W., 2008. Lifecycle sustainability assessment of products. Int. J. Life Cycle Assess. 13 (2), 89. https://doi.org/10.1065/lca2008.02.376.

Lee, H., Lee, C., Han, H., Lee, J., 2024. A study on development of construction standard production rates and cost analysis for off-site construction (OSC)-Based PC structure construction costs - comparison with RC method -. Kor. J. Construct. Eng. Manag. 25 (2), 56–68. https://doi.org/10.6106/KJCEM.2024.25.2.056.

Li, X.J., Zheng, Y.D., 2020. Using LCA to research carbon footprint for precast concrete piles during the building construction stage: a China study. J. Clean. Prod. 245, 118754. https://doi.org/10.1016/j.jclepro.2019.118754.

Li, X., Xie, W., Jim, C.Y., Feng, F., 2021a. Holistic LCA evaluation of the carbon footprint of prefabricated concrete stairs. J. Clean. Prod. 329, 129621. https://doi.org/10.1016/j.jclepro.2021.129621.

Li, X., Lai, J., Ma, C., Wang, C., 2021b. Using BIM to research carbon footprint during the materialization phase of prefabricated concrete buildings: a China study. J. Clean. Prod. 279, 123454. https://doi.org/10.1016/j.jclepro.2020.123454.

Li, X., Xie, W., Xu, L., Li, L., Jim, C.Y., Wei, T., 2022. Holistic life-cycle accounting of carbon emissions of prefabricated buildings using LCA and BIM. Energy Build. 266, 112136. https://doi.org/10.1016/j.enbuild.2022.112136.

Li, X., Xie, W., Yang, T., Lin, C., Jim, C.Y., 2023. Carbon emission evaluation of prefabricated concrete composite plates during the building materialization stage. Build. Environ. 232, 110045. https://doi.org/10.1016/j.buildenv.2023.110045.

Liu, M., Li, Y.Q., Zhan, X., 2011. Generic model for energy carbon emission of building materials. In: Advanced Materials Research, vol. 168. Trans Tech Publications, 365e368. https://doi.org/10.4028/www.scientific.net/AMR.168-170.365.

Migilinskas, D., Popov, V., Juocevicius, V., Ustinovichius, L., 2013. The benefits, obstacles and problems of practical BIM implementation. Procedia Eng. 57, 767–774. https://doi.org/10.1016/j.proeng.2013.04.097.

Musa, S., Marshall-Ponting, A., Nifa, F.A.A., Shahron, S.A., 2018. Building information modeling (BIM) in Malaysian construction industry: benefits and future challenges. In: AIP Conference Proceedings. AIP Publishing LLC. https://doi.org/10.1063/1.5055507.

Novakova, I., Perumal, P., Cwirzen, A., Wallevik, O.H., 2023. Low carbon concrete possibilities: EPD and regulations in Northern Periphery and Arctic. Mater. Process. 13, 14. https://doi.org/10.3390/materproc2023013014.

Obrecht, T.P., Rck, M., Hoxha, E., Passer, A., 2020. BIM and LCA integration: a systematic literature review. Sustainability 12 (14), 5534. https://doi.org/10.3390/su12145534.

O'Born, R., 2018. Lifecycle assessment of large scale timber bridges: a case study from the world's longest timber bridge design in Norwa. Transp. Res. Part D: Transp. Environ. 59, 301–312. https://doi.org/10.1016/j.trd.2018.01.018.

Pai, V., Elzarka, H., 2021. Whole building lifecycle assessment for buildings: a case study ON HOW to achieve the LEED credit. J. Clean. Prod. 297, 126501. https://doi.org/10.1016/j.jclepro.2021.126501.

Penadés-Plà, V., García-Segura, T., Martí, J., Yepes, V., 2018. An optimization-LCA of a prestressed concrete precast bridge. Sustainability 10, 685. https://doi.org/10.3390/su10030685.

Ranathungage, A., Alwan, Z., Fernando, N., Gledson, B., 2018. Estimating embodied carbon emissions of buildings in developing countries: a case study from Sri Lanka. In: International Sustainable Ecological Engineering Design for Society Conference 2018. Dublin Institute of Technology (DIT), Dublin, Ireland. https://www.leedsbeckett.ac.uk/leeds-sustainability-institute/seeds-conference-2018/.

Rangelov, M., Dylla, H., Mukherjee, A., Sivaneswaran, N., 2021. Use of environmental product declarations (EPDs) of pavement materials in the United States of America (USA) to ensure environmental impact reductions. J. Clean. Prod. 283, 124619. https://doi.org/10.1016/j.jclepro.2020.124619.

Teng, Y., Li, K., Pan, W., Ng, T., 2018. Reducing building lifecycle carbon emissions through prefabrication: evidence from and gaps in empirical studies. Build. Environ. 132, 125–136. https://doi.org/10.1016/j.buildenv.2018.01.026.

The Norwegian EPD Foundation. EPD-norge digi. https://digi.epd-norge.no/. (Accessed 1 December 2023).

Vasishta, T., Mehany, M.H., Killingsworth, J., 2023. Comparative lifecycle assessment (LCA) and lifecycle cost analysis (LCCA) of precast and cast–in–place buildings in United States. J. Build. Eng. 67, 105921. https://doi.org/10.1016/j.jobe.2023.105921.

Vruno, D.M., 2011. Concrete delivery time study, research project of Minnesota department of transportation. https://trid.trb.org/view/1139553. (Accessed 1 December 2023).

Wang, Z., Hu, H., Gong, J., Ma, X., Xiong, W., 2019. Precast supply chain management in offsite construction: a critical literature review. J. Clean. Prod. 232, 1204–1217. https://doi.org/10.1016/j.jclepro.2019.05.229.

Wang, H., Liu, Y., Li, Jing, Liu, S., Yang, J., Luo, S., Huang, W., 2023. Environmental lifecycle assessment of bridge deck pavement and case studies of two bridges in China. Case Stud. Constr. Mater. 18, e02115. https://doi.org/10.1016/j.cscm.2023.e02115.

L. Wastiels, R. Decuypere, Identification and comparison of LCA-BIM integration strategies, In: Proceedings of the IOP Conference Series Earth and Environmental Science, Graz, Austria, 11-14 September 2019 Volume vol. 323. https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012101.

Witte, A., Garg, N., 2024. Quantifying the global warming potential of low carbon concrete mixes: comparison of existing lifecycle analysis tools. Case Stud. Constr. Mater. 20, e02832. https://doi.org/10.1016/j.cscm.2023.e02832.

Yu, D., Tan, H., Ruan, Y., 2011. A future bamboo-structure residential building prototype in China: lifecycle assessment of energy use and carbon emission. Energy Build. 43 (10), 2638e2646. https://doi.org/10.1016/j.enbuild.2011.06.013.