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THE IMPACT OF BUILDING INFORMATION MODELING ON REDUCING GREENHOUSE GASES THROUGH DESIGN VALIDATION

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Abstract. This study proposes a method to reduce rework due to design errors by applying building information modeling (BIM) to reduce greenhouse gas (GHG) emissions during the construction stage. The study focuses on reducing waste in construction materials, transportation, and recycling, with the analysis grounded on expert opinions using fuzzy theory and life cycle inventory data. Applying the proposed method to the case building reduced emissions by 113,211 kg CO_2eq, which is 64 times the GHGs emissions from driving a car or van for 10 or fewer passengers over 20,000 km. To offset 113,211 kg CO_2eq, about 12,441–13,977 pine trees would be required. Reducing wasted concrete contributes to approximately 79.9% of the total GHGs emissions decrease. Among the buildings that started construction in South Korea between July 2022 and February 2023, 68.3% are reinforced concrete structures based on gross floor area. Applying BIM to these structures could yield even greater benefits than those reported in this study. This study also introduces a method based on fuzzy analytic hierarchy process (AHP) for decision makers to prioritize design changes. This method provides quantitative data to enrich qualitative discussions among construction, BIM, and estimation managers regarding design changes.

Keywords: building information modeling, design error, rework, greenhouse gas, carbon neutrality, fuzzy AHP.

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1. Introduction

Thirty-nine percent of global carbon emissions are emitted from the operation stage of buildings (28%) and from the production of construction materials and construction stage of buildings (11%) (World Green Building Council, 2019). The carbon in the operating stage is emitted as a result of using the building for more than 40 years (Ministry of Economy and Finance, 2022). The carbon during the construction phase is emitted over a relatively short period of two to three years, so the amount of carbon emissions is high relative to time. The amount of waste generated in the construction stage and the amount of greenhouse gases (GHGs) in the waste treatment process are also high. In South Korea, 44.2% of the total waste is generated during the construction stage (Korea Environment Corporation, 2021). The amount of carbon emitted from the production and construction stages announced by the World Green Building Council (2019) did not include the amount of carbon emitted from waste treatment. Moreover, the amount of carbon emitted when the materials produced in the factory are transported to the construction site was not considered. If these are included, the difference between the amount of carbon emitted in the operation phase and in the material production and construction phases will be significantly decreased.

However, global carbon emission reduction policies, including those in South Korea, are being established with a focus on the operation stage of buildings (Korea Research Institute for Human Settlements, 2022). There is a need for a plan to reduce emitted GHGs during the construction stage, which can be achieved by using materials with low GHG emissions during material production and waste disposal. Unfortunately, construction materials cannot be selected based only on GHG emissions because various factors must be considered, such as economics, energy efficiency, and building occupants' satisfaction.

Reducing rework caused by design errors in the construction stage can reduce the amount of wasted construction materials. A reduction in rework is also linked to reductions in emitted GHGs from material production, transportation from production plants to construction sites, transportation to waste treatment and recycling sites, and waste treatment and recycling. To reduce rework, it is necessary to minimize design errors and design changes, that is, to improve design completeness. To improve design completeness, the South Korean government is continuously announcing policies to promote building information modeling (BIM) (Ministry of Land Infrastructure and Transport, 2021). Several previous studies have analyzed the economic effect of applying BIM to the construction stage (Lee et al., 2012; M. Lee & U. Lee, 2020). However, the reduction of GHG emissions has not been analyzed. Prior works have not analyzed the reduction effect of BIM application on GHG emissions in construction stage, but several previous studies analyzed energy consumption and GHG emissions by applying BIM in the operation and design stages (Abbasi & Noorzai, 2021; Hao et al., 2020; Shi & Xu, 2021; Yi et al., 2017).

This study proposed (1) a method of reducing design errors and rework by applying BIM and analyzed the effect of reducing GHG emissions. BIM has been selected by the South Korean government as a key technology in the digital transformation of the construction industry (Ministry of Land Infrastructure and Transport, 2021). The subjects of analysis are the reduced amount of wasted construction materials by rework, reduced amount of materials transportation from the material factory to the construction site, reduced amount of materials transportation from the construction site to the waste treatment and recycling site, and the reduced amount of GHGs generated in the recycling stage. In addition, this work proposed (2) a decision-making support method that can analyze the priority of design change alternatives when a design error occurs.

2. Literature review

The goal of this study was to analyze the BIM effect on the reduction of GHG emissions through design validation. It differed from previous studies that used BIM to analyze environmental impacts, such as GHGs emitted during the design and operation stages. In other words, whereas previous studies used BIM to analyze GHG emissions, this study applied BIM to reduce GHG emissions. This is the main difference. Especially, there are no studies on reducing GHGs generated during the construction phase, which is the goal of this study. Since GHGs generated during the construction and material production stages account for 11% of global greenhouse gas emissions, a study focusing on the construction stage is needed (World Green Building Council, 2019).

Abbasi and Noorzai (2021) proposed a multi-object optimization algorithm based on BIM and life cycle assessment (LCA) to analyze the trade-off between energy consumed in the building operation stage and embodied energy, focused on the use of renewable energy, such as from solar panels. The method can also derive a range of renewable energy uses that maximize embodied energy to reduce energy consumption in the operational phase. Cavalliere et al. (2019) proposed an LCA method that can evaluate embodied environmental impacts at all stages of building design based on data provided by BIM. Since building elements are not modeled with the same specific level of development (LOD) at each design stage, their proposed method includes combining different LODs in the BIM model. Soust-Verdaguer et al. (2020) proposed a method of quantitatively evaluating environmental impacts at the design stage by combining BIM and LCA, and comparing the environmental impacts of a timber-frame single-family house and a concrete-masonry-based house.

Similar to this study, previous studies applied advanced technologies to reduce GHGs emitted from building projects. Hao et al. (2020) used BIM to analyze the reduction of GHG emissions by applying the prefabrication method to the materialization stage of a building project. The analysis targets were building materials production, transportation, and on-site construction. Whereas in Hao's et al. study, the reduction of GHG emissions was analyzed in the process to which the prefabrication method was applied, the current study analyzed the entire process. Moreover, as with other previous studies, Hao et al. (2020) is different from this study because it did not use BIM to reduce greenhouse gas emissions but used BIM to analyze emissions. Although BIM was not applied in their study, Yi et al. (2017) proposed a method to estimate carbon emission stochastically based on atomic work tasks, utilizes hourly equipment fuel consumption and hourly laborer respiratory rates in the construction stage. Moreover, for optimal resource combination, an eco-economic performance metric was proposed that considered GHG emissions, the operation completion time, the operation completion cost, and productivity.

Since the goal of the current study was to analyze the effects of BIM application, previous studies that analyzed BIM's effect from an economic perspective rather than from a GHG emissions perspective were also reviewed. Similar to the current study, Lee et al. (2012) and M. Lee and U. Lee (2020) applied BIM in the design validation stage to detect design errors and analyzed the economic effects of resolving the errors before construction. The economic effects were calculated by subtracting the cost of the BIM application from the sum of the reductions in the material costs, labor costs, and expenses. Lee et al. (2012) analyzed the BIM effect by resolving the design errors at the design review stage from the perspective of return on investment (ROI). As a result, the ROI was 172–247%, and the delay during the construction period was also prevented. M. Lee and U. Lee (2020) analyzed the reduction level of re-construction and obtained an ROI of 476.72% through design review. They found it to be 15–41% for reinforced concrete buildings. The effect of reducing material waste by reducing design errors (Lee et al., 2012; M. Lee & U. Lee, 2020) was converted into the effect of reducing the GHGs emitted from the production, transportation, disposal, and recycling of materials. The current study also proposed a decision-making method to support the selection of design alternatives, considering economics, constructability, and GHG emissions when design errors occur.

3. The emitted greenhouse gases from construction

To identify the types of GHG emitted during the construction stage, this study reviews South Korea's national GHG inventory. The national GHG inventory in South Korea is divided into energy; industrial processes; agriculture; land use, land use change and forestry (LULUCF); and waste (Greenhouse Gas Inventory and Research Center, 2022). The construction industry is classified under the energy sector and only includes GHGs emitted from the construction stage, that is, limiting measured GHG emissions from construction to those that take place directly at the construction site (Table 1). However, GHGs emitted from the construction stage are linked to GHGs emitted from the production, transportation, and construction of construction materials and to GHGs emitted from waste treatment and recycling necessitated by rework (Figure 1). Therefore, it is also linked to GHG emissions from mineral production, the chemical industry, metal production in industrial processes, and transportation in the energy sector, as well as to waste landfill and incineration in the waste sector. The goals of this study are to reduce rework through a preliminary review of design errors according to BIM application and to analyze the BIM impact in terms of reducing GHG emissions. Thus, the scope of analysis includes the production, transportation, construction, disposal, and recycling of construction materials that are related to the reduction in rework.

4. Research methodology

This study applied BIM to analyze the reduction levels of design errors, reconstruction, and GHG emissions, as well as a method to analyze the priorities of various design change alternatives. First, to analyze the reduction level of GHG emissions, design errors and the need for re-construction were identified. The reduction effect of material quantity was analyzed by a reduction in re-construction,

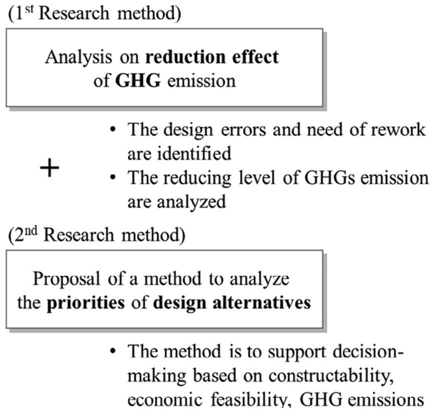

Figure 2. Research methodology

and the reduction effect of GHG emission was analyzed by quantity reduction. Next, to analyze the priorities of alternatives for design change, a method for analyzing decision-makers' preferences based on constructability, economic feasibility, and GHG emissions was applied (see Figure 2).

4.1. An analysis on the reduction of GHG emissions

To analyze the effect of reducing GHG emissions in the construction stage through the application of BIM, information on materials wasted by rework was collected and organized based on the pre-review design error report extracted from the BIM model. The following steps were sequentially applied: reviewing design errors and analyzing the need for rework based on experts' opinions, analyzing the effect of reducing the amount of materials by reducing rework based on the comparison of cases in which design error is not modified and design error is modified, and analyzing the effect of reducing GHG emissions by decreasing the amount of materials used during the production, transportation, recycling, and disposal of materials in construction (see Figure 3).

Table 1. Divisions and sectors of national GHG inventories in South Korea

Division	Sector
Energy	■ Fuel burning: energy industry, manufacturing and construction industry, transportation ■ Fleeing: solid fuels, petroleum, and natural gas
Industrial process	■ Mineral production, chemical industry, metal production
Agriculture	■ Livestock: intestinal fermentation, livestock manure treatment ■ Seeds: rice cultivation, agricultural soil, crop residue incineration
LILUCF	■ Forest land, agricultural land, grassland, wetland, harvested wood products
Waste	■ Waste landfill, wastewater treatment, waste incineration

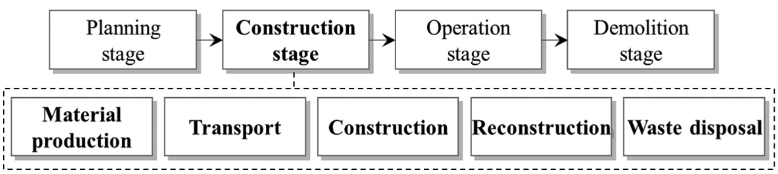

Figure 1. GHG emission factors for construction stage in life cycle of building

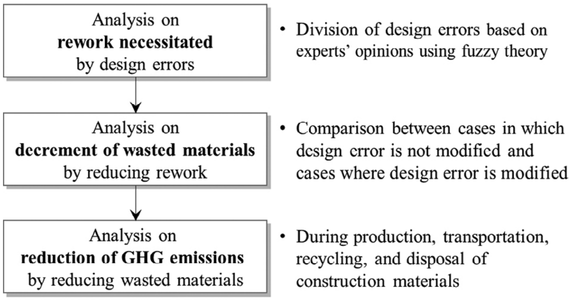

Figure 3. Analysis method for GHG reduction through the use of BIM

4.2. Priority analysis of design change alternatives

If a design error is confirmed, design change alternatives are determined through consultation between the person in charge of the construction, the person in charge of estimation, and the person in charge of BIM. At this point in the consultation process, it is necessary to not only solve the design error, which is a problem in the drawing, but also consider both economic feasibility and constructability (Won et al., 2021). This study proposes a priority analysis method for design change alternatives that can help decision-makers review the applicability of the proposed method when design change alternatives occur. The analysis criteria of the proposed method were the constructability and economic feasibility of the design change alternative and the GHG emission reduction effect analyzed sequentially.

First, the rework possibility was analyzed based on experts' opinions, similar to what was mentioned in Section 4.1, and then the preference of decision-makers was analyzed through weight analysis of economic feasibility, constructability, and GHG emission. Next, the design error was resolved sequentially and decision-makers are determined. If the decision-makers did not agree on the priory alternatives, the sequential resolution for design errors of second priority were once again resolved sequentially (see Figure 4).

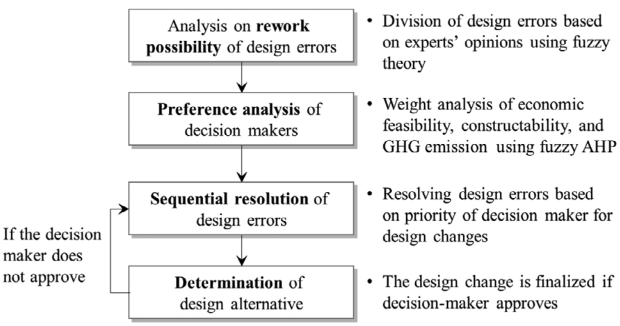

Figure 4. Method for correcting design errors and determining design alternatives

5. Analysis and results

5.1. An analysis of the reduction of GHG emissions

5.1.1. Analysis of the need for rework of design errors

Design errors that can be identified in the 2D-based design review and those that cannot be identified in the 2D-based design review but do not require rework should be excluded from the effect analysis. Figure 5 shows an example of a design error in the 2D drawing: the ceiling height is low, and the window is blocked. It is an error that can be solved by changing the ceiling height and wall finish, and it does not require rework because workers can recognize it during construction.

To classify errors in the BIM model that do not require rework, as well as those that do, 5-step classification criteria (see Figure 6) were applied using previous studies as reference (Lee et al., 2012; M. Lee & U. Lee, 2020):

- Step 1: This is a case in which design errors can be found without using BIM; therefore, rework is not required. The design errors are related to errors and omissions of drawing markings, and there is no possibility of rework.
- Step 2: The design errors can be found before the construction phase by using BIM, but the necessity of rework is low. These can be solved by modifying the drawing through simple consultation and discussion.
- Step 3: These errors make it difficult to determine whether or not to rework. This is because the expert evaluating the need for rework has not experienced these design errors related to the type and characteristics of a building.
- Step 4: If BIM is not used, it is difficult to find design errors before the construction stage, and the need for rework is high.

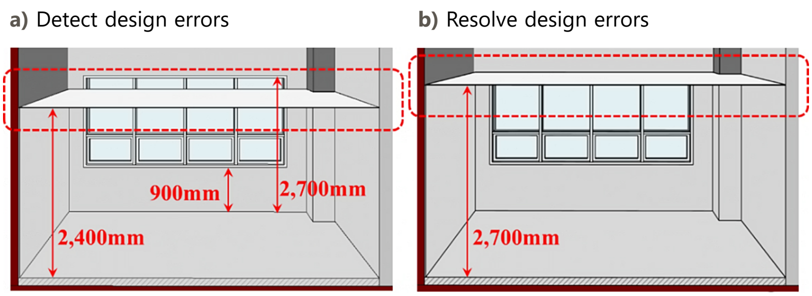

Figure 5. Example of a design error that can be reviewed in the 2D drawing

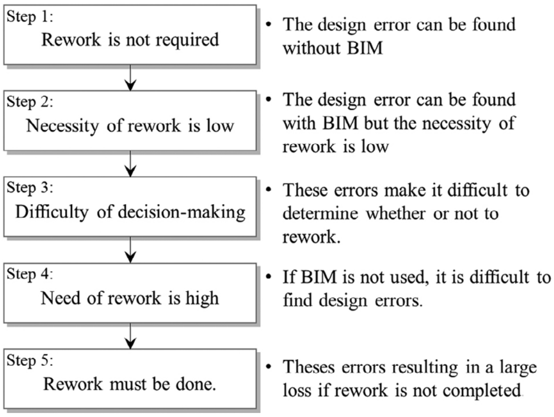

Figure 6. Procedure of design error identification

- Step 5: If BIM is not used, it is difficult to find design errors before the construction stage, and rework must be done. These errors greatly affect the construction cost and construction period, resulting in a large loss if rework is not completed.

When a design error occurs in a construction project that applies BIM, the need for rework is determined based on the opinions of the construction manager, estimator, and BIM manager. Differences in expertise, differences in perception of the need for rework, and ambiguity in language expressions may occur because of the need for rework for design errors that have not yet been built. In this study, fuzzy theory is applied to mitigate the differences between experts. Fuzzy theory converts information that is difficult to define clearly into useful information and solves the problem of ambiguity in human language (C. Lee & C. Lee, 2017). The triangular fuzzy number is commonly used because the fuzzy membership function is composed of upper, middle, and lower values, making mathematical access easy (Lee, 2022). For example, if step 4, which requires rework, is selected, an upper value of 9, middle value of 7.5, and lower value of 6, corresponding to "High" in Table 2, should be applied.

5.1.2. Analysis of the reduction effect of wasted materials due to a reduction in rework

By reducing rework, construction material waste is also reduced. The units of materials vary by volume, weight, and area. In Eqn (1), Q is the quantity of construction materials. The volume (m^3) for concrete, weight (kg) for steel materials, such as H-beams, and the area (m^2) for plaster boards are unit. T is the triangular fuzzy number for the rework necessity evaluated by experts for design errors identified using BIM.

$$Q_{rework} = Q \times T, \quad (1)$$

where Q_{rework} is the quantity of construction materials wasted due to rework; Q is the quantity of construction materials corresponding to design errors evaluated using BIM; T is the triangular fuzzy number for the need for rework of design errors evaluated using BIM.

When rework is performed, the operation of the equipment used when constructing the wasted construction material is also wasted, and construction equipment is additionally operated for the demolition of the materials. Therefore, it is necessary to analyze GHG emissions from the operation of construction equipment. However, the National Life Cycle Inventory Database (LCI DB) of South Korea does not provide GHG emission factors for construction equipment, so changes in GHG emissions cannot be analyzed (Korea Environmental Industry and Technology Institute, 2022). In this study, GHG emissions from the operation of construction equipment used for the construction and demolition of materials were excluded from the scope of analysis.

Rework wastes the fuel consumed when transporting wasted materials from the factory to the construction site, and additional fuel is required to transport the demolished materials to the waste disposal site and recycling facility. In this study, it was assumed that trucks are used for transportation, and GHG emissions were analyzed by referring to the evaluation coefficient of the Environmental Product Declaration provided by the National LCI DB (Korea Environmental Industry and Technology Institute, 2023). The demolished materials were classified into materials that could be recycled and those that had to be disposed of through other methods. Since concrete and metal materials, such as reinforcing bars and H-steel, are frequently used for construction, waste concrete and waste metal recycling were included in the scope of analysis. Incineration was excluded from the scope of analysis because it accounts for 2% of the total construction waste treatment methods (Lee, 2002).

5.1.3. Analysis of the reduction effect of reducing waste materials on GHG emissions

When calculating GHG emissions, the emission of GHGs other than carbon dioxide must also be considered, and CO_2-equivalent (CO_2eq) is generally used to express this concept. CO_2eq is the amount of GHG emissions produced by converting six GHGs into carbon dioxide. The six types of GHGs that cause global warming are carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (Greenhouse Gas Inventory and Research Center, 2022). To analyze the effect of reducing GHG emissions due to a reduction in rework, the GHG emission factor generated in the production, transportation, and recycling of construction materials is required.

Table 2. Triangular number for evaluating the need for rework

Division	Very low (1st step)	Low (2nd step)	Medium (3rd step)	High (4th step)	Very high (5th step)
Triangular fuzzy number	(0, 0, 2)	(1, 2.5, 4)	(3, 5, 7)	(6, 7.5, 9)	(8, 10, 10)

The National LCI DB provides GHG emission factors for each manufacturer of construction materials, for transportation, and for recycled materials. However, since these vary for each construction project, GHG emissions in this study were analyzed by applying an average value. Table 3 presents the average GHG emission factors applied in this study (Korea Environmental Industry and Technology Institute, 2022, 2023).

The reduction in GHG emissions through the use of BIM can be calculated by multiplying the reduced quantity of construction materials (Eqn (1)) and the GHG emission factor (Eqn (2)). For example, if the reduced volume of concrete is 1,000 m^3 and the GHG emission factor is 241.44 $kgCO_2eq/m^3$, the GHG emission of concrete is calculated as 241,440.55 $kgCO_2eq$.

$$\text{GHG emissions} = \sum_{i=1}^{I} \left(EF_i \times Q_i \right), \quad (2)$$

where EF_i is the GHG emission factor of construction material i; Q_i is the additional quantity due to rework of construction material i.

5.1.4. Case study

The proposed method was applied to a case building for which BIM was used to analyze the effect of a reduction in rework on GHG emissions. The case building was a steel frame structure and a reinforced concrete structure. BIM was applied for architectural modeling, structural modeling, mechanical, electrical, and plumbing (MEP) modeling, and the pre-construction design review (Figure 7).

- Gross floor area: 25,661.45 m^2;
- Structural type: Steel structure, steel frame/reinforced concrete;
- Construction period: July 2015–September 2017 (28 months);
- Major use: Sports facility, business facility, apartment house;
- Range of BIM application: Architectural; structural; mechanical, electrical, and plumbing (MEP) modeling; pre-construction design review.

The type of work that would be analyzed was selected based on the report of the pre-construction design review derived through the BIM model. The total number of design errors identified in the case model was 237; the number of errors related to architecture, structure, civil engineering, and landscaping was 127; and the number of errors related to MEP was 110. Design errors were classified based on the judgment of an expert group composed of two people in charge of building construction, one person in charge of civil engineering, three people in charge of MEP construction, and one person in charge of BIM. The expert group decided whether to change the

Table 3. GHG emission factors of construction materials, transportation, and recycled materials (Korea Environmental Industry and Technology Institute, 2022, 2023)

GHG emission source		GHG emission factor	
Construction materials	Concrete	241.44055	$kgCO_2eqe/m^3$
	Reinforcing bars	0.45146	$kgCO_2eqe/kg$
	Tile	4.72399	$kgCO_2eqe/m^2$
	H-beam	0.51420	$kgCO_2eqe/kg$
	Collector well	225.43520	$kgCO_2eqe/unit$
	Plaster board	1.01523	$kgCO_2eqe/m^2$
	Paving block	241.48501	$kgCO_2eqe/m^3$
Transportation	Truck	0.19240	$kgCO_2eqe/ton.km$
Recycled materials	Waste concrete recycling	0.0138	$kgCO_2eqe/kg$
	Waste ferrous metal Recycling	0.0038	$kgCO_2eqe/kg$

Notes: The concrete is ready-mixed concrete (25-24-150), reinforcing bars exclude hollow reinforcing bars, and blocks refer to autoclaved lightweight concrete (ALC) blocks.

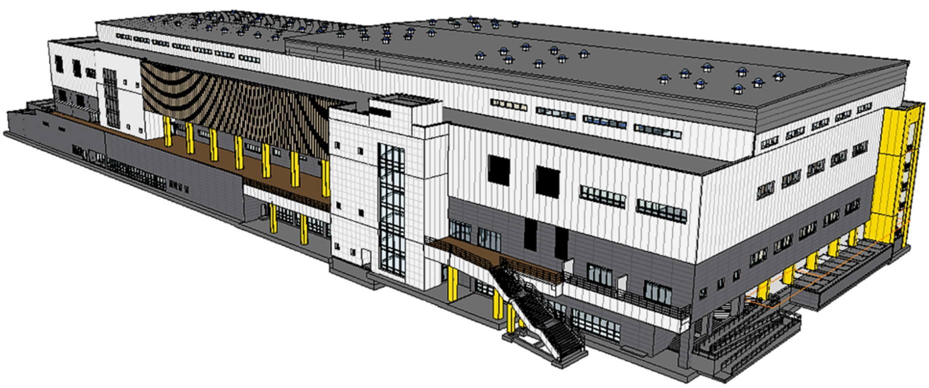

Figure 7. BIM model of case analysis

design when design errors occurred at the construction site. Most of the design errors related to MEP were simple errors and omissions in drawings, so the need for rework was classified as low, and MEP errors were excluded. The GHG reduction effect of BIM application was analyzed for 127 design errors in architecture, structure, civil engineering, and landscaping construction.

Based on the criteria of the five stages of design errors presented in this study, a group of experts evaluated the need for rework for 127 design errors (Table 4). There were three design errors that required rework (2%, step 5), 38 design errors that were highly likely to require rework (30%, step 4), 31 design errors for which it was difficult to determine whether rework would be necessary (24%, step 3), 21 design errors with a low likelihood to require rework (17%, step 2), and 34 design errors that did not require rework (27%, step 1). Excluding the design errors of step 1, which did not require rework, 93 cases (73%) of design errors were analyzed for GHG reduction effects according to BIM application.

Figure 8 is an example of a design error that requires rework. Currently, the ceiling height is 2,700 mm, but the shutter height is 3,000 mm, so the shutters cannot be installed. It is necessary to change the design by raising the ceiling height to 3,000 mm or lowering the shutter height to 2,700 mm. If BIM is not applied, ceiling materials or shutters are wasted, which leads to unnecessary GHG emissions in the production, transportation, disposal, and recycling of materials.

Detailed data on construction materials and transportation distance are needed to calculate GHG emissions due to a reduction in rework. In the case of the BIM model, information about this was lacking, so several assumptions were applied:

Assumption 1. Since the number of reinforcing bars in reinforced concrete structures varies widely, the estimated value of the ratio of reinforcing bars to concrete were based on the reinforced concrete design guidelines of the Buildings Department of Hong Kong (Buildings Department, 2013). This is because the BIM model applied to the case building did not include information on the number of reinforcing bars for each member of the concrete structure. For example, 99.41% of concrete is applied to reinforced concrete beams, and 0.59% is applied to reinforcing bars (Table 5).

Assumption 2. In order to conservatively analyze the effect of reducing GHG emissions by applying BIM, construction materials that are not assigned GHG emission factors in the National LCI DB of South Korea were excluded from the analysis. Since the GHG emission factor for construction equipment used for construction and demolition was not provided by the National LCI DB, it was excluded from the analysis. Therefore, the actual reduction effect of GHG emissions via the application of BIM is expected to be greater than the results of the case study.

Assumption 3. The National LCI DB provides GHG emission factors for products certified by the Korea Environmental Industry and Technology Institute (2022, 2023). Therefore, even for the same product, the GHG emission factor differs depending on the manufacturer. If different companies produced the same product, the average value was applied as the GHG emission factor.

Assumption 4. If the unit of the construction material and the unit of the GHG emission factor were different, they were unified by applying the unit weight. For example, the unit of H-beam is "meter", but the unit of GHG emission factor is $kgCO_2e/kg$. The GHG emissions were calculated by applying the unit weight (kg/m) of the type of H-beam used at the case site.

Assumption 5. In order to conservatively and strictly analyze the GHG reduction effect by the reduction of rework, the shortest possible transportation distance was selected. A workplace that carried out both waste treatment and recycling treatment was selected as the construction waste transport target (Figure 9). The workplace that was closest to the case construction site (13 km) was chosen as the target. Since construction materials are selected according to the preferences of the owner and the construction company, the location of the factory in which the construction materials are manufactured also varies. It was assumed that the transportation distance of materials manufactured in a factory to the construction site was 13 km, which is the same as the distance to the waste and intermediate treatment site because the transport distances must be similar for a rigorous analysis.

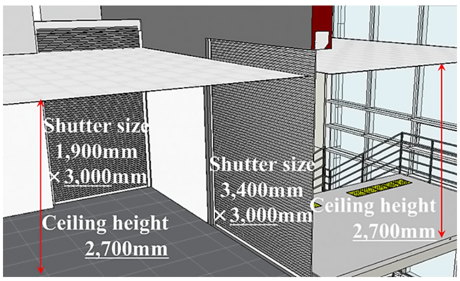

Figure 8. Example of a design error that requires rework: difference between ceiling height and shutter height

Table 4. Evaluation result of rework need of design error

Division	1st step	2nd step	3rd step	4th step	5th step	Sum
Number of design error (ratio)	34 (27%)	21 (17%)	31 (24%)	38 (30%)	3 (2%)	127 (100%)

Table 5. Proportion of rebar in reinforced concrete structures (Buildings Department, 2013)

Reinforced concrete member	Beam	Column	Wall	Slab	Foundation
Ratio of reinforcing bars	0.59%	0.80%	0.70%	0.59%	0.80%

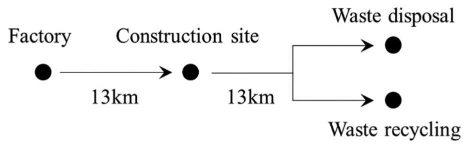

Figure 9. Transportation distances for the construction, disposal, and recycling of construction materials

Among the construction materials that decrease as BIM is applied, GHG emissions from the production, transportation, and recycling of concrete, reinforcing bars, tiles, H-beams, collector wells, plaster board, and paving blocks, which are all assigned GHG emission factors in the National LCI DB, were analyzed. A truck was set as the means of transportation, and waste concrete recycling and waste ferrous metal recycling were selected for recycling materials.

From the analysis of the 93 design errors classified as requiring rework (Table 6), the following reductions were found: 374.72 m^3 of concrete, 55.84 kg of reinforcing rebar, 13.60 m^2 of tile, 1,857.54 kg of H-beam, and 0.76 units of collector well. It was found that plaster board use decreased by 222.4 m^2, while sidewalk block use decreased by 62.80 m^3. It was also found that 833 one-ton trucks were needed to transport materials to the construction site (13 km) and to the recycling site (13 km), and 827 one-ton trucks were needed to transport materials from the recycling site to the construction site (13 km). The waste concrete recycling transportation was reduced by 824,393.98 kg, and waste ferrous metal recycling transportation was reduced by 1,913.37 kg.

The reduced quantity and transportation distance of recycled materials (Table 6) were multiplied by the GHG emission factor (Table 3) to analyze the effect of reducing GHG emissions (Table 7, Figure 10). The reduction in GHG emissions by applying BIM was determined to be 113,211.24 $kgCO_2eq$. Of this, the reduced GHG of concrete emissions accounted for 90,473.70 $kgCO_2$ or 79.9% of the total reduction. The recycling of waste concrete (11,376.64 $kgCO_2eq$, 10.0%) and trucks (8,303.98 $kgCO_2eq$, 7.3%) accounted for a large share of GHG emissions. It was found that GHG emissions were greatly reduced in concrete products containing cement.

Since the reduction effect on GHG emissions through the application of BIM was analyzed by applying strict standards, the actual reduction in GHG emissions is expected to be even greater. This is because construction materials and equipment not provided by the National LCI DB were excluded from GHG emissions, and the transportation distance was minimized by selecting the closest product manufacturing plant and disposal/recycling site to the case site. In addition, the structure of the case building is a steel frame structure and a reinforced concrete structure, so the ratio of concrete use is low. If BIM is applied to buildings for which a large amount of concrete is used, such as reinforced concrete structures, GHG emissions can be reduced more significantly. Among the buildings that began construction in Korea between July 2022 and February 2023, the average monthly gross floor area of concrete structures was about 5,381,446 m^2, which is about 68.34% of the total, while the average of steel frame and reinforced concrete structures was about 625,182 m^2, which

Table 6. Reduced volume of construction materials, transportation, and recycled materials through the application of BIM

Division	Reduced quantity by GHG emission source	
Construction materials	Concrete	374.72 m^3 (824,393.98 kg)
	Reinforcing bars	55.84 kg
	Tile	13.60m^2 (312.80 kg)
	H-beam	1,857.54 kg
	Collector well	0.76 units (750 kg)
	Plaster board	222.4 m^2 (1,557.10 kg)
	Paving block	4.75 m^3 (3,165.12 kg)
	Sum	832,092.37 kg
	Transportation	833 one-ton trucks, 26 km
Recycled materials	Waste concrete recycling	824,393.98 kg
	Waste ferrous metal recycling	1,913.37 kg
	Sum	826,307.35 kg
	Transportation	827 one-ton trucks, 13 km

Notes: (a) 2,200 kg was used as the unit weight of 1 m^3 of concrete; (b) the unit weight of 3.040 kg/m of reinforcing bar D22 was used to convert unit of the reinforcing bar (m^3) included in concrete to kilogram; (c) a unit weight of 23 kg/m^2 was applied for porcelain tile; (d) the H-beam standard is H-200×200×8×12, and the unit weight was 49.9 kg/m or 72.4 kg/m, depending on the H-beam type applied; (e) for the collection well, 750 kg/piece, the size of collection well 400×400×900 was applied; (f) the unit weight of 7 kg/m^2 was applied for general plaster board 12.5T; (g) the weight of standard autoclaved light weight concrete (ALC) was applied (600×400×75), and each sheet weighed 12 kg; (h) the transportation distance of materials was 13 km from the production plant to the construction site and 13 km from the construction site to the recycling treatment plant; (i) recycled materials included concrete and metal (rebar, steel frame), which accounted for the majority of construction waste; and (j) the transportation of recycled materials covered a distance of 13 km from the recycling treatment plant to the construction site.

Table 7. Reduction effect of GHG emissions due to the application of BIM

Division	GHG emissions (unit: $kgCO_2$)	
Construction materials	Concrete	90,473.70
	Reinforcing bars	25.21
	Tile	64.25
	H-beam	1,416.54
	Collector well	171.33
	Plaster board	225.83
	Paving block	1,146.49
	Sum	93,523.35
	Transportation	4,167.00
Recycled materials	Waste concrete recycling	11,376.64
	Waste ferrous metal recycling	7.27
	Sum	11,383.91
	Transportation	4,136.98
Total		113,211.24

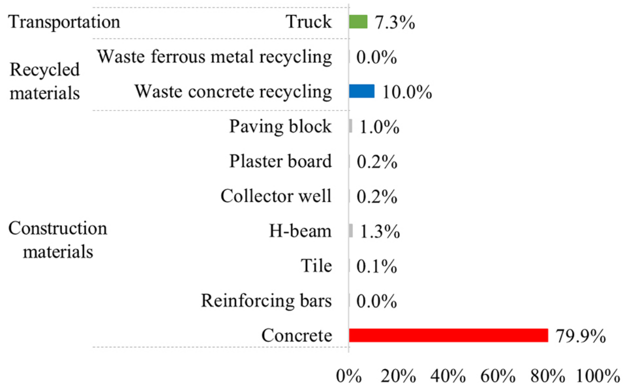

Figure 10. Reduction of GHG emissions by applying BIM

is about 7.94% of the total (Korean Statistical Information Service, 2023). Considering the ratio of reinforced concrete buildings to steel frame/reinforced concrete buildings, the reduction of GHG emissions by the application of BIM is expected to be even greater.

To move toward carbon neutrality, the South Korean government announced the average GHG standard for automobiles (2021–2030): the GHG emissions from cars and vans carrying less than 10 people are limited to 89 gCO_2/km in 2025 and 70 gCO_2/km in 2030 (Ministry of Environment, 2021). If a car is driven 20,000 km in a year, the GHG emitted by that car in 2025 must be below 1,780 $kgCO_2eq$. The GHG emission reduction achieved by applying BIM to the case building, 113,211.24 $kgCO_2eq$, is equivalent to the effect of not emitting GHGs from about 63.6 cars. If applying 70 gCO_2/km (the 2030 standard), the GHG emissions when a car is driven 20,000 km in one year is 1,400 $kgCO_2eq$/km. Compared to the case building, this is equivalent to the effect of not emitting GHGs from about 80.9 cars (Table 8).

A 30-year-old pine tree in the central region of South Korea absorbs 9.1 $kgCO_2eq$ per year, and a pine tree in Gangwon region of South Korea absorbs 8.1 $kgCO_2eq$ per year (National Institute of Forest Science, 2019) (Table 9). To generate the same effect as applying BIM to the case building would require the planting of 12,441 pine trees in the central region or 13,977 pine trees in the Gangwon region.

Previous studies have found that the application of BIM can contribute to economic feasibility and productivity improvement (Lee et al., 2012; M. Lee & U. Lee, 2020), and this study found that the application of BIM can contribute to reducing GHG emissions and making strides toward carbon neutrality. If GHG emission is considered when deciding on design change alternatives due to design errors, a greater contribution can be made to carbon neutrality.

5.2. Priority analysis of design change alternatives

5.2.1. The procedure of solving the design error

After identifying design errors, the rework need of the design error was analyzed, and the process is the same as shown in Section 4.1. The priority for resolving design errors was then determined by analyzing decision-makers' preferred design change alternatives for constructability, economic feasibility, and GHG emissions. For analysis, fuzzy analytic hierarchy process (AHP) and triangular fuzzy number were applied (Table 2). AHP is applied when prioritization is derived through mutual comparison of issues that require decision-making, but there are cases in which there is a lack of consistency, such as ambiguity in language expressions and differences in expertise among evaluators. To alleviate these problems, fuzzy AHP, which combines fuzzy theory and AHP, was applied (Lee, 2022).

Table 8. The emitted GHG limit standards for automobiles (unit: g/km) (Ministry of Environment, 2021)

Year	'21	'22	'23	'24	'25	'26	'27	'28	'29	'30
Car or van of 10 people or less	97	97	95	92	89	86	83	80	75	70
Van (11–15 people), small truck	166	166	164	161	158	158	155	152	149	146

Table 9. Annual absorption of CO_2 per tree (unit: $kgCO_2eq$) (National Institute of Forest Science, 2019)

Division	Tree age									
	10	15	20	25	30	35	40	45	50	55
Pine tree in Gangwon region	1.4	3.2	5.0	6.7	8.1	8.8	9.0	9.2	9.2	9.0
Pine tree in central region	1.0	2.2	3.9	9.8	9.1	7.9	6.6	4.9	4.0	3.2

Next, the constructability, economic feasibility, and GHG emissions of each design alternative were analyzed. High and low constructability were evaluated based on the opinion of the person in charge of the construction, and the fuzzy theory was applied. The economic feasibility was calculated through the volume and unit price of each design change alternative entered into the BIM model. GHG emissions were analyzed by applying the method in Section 4. The decision-makers' preference analyzed in the second step above was weighted on the evaluation results of the constructability, economic feasibility, and GHG emissions of each design alternative. For example, if the decision-makers' preference is analyzed as constructability first (0.40), economic feasibility second (0.35), and GHG emission third (0.25) through fuzzy AHP, the preference value is weighted to the constructability, economic feasibility, and GHG emissions of each design change alternative. Based on this, the priorities for sequential resolution of design errors were analyzed, but another design error may have occurred depending on the selection of the design change alternatives (Figure 11). Since the BIM model includes parametric objects, which means that when one object is modified, the geometric information of the related objects is also modified according to parametric rules (Eastman et al., 2009). If additional design errors occurred, the priority of design change alternatives was analyzed again. If no additional design errors occurred, design change alternatives for the analyzed design errors with the second highest priority were selected. By repeating this sequence, the design error resolution was completed.

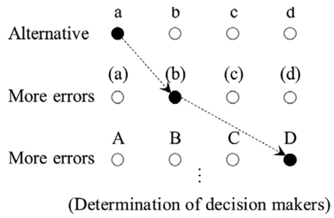

Figure 11. The method to solve the design error sequentially

5.2.2. Applicability analysis

Applicability was analyzed by applying the proposed priority analysis method to the case building BIM model (Figure 7). The design change alternatives (Ⓐ, Ⓑ, Ⓒ, Ⓓ, Ⓔ) for the five design errors (ⓐ, ⓑ, ⓒ, ⓓ, ⓔ) were applied as examples (Figures 12–16).

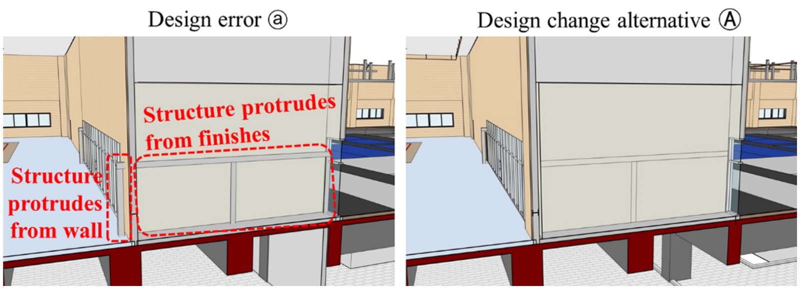

Figure 12. Design error ⓐ and design change alternative Ⓐ

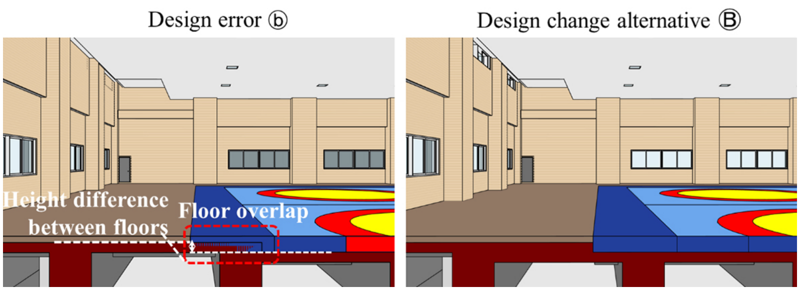

Figure 13. Design error ⓑ and design change alternative Ⓑ

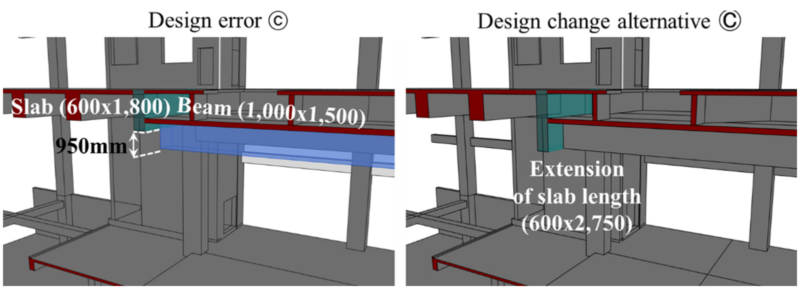

Figure 14. Design error ⓒ and design change alternative Ⓒ

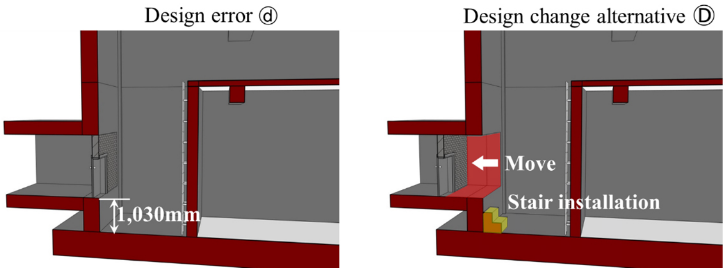

Figure 15. Design error ⓓ and design change alternative Ⓓ

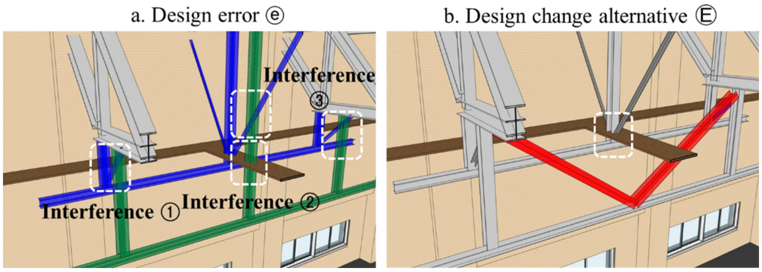

Figure 16. Design error ⓔ and design change alternative Ⓔ

Design error ⓐ is one in which the structure protrudes out of the wall (a design error in which the structure protrudes out of the finishing material). An alternative design change is to adjust the length of the structure, remove the structure protruding from the wall, and change the position of the structure in the finishing material (Figure 12).

In the case of design error ⓑ, an overlapping phenomenon occurs due to a difference in floor height. The alternative design change Ⓑ eliminates the difference in floor height and makes the floor height the same by attaching an additional layer (Figure 13).

In the case of design error ⓒ, the beam cannot be installed because the slab length is too small (950 mm). The design change alternative Ⓒ is to change the slab length from 600×1,800 to 600×2,750 (Figure 14).

In the case of design error ⓓ, stairs are not installed for movement. The design change alternative Ⓓ is to install the stairs, move the masonry wall, and create a stairwell entrance in its place (Figure 15).

The case of design error ⓔ is interference between structures. The alternative Ⓔ removes the interference by deleting the structure ② and reinforcing the structure by adding braces (Figure 16).

As a result of the analysis of the possibility of rework, which was the first step in analyzing the priority of design alternatives, it was assumed that all rework was necessary. In the second step, decision-makers' preferences for constructability, economic efficiency, and GHG emissions were analyzed by applying fuzzy AHP. Since the construction was completed, it was not possible to investigate the owner's opinion, so the applicability was analyzed through an interview with the person in charge of BIM. The importance of constructability was highest (0.444), followed by economic feasibility (0.351) and GHG emissions (0.205) (Figure 17).

In the third step, the constructability, economic feasibility, and reduction effect of GHG emissions were evaluated for the five cases (Table 10). To evaluate constructability, a survey was conducted on March 28, 2023 with two BIM practitioners who participated in the case construction (Figure 7). For economic feasibility, the cost change when the design change alternative was applied to solve the design error was analyzed. The reduction effect of GHG emissions was analyzed by applying the method proposed in this study. The priorities in Table 10 were calculated through relative evaluation of the five cases. To explain economic feasibility with an example, the priority of economic feasibility was calculated by comparing the reduction cost of each case against the sum reduction of costs achieved by applying design change alternatives to the five cases. If the cost of case ⓐ is reduced by 930,000 won by the application of design change alternative Ⓐ, and the sum of the reduced costs in the five design change alternatives is 12,508,000 won, then design change alternative Ⓐ has a relative economic value of 7.4%.

Next, the preference of the decision-makers (Table 10) was assigned as a weight to the evaluation results (Figure 17) of the cases, and the priority of final design change was analyzed (Figure 18). The design change alternative Ⓑ of design error ⓑ had the highest priority, followed by design change alternatives Ⓒ → Ⓔ → Ⓓ → Ⓐ. After resolving design errors in design change alternative Ⓑ, a check was completed to identify if any additional design errors had occurred. If so, the process of evaluating the priority of design change alternatives to resolve the design error would have to be conducted again. If no additional design changes occurred, the process would go to the final step: the decision-makers' confirmation and approval process.

Table 10. Evaluation results of constructability, economic feasibility, and GHG emissions in each case

Case	Constructability	Economics	GHG emissions	Sum	Priority
Ⓐ	0.168	0.074	0.000	0.242	5
Ⓑ	0.197	0.358	0.562	1.116	1
Ⓒ	0.220	0.300	0.435	0.955	2
Ⓓ	0.220	0.027	0.000	0.247	4
Ⓔ	0.197	0.241	0.003	0.440	3

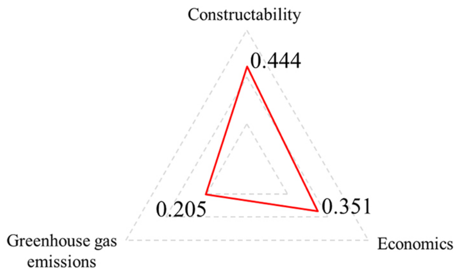

Figure 17. The preference analysis of decision-makers

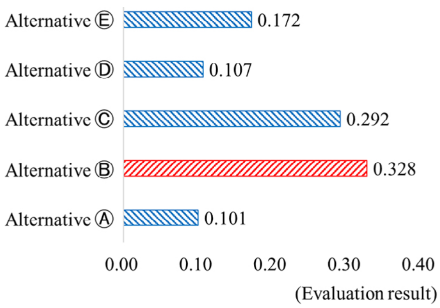

Figure 18. The priority of design change

If the decision-makers approve the application of design change alternative Ⓑ, design change alternative Ⓑ would be preferentially applied. If the decision-makers' approval was not obtained, the design error would be resolved by applying design change alternative Ⓒ, which had the second highest priority. Finally, the process of requesting confirmation and approval from the decision-maker is completed again.

If the proposed method is applied, it is possible to obtain quantitative data that can be referred to in the qualitative consultation process between the construction manager, the BIM manager, and the estimation manager to resolve design errors.

6. Discussion and implication

This study proposes methods to analyze GHG emissions that decrease with the application of BIM and to support decisions on design alternatives by considering economics, constructability, and GHG emissions. For the proposed method to be used in reducing GHG emissions from construction sites in actual practice, the additional program development and government support are required (see Figure 19).

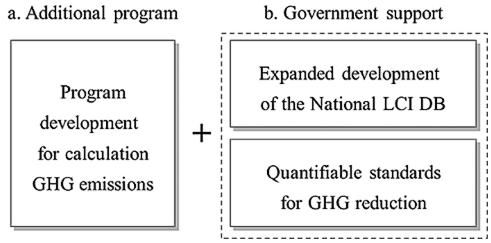

Figure 19. Implications for practice

First, it is necessary to develop a program that can easily calculate the reduction in GHG emissions caused by applying BIM. To calculate GHG emissions, it is necessary to quantify the amount of construction materials that change according to the reduction of design errors, the quantity of discarded construction materials, material transportation distance, and changes in construction equipment operation rate. This is because changes in GHG emissions can be automatically calculated based on these.

Next, the expanded development of the National LCI DB is necessary for the government to support the reduction in GHG emissions generated at construction sites. For using construction materials with low embodied carbon, the GHG emission information of various materials is needed. Currently, the South Korean government provides GHG emission information for only 27 types of construction materials and does not provide such information for construction equipment. Only 9 types of GHG emission from land transportation of construction materials are presented, and GHG emissions at the disposal stage are presented only for 3 products for landfill disposal, 10 for incineration, and 19 for recycling (Korea Environmental Industry and Technology Institute, 2022).

Finally, on the basis of the expanded development of the National LCI DB, the government can also establish quantitative standards to determine the amount of GHG reduction. The level of reduction in GHG emissions resulting from the application of BIM can be calculated using the method proposed in this study, but there is no quantified standard for the total GHG emitted during the construction process. If there are quantified standards, the goals related to reducing GHG emissions can be set; thus, data on GHG emissions according to the type and characteristics of the building, construction method are needed.

This study analyzed the effects of applying BIM on the reduction of GHG emissions, whereas previous studies have analyzed the economic effects of applying BIM to design verification (Lee et al., 2012; M. Lee & U. Lee, 2020). However, in a survey among BIM managers of public construction projects, none of the managers reported a stable and widespread application of BIM. The survey was conducted among 11 respondents from 4 organizations that ordered public construction in South Korea from December 14 to 21, 2022. The number of respondents was small because only those in charge of ordering current BIM projects in each public institution were included in the survey. This study contributes to the expansion of the application of BIM by analyzing the effect of applying BIM and the development of a system that can perform other BIM-based functions such as analyzing GHG emissions. The findings of this study would help potential BIM users recognize the benefits of applying BIM to construction and society.

7. Conclusions

Carbon neutrality is a global concern and is driving socioeconomic change. South Korea has established a carbon neutral promotion strategy to realize a carbon neutral country by 2050 (The Relevant Ministry, 2021). In this study, a method of rework reduction was proposed to reduce GHG emissions during the construction stage. This method is meant to reduce wasted construction materials by reducing design errors and rework through the application of BIM and to analyze the reduced GHG emissions. The subjects of analysis are GHG emissions by wasted construction materials, transportation distances of materials, and during the recycling of the materials. The GHG emissions were analyzed by applying GHG emission factors provided by the National LCI DB (Korea Environmental Industry and Technology Institute, 2022). The GHGs emitted from the production processes of materials and from the use of construction equipment, which were not provided by the National LCI DB, were excluded for conservative and strict analysis. The analysis consisted of four stages: ① data collection, ② analysis of design errors and necessity of rework, ③ analysis of the reduction in material quantity due to reduction in rework, and ④ analysis of the effect of reducing GHG emissions according to reductions in material quantity. Fuzzy theory was applied to mitigate the lack of consistency in judgements by experts when identifying design errors and the need for rework. The proposed method was applied to steel and reinforced concrete buildings to analyze the GHG reduction effect according to BIM application.

The analysis revealed that GHG emissions were reduced by 113,211.24 kgCO_2eq. Assuming that cars and vans with less than 10 passengers emit 89 gCO_2/km of GHGs (Ministry of Environment, 2021), the reduced GHG emissions is 63.6 times the amount of GHGs emitted when driving 20,000 km. It also requires 12,441–13,977 pine trees to remove 113,211.24 kgCO_2eq of GHGs (National Institute of Forest Science, 2019). Of the total GHG reduction, 79.9% was due to a reduction in concrete, and the proportion of waste concrete recycling (10.0%) was also high. The proportion of GHGs emitted through truck transportation (7.3%) was higher than that of other materials, but construction materials related to cement showed the highest GHG emissions. Among the buildings that started construction in South Korea from July 2022–February 2023, reinforced concrete buildings accounted for 68.34% based on gross floor area (Korean Statistical Information Service, 2023). This means that the effect of applying BIM can be greater than the results of the study.

A method of analyzing the priority of design change alternatives that decision-makers can refer to when deciding whether to rework is also proposed. The method consists of the following: 1) analysis of the possibility of reworking design errors, 2) analysis of decision-makers' preferences, 3) sequential resolution of design errors, and 4) confirmation of design change alternatives. The analysis criteria are the economic feasibility and constructability presented in previous studies (Won et al., 2021) and the reduction effect of GHG emissions proposed in this study. The first step, the analysis of the possibility of reworking design errors, is the same as the method applied in the GHG emission reduction effect. The second step, the decision-makers' preference analysis, is designed to reflect the decision-makers' preference for constructability, economic feasibility, and GHG emissions when resolving design errors, for which fuzzy AHP and fuzzy theory were applied. Since the objects constituting the BIM model have parametric characteristics, resolving one design error may cause new design errors in other objects. To reflect this, the sequential solutions method was included in the third step. Finally, the decision-makers confirm and approve the priorities of the analyzed design alternatives, completing the process. If the alternative is not approved, the process returns to the third step, and the process of analyzing the solution of the next design alternative is executed.

The economic effects of BIM have been analyzed through design validation by previous studies (Lee et al., 2012; M. Lee & U. Lee, 2020), but the reducing effect of GHGs has not been analyzed, even though eleven percent of global carbon emissions are emitted from the production of construction materials and the construction stage of buildings (World Green Building Council, 2019). This study verifies that the application of BIM can help reduce GHG emissions and provide economic benefits. The results contribute to BIM activation and decision-making regarding the selection of design alternatives and reducing GHG emissions. In future research, we intend to survey the success and failure factors of BIM with the implementation effect and compare them with other countries.

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Author contributions

Chijoo Lee planned the main content and methodology of the study, performed data collection and analysis, and wrote and revised the paper.

Disclosure statement

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

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