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Integrated building life-cycle assessment model to support South Korea's green building certification system (G-SEED)

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ABSTRACT

In the construction industry, concerted efforts are being made to quantitatively evaluate the environmental impacts of building materials and buildings using the life cycle assessment (LCA) approach. However, the existing building LCA model applies different evaluation systems and standards to building materials and buildings; thus, interlinking and integrating their evaluated values are made difficult. To overcome this problem, this study aims to develop an integrated building LCA model that enables the integration of all LCA results related to building materials used for constructing a building, the building components, and the whole building. First, the building LCA methods and certification criteria employed by major green building certification systems [Leadership in Energy & Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Building Research Establishment Environmental Assessment Methodology (BREEAM), and Green Standard for Energy and Environmental Design (G-SEED)] were analyzed. Then, an integrated building LCA model that allows integration of the LCA results for building materials into those of the LCA of building components and the whole building was developed. Finally, we established an application plan for a stepwise application of the integrated building LCA model to G-SEED, a Korean green building certification system. The feasibility of the integrated building LCA model was confirmed by comparing it with the existing building LCA model in a case analysis, which demonstrated the applicability of the proposed integrated building LCA method in terms of building materials, building components, and whole building.

1. Introduction

Environmental threats have recently reached a global level. For example global warming, ozone layer depletion, and depletion of resources have become the common agenda of all countries around the world. Worldwide, maximum efforts have been exerted to secure green technologies to minimize environmental loads caused by each country's industrial sectors [1–3]. Amid such concerted efforts, growing awareness arises for the quantitative evaluation of environmental loads coming from building life cycle stages, i.e., building material production, construction, use, maintenance, and demolition, from the perspective of life cycle assessment (LCA) at the design stage prior to construction [4–7].

Advanced countries have developed building LCA methods best suited for their own environments and conditions and apply them to their own green building certification systems [8]. In particular, Leadership in Energy & Environmental Design (LEED), the green building certification in the U.S., is granted on the basis of the LCA of building components as evaluation item “MR Credit 1″, Building Life Cycle Impact Reduction (Option 4. Whole Building LCA). In the LEED system, building LCA is performed under three or more environmental impact categories, including global warming potential (GWP), with the external program Athena EcoCalculator for Assemblies or Building for Environmental and Economic Sustainability (BEES) [9,10]. The Comprehensive Assessment System for Built Environment Efficiency (CASBEE), the green building management system in Japan, implements the LCA of major building materials under “L2.2.2″ Continuing Use of Existing Structural Frame, etc. Therein, the major building materials refer to concrete, blast furnace slag cement concrete, steel, iron, and wood, and only the GWP is assessed [11]. Building Research

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Establishment Environmental Assessment Methodology (BREEAM) system which is based on the U.K. implements the building LCA of building components on the basis of the generic ratings of the evaluation item Mat01. Life Cycle Impacts. Using the Green Guide, which is a BREEAM specific database (DB) for environmental performance of building materials and components, it evaluates a total of 13 environmental impact categories, including the GWP. Alternatively, an external program IMPACT is also used to evaluate the environmental impacts [12,13].

However, the currently available building LCA for a green building certification system refers to the building LCA in terms of ready to use life cycle inventory DBs (LCI DBs) for standard building materials. On the other hand, the environmental effects of building materials actually used for building construction are evaluated by a separate process. In other words, the LCA results of the building materials are independently used for individual building components or the entire building without any interoperating linkage among the building materials, building components, and the building itself. This absence of linkage results in the need for R & D of an integrated building LCA model with a hierarchical structure so that the LCA results of the building materials actually used for construction can be directly applied to their respective building components and the building itself in a systematically interoperable method.

Against this background, this study aims to develop an integrated building LCA model that allows an interlinked application of the LCA results among the building materials, building components, and the whole building and proposes a method for stepwise application of the integrated building LCA model to the Green Standard for Energy and Environmental Design (G-SEED), a Korean green building certification system.

2. Literature review

International green building certification systems, such as the LEED, CASBEE, and BREEAM employed in the U.S., Japan, and the U.K., respectively, have introduced the building LCA criteria as part of the strategies to reduce the environmental loads of buildings in their respective countries by introducing necessary revisions.

As a preliminary study in developing the proposed integrated building LCA model, recent international trends and directions of building LCA approaches, LCA methods, and evaluation systems of the aforementioned representative green building certification systems were analyzed to establish a system that addresses the problems of currently available approaches and systems. Table 1 lists an overview of the methods and scopes of the LCA applied to these green building certification systems.

2.1. LEED

Building LCA was first introduced into the U.S. green building certification system in 2009 by adding “Innovation in Design” to LEED as an optional certification evaluation item. Using external LCA programs such as ATHENA EcoCalculator, the environmental impacts of building components are quantitatively evaluated [14]. In LEED, building LCA is simultaneously used for environmental performance evaluation in terms of building materials using a green labeling certification system for building materials. In this system, scores are given in terms of the ratio of the costs of the green labeled building materials to the total costs of the building materials used for construction.

The LEED V4, revised in 2014, reflects the building LCA results by specifying the certification standards for building life cycle impact reduction of “Materials and Resources.” Using LCA programs to evaluate three of the environmental impact categories of GWP, abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), and photochemical oxidant creation potential (POCP), where GWP should be one of the three categories, scores are given if at least a 10% cost reduction relative to the reference building cost can be documentarily proven. This revision in the LEED certification standard contributed to the expansion of the scope and method of LCA evaluation and increase in its scoring weight [8]. However, despite the inclusion of green building materials in the current building LCA, they are still evaluated on the basis of the LCI DB of standard building materials relative to existing standard buildings.

2.2. CASBEE

CASBEE evaluates only the greenhouse gases (GHGs) emitted from buildings to provide information on GHG emissions and the reduction effects for users.

In particular, CASBEE implements building LCA using an internally developed spreadsheet without using any external programs [15]. However, this spreadsheet contains only basic items, such as the purpose, service life, and main architectural structure of the building, which form the basis where LCA is performed using internally developed DBs and algorithms. Moreover, the evaluation is performed by comparing the building with an imaginary reference building corresponding to level three on a scale of 1–5, thereby applying the building LCA method on the basis of major building materials, namely, concrete, steel, rebar, and wood. As a limitation, the embedded quantity DB was found to be uniformly used in the material types without separate input of actual quantities of building materials. Thus, it fails to reflect the use of green building materials in the evaluation results.

2.3. BREEAM

BREEAM, the environmental assessment method developed by the U.K. Building Research Establishment, is the first green building certification system that introduced the building LCA concept. BREEAM manages the DBs of green building materials using the Environmental Profile Methodology that governs the green performance evaluation of building materials. The Green Guide provides the environmental DBs of building materials. This building material environmental information is integrated into the environmental performance evaluation of building components using the Green Guide Calculator where the green information of building materials is provided as DBs for comparison with other products as well as the environmental performance evaluation of buildings [16,17]. Furthermore, BREEAM has continuously revised the items related to building LCA based on the building materials, with the 2014 version being the most recent revision.

For example, the BREEAM 2009 version evaluates at least three environmental impact categories, including climate change, using the Green Guide Calculator of Mat 01 Materials Specification (which evaluates using building components) or external LCA programs. It then assigns scores if environmental impact reduction effects are demonstrated relative to the standard building components in the same region [18]. On the other hand, the BREEAM 2011 and later versions include a regular LCA item “Mat 01 life cycle impacts” within the item clusters related to the materials, and their obtainable score weight is increased from four to six points. Moreover, BREEAM recommends the use of IMPACT, a domestically developed tool for LCA for Building Information Modeling (BIM) based building structures. In summary, BREEAM is a domestically developed LCA based green building evaluation system with a guideline that performs whole building LCA on the basis of environmental information on the building materials [19]. However, because of the inclusion of all building materials used in the construction in the LCA, BREEAM requires considerable time and cost to obtain the environmental information on all building materials.

Table 1
Methods and scopes of the LCA currently applied to representative green building certification systems.

Classification	LEED (U.S.)		CASBEE (Japan)	BREEAM (U.K.)		G-SEED (Rep. Korea)
	V3	V4		2009	2014	
Evaluation items	Innovation in design	MRc1. Building life-cycle impact reduction	Resources and Materials	Mat 01 Materials Specification	Mat 01 Life Cycle Impacts	–
	Optional	Obligatory (selection)	Obligatory	Optional	Obligatory (selection)	–
Evaluation scope	Cradle to grave with options		Cradle to gate	Cradle to grave with options		–
Maximum score	1	3	BEE	4	6	–
LCI DB	Ecoinvent	Ecoinvent	Internal DB	Individual company DB U.K. Trade associations Ecoinvent		–
Building material evaluation	EPD	EPD	Eco Mark, Eco-friendly products	Green Guide, EPD	Green Guide, EPD	Green label, GR mark, Carbon label
Evaluation program	any LCA program	any LCA program	Internal spreadsheet	Mat Calculator or any LCA program	Mat Calculator or any LCA program	–
Comparison with the standard building	×	○	○	○	○	–
Environmental impact categories	seven categories including GWP	GWP, ODP, AP, EP, POCP, ERS	$LCCO_2$	three or more categories including GWP	11 categories including GWP	–

Cradle to grave: Cradle-to-grave is the full Life Cycle Assessment from resource extraction ('cradle') to use phase and disposal phase ('grave').
Cradle to gate: Cradle-to-gate is an assessment of a partial product life cycle from resource extraction ('cradle') to the factory gate (i.e., before it is transported to the consumer)
EPD: Environmental Product Declaration

2.4. G-SEED

G-SEED does not consider the building LCA as an evaluation item, but scores are assigned by the number of products that obtain a green label, a carbon label, and a green recycle mark under the item cluster of “Materials and Resources” [20]. This evaluation method cannot quantify the contribution of green building materials in terms of eco friendliness of the entire building. The ongoing G-SEED revision process considers inclusion of the GHG evaluation standards for building materials in the green building evaluation.

3. Development of an integrated building LCA model

Fig. 1 shows that the integrated building LCA model is a hierarchical evaluation system in which the green building materials chosen by the user at the design stage of the building construction are automatically reflected in the LCA of the building components and the building. The LCA scope can be broken down into energy related environmental impacts of the building materials arising from the energy consumption at the use stage and the inherent environmental impacts indirectly brought in during the production, construction, maintenance and management, and demolition processes [21,22].

In this study, only the inherent environmental impacts were set as the scope of the integrated building LCA model to focus on the contribution of the building materials selected by the user to the total environmental load of the building. Additionally, to implement the integrated building LCA model proposed in this study, the evaluation methods and DBs were divided in terms of the building material, building component, and the building itself.

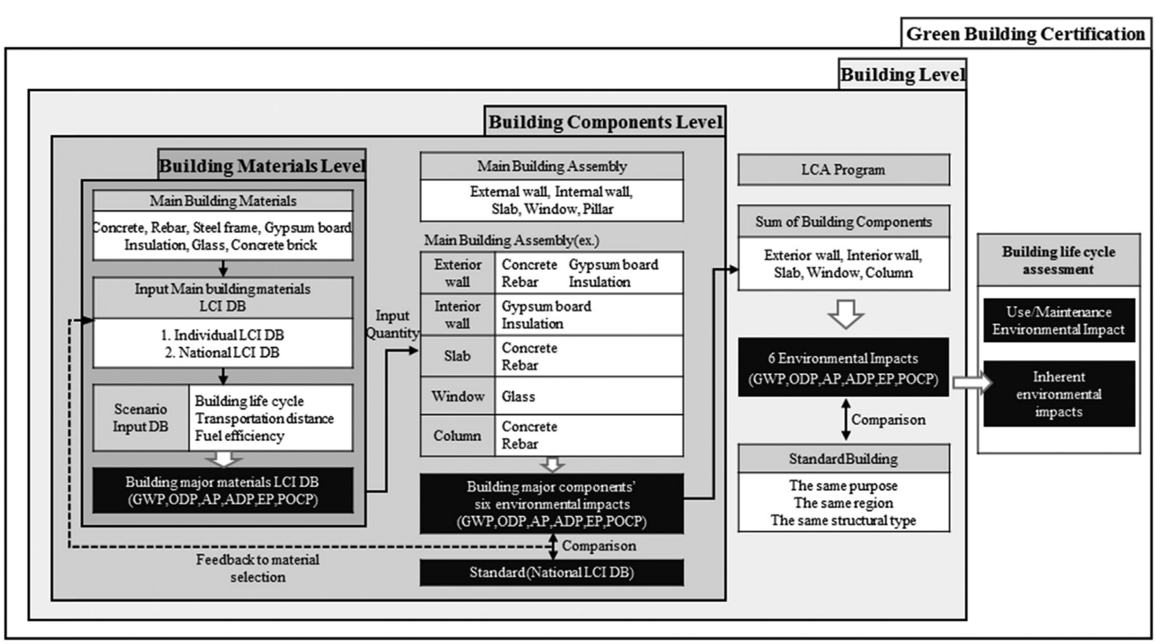


Fig. 1. Conceptual chart of the integrated building LCA model.

3.1. Evaluation of building materials

The existing building LCA method requires the LCI DB of all building materials used in the construction and the scenario of each life cycle stage. The huge amount of data to be collected inevitably involves a large amount of time, budget, and human resources. To address this problem, ISO 14040 defines the cut off criteria to reduce the data collection related time and costs and presents an efficient evaluation system [23,24].

In accordance with the ISO 14040 cut off criteria, seven major building materials (concrete, rebar, steel, glass, insulation, gypsum board, and concrete products) were applied, which account for over 95% of the environmental loads of a building in Korea. And the major building materials were selected by referring to the results of the study on apartment building which are the most residential type in Korea [25,26]. The existing building LCA model evaluates the environmental loads from information on the building materials used at each life cycle stage and in per-unit value. The per-unit value is the value that quantifies the environmental load yielded by a functional unit of a building material, mostly using the same LCI DB. The uniform application of per-unit values without regard to the environmental performance of the individual materials (products) diminishes the effectiveness of the building LCA results. Moreover, most of the LCI DBs created thus far have their scope of analysis limited to the building material production stage only; thus, collecting additional data to evaluate the inherent environmental impacts is required. This problem is solved by systemizing the process of extracting the environmental impact (per-unit value) of each of the major building materials by pre inputting the scenarios of each LCA stage, as shown in Fig. 2. In other words, the values per functional unit of the six environmental impact categories (GWP, ADP, AP, EP, ODP, and POCP) of the major building materials are made available from the pre entered information on the LCI DB, transport, and fuel efficiency [27,28], which enables easy evaluation of the inherent environmental impacts of the building life cycle from the LCI DB information using the types of major building materials alone [29].

3.2. Evaluation of building components

The environmental impact (per-unit value) of a building component can be calculated by combining its building materials. Because the environmental impact evaluation results vary according to the building material types within the same building component, the building materials must be selected at the design stage of the building [30–32]. In Korea, detailed specifications on building components have not yet been established. Therefore, for suggesting the assessment method of building components in the certification, the BREEAM which already has assessment system integrated with building components and the Construction information classification systems (CICS) were referenced in this study. So the building components were classified as exterior wall, interior wall, slab, window, and column [33–36].

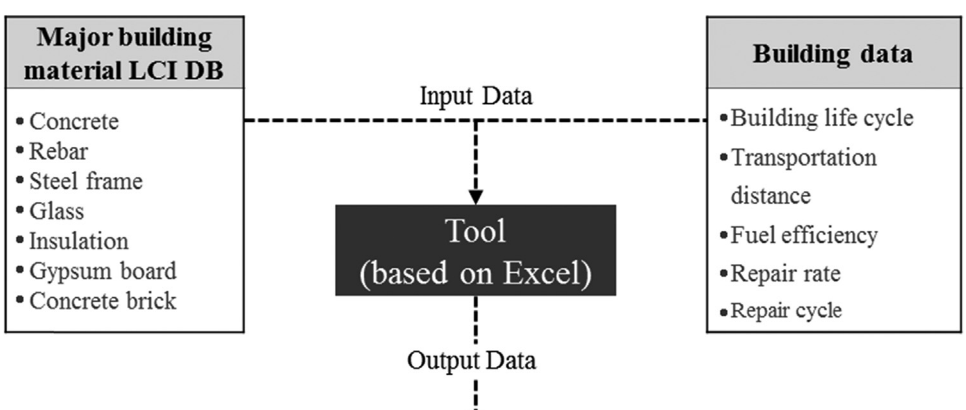
3.3. Evaluation of a building

The environmental impact at the whole building level can be quantitatively evaluated by adding the values resulting from the combination of the six environmental impact category DBs of major building materials (concrete, steel, rebar, gypsum board, insulation, and concrete products) and the building components.

The results of the environmental impact evaluation of the building under investigation can be used to quantify its contribution to the environmental load by comparing it with the environmental impact evaluation of a reference building. In this study, reference building is defined as a building with comparable region, purpose, and structure, and the per-unit value of the environmental impacts of all building materials is to be derived from the national LCI DB.

4. Proposal of the phased application methods for G-SEED

In the current G-SEED version, only the number of building materials granted with carbon label or green recycle mark or the evaluation items associated with energy consumption in the use stage are reflected in the certification system. Therefore, to implement the interlinkage of the integrated building LCA model with G-SEED, the



Life cycle DB of each major building material(per-unit value)

Classification	GWP	ADP	AP	EP	ODP	POCP
Concrete(m^3)	4.10E+02	1.87E+00	6.84E-01	7.98E-02	4.65E-05	1.02E+00
Rebar(kg)	3.53E-01	2.93E-03	2.31E-03	3.48E-04	1.04E-08	3.41E-04
Glass(kg)	1.02E+00	9.20E-03	4.77E-03	6.81E-05	3.95E-07	1.16E-03
Insulation(kg)	2.74E+00	2.33E-01	5.40E-02	3.67E-03	3.85E-08	8.52E-03
Gypsum board(kg)	4.99E+00	5.03E-01	1.02E+00	1.71E-01	1.84E-05	2.47E-01
Concrete brick(kg)	1.24E-01	2.64E-04	1.57E-04	2.27E-05	4.72E-09	1.32E-05

Fig. 2. DB creation process for the environmental impacts of the building material LCA.

Table 2
Application plan of the integrated building LCA model in G-SEED.

Classification	Phase 1	Phase 2	Phase 3
Evaluation item	GWP	Six environmental impact categories	Six environmental impact categories
Scope of evaluation	Production stage	Life cycle stage (except use stage)	Life cycle stage
Evaluation tool	LCA program Phase 1	LCA program Phase 2	LCA program Phase 3
Evaluation method	Simple grading	Detailed grading	Single index
Target materials	Two major materials	Seven major materials	Seven major materials
LCI DB	National	Individual, National	Individual, National

proposed integrated building LCA model should be stepwise applied by taking into account the current situations.

In this context, the LCA level is categorized into the scope of evaluation, evaluation target, and items of evaluation, and a stepwise application plan is proposed for the integrated building LCA model from phase 1 (its introduction) to phase 3 (its application) to all environmental performance evaluation levels, as listed in Table 2.

4.1. Phase 1

Phase 1 is the initial application of the building LCA to G-SEED. It aims to set the trend for building material based environmental impact evaluation and to popularize the concept of green performance evaluation, rather than concrete evaluation [37].

Among the six environmental impact categories, the GWP was proposed for the building material production stage. Among the major building materials, concrete, steel, and rebar were selected as the target materials. Development of an LCA program was also planned, which was tailored for the Korean situation that is capable of quantitative evaluation of the environmental impacts as well as configuring the evaluation results to be compared with the standard values in terms of purpose and structure.

4.2. Phase 2

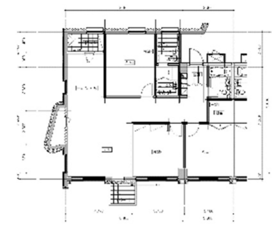
In Phase 2, the inherent environmental impacts of the whole life cycle of a building, except for the use stage, are evaluated. In this phase, the use stage is excluded because a scenario is required to estimate the energy consumption at this phase.

Specifically, evaluation of the six major environmental impacts (GWP, ADP, AP, EP, ODP, and POCP) of the seven major building materials (concrete, steel, rebar, insulation, glass, gypsum board, and concrete products) was proposed using the inherent environmental impact DB (Fig. 2). Additionally, environmental impact evaluation at the building component level is performed in this phase, and the evaluated values are checked against the standard values.

4.3. Phase 3

In Phase 3, six environmental impact categories of all building life cycle stages, including the use stage, were proposed to be evaluated. Furthermore, in line with the recent trend of switching from 2D information based CAD programs to BIM programs, including 3D and various building information, the proposed LCA program (Phase 3) can be linked to the BIM data [38,39]. Therefore, users of BIM programs will likely perform LCA using the BIM takeoff and energy simulation functions.

Table 3
Overview of the evaluated target building.

Classification	Detail	Reference floor plane
Purpose	Apartment building	
Structure	Steel-reinforced concrete	
Size	eight stories, 15 units	
Total floor area	2235.09 m^2	
Building area	338.30 m^2	
Building coverage ratio	18.05%	
Floor area ratio	43.54%	

5. Case study

A case analysis was carried out to test the feasibility of the integrated building LCA model proposed in this study and the stepwise implementation of LCA items in G-SEED. The existing evaluation method and the method based on the proposed integrated building LCA model were analyzed and compared in the case study.

5.1. Evaluation target

Table 3 lists the information of an eight-story passive apartment building with 15 living units used in the case analysis. Because a passive apartment building needs more building materials for construction than a general apartment building, its inherent environmental impacts based on the building material LCA are expected to be greater than those of a general apartment building, which makes it suitable for an efficient case analysis.

5.2. Evaluation method

5.2.1. Existing LCA model

The existing building LCA model performs LCA by dividing the building life cycle into construction, use and maintenance, and demolition and disposal stages.

The production process in the construction stage calculates the quantity of each building material used for construction, as listed in Table 4, and evaluates the environmental impacts by per-unit value. The environmental impacts of the transportation and construction processes are evaluated using the estimation model proposed in the literature. In the use and maintenance stage, the repair rate and repair cycle specified in the Housing Act were utilized to evaluate the environmental impacts of the building materials additionally used for repair and maintenance in the same manner as that in the production process. To evaluate the environmental impacts during the demolition and disposal stage, a volume increase factor of 1.5 was applied to the quantity of building materials calculated in the production process and the fuel efficiency (diesel) of 4.75 L/ton per backhoe (0.4 m^3) and giant breaker (0.4 m^3) presented in the literature. The vehicle used to transport the demolished building materials calculated in the demoli-

Table 4
Quantity of major building materials of the target building.

Item	Unit	Quantity
Concrete	m^3	1138.38
Steel	ton	91.12
Gypsum board	ton	5.75
Glass	ton	11.97
Insulation	ton	1.04
Concrete products	ton	5.22

Table 5
Building material application conditions of the target building.

Classification		Reference building	Case 1	Case 2
Slab	Concrete	National LCI DB	Carbon label	National LCI DB
	Steel		National LCI DB	
Exterior wall	Concrete		Carbon label	
	Steel		National LCI DB	
	Insulation			
	Gypsum board			Low carbon
Interior wall (partition)	Gypsum board			Low carbon
	Concrete products			National LCI DB
Window	Glass			
Column	Concrete		Carbon label	
	Steel		National LCI DB	

tion and disposal stage was assumed to be a 10-ton truck, and the transport distance was set to be 30 km.

5.2.2. Integrated building LCA model

Table 5 lists the configurations of the integrated building LCA model under three conditions of applying the building materials: reference building, Case 1, and Case 2. For the reference building, the national LCI DB was applied for the environmental impact evaluation of all building materials. Cases 1 and 2 were configured to be a carbon labeled concrete LCI DB [40] and an LCI DB of gypsum board with 10% reduction relative to the reference value, respectively.

At the building component level, the evaluated items were divided according to the major component classification system (exterior wall, interior wall, column, slab, and window), and for the component combination, six major building materials were used. For example, the exterior wall was configured to comprise concrete, steel, insulation, and gypsum board in which their respective LCI DBs were applied.

At the whole building level, the LCA results for the building materials and building components evaluated earlier according to the cases were used to calculate the overall environmental impact of the building for comparison.

5.3. Evaluation results

5.3.1. Existing LCA model

Table 6 lists the results of the environmental impact evaluation using the existing building LCA model. The evaluation results were derived as the sum of all six environmental impacts of the building regardless of the per-unit value of the building materials and building

Table 6
Results of the environmental impact evaluation using the existing LCA model.

Classification	Construction	Use/Maintenance	Demolition/ Disposal	Sum
GWP ($kg\text{-}CO_{2eq}$)	5.96. E+05	5.01. E+05	1.51. E+03	1.10. E +06
ADP (kg)	2.26. E+04	1.00. E+04	1.25. E+03	3.39. E +04
AP ($kg\text{-}SO_{2eq}$)	4.21. E+04	1.93. E+04	2.70. E+01	6.14. E +04
EP ($kg\text{-}PO_4{}^{3-}{}_{eq}$)	6.89. E+03	3.37. E+03	2.20. E+00	1.03. E +04
ODP ($kg\text{-}CFC\text{-}11_{eq}$)	9.66. E−01	1.64. E−01	2.44. E−05	1.13. E +00
POCP ($kg\text{-}Ethylene_{eq}$)	1.18. E+04	3.90. E+03	1.55. E+00	1.57. E +04

Table 7
Results of environmental impact evaluation using the integrated building LCA model.

Evaluation method			Unit	Quantity	GWP ($kg\text{-}CO_{2eq}$/unit)	ADP (kg/unit)	AP ($kg\text{-}SO_{2eq}$/unit)	EP ($kg\text{-}PO_4{}^{3-}{}_{eq}$/unit)	ODP ($kg\text{-}CFC\text{-}11_{eq}$/unit)	POCP ($kg\text{-}Ethylene_{eq}$/unit)
Conventional			–	–	1.10. E+06	3.39. E+04	6.14. E+04	1.03. E+04	1.13. E+00	1.57. E+04
Integrated building LCA model (standard)	Slab	Concrete	m^3	593.30	2.43. E+05	1.11. E+03	4.06. E+02	4.73. E+01	2.76. E−02	6.05. E+02
		Steel	ton	44.50	1.57. E+05	1.30. E+03	1.03. E+03	1.55. E+02	4.64. E−03	1.52. E+02
	Outer wall	Concrete	m^3	473.82	1.94. E+05	8.87. E+02	3.24. E+02	3.78. E+01	2.20. E−02	4.83. E+02
		Steel	ton	40.44	1.43. E+05	1.19. E+03	9.35. E+02	1.41. E+02	4.21. E−03	1.38. E+02
		Insulation	ton	1.87	1.06. E+04	9.54. E+01	4.94. E+01	7.06. E−01	4.09. E−03	1.21. E+01
		Gypsum board	ton	1.04	9.35. E+04	9.42. E+03	1.90. E+04	3.21. E+03	3.45. E−01	4.63. E+03
	Inner wall	Gypsum board	ton	3.87	1.93. E+05	1.95. E+04	3.94. E+04	6.64. E+03	7.14. E−01	9.58. E+03
		Concrete products	ton	5.22	6.44. E+02	1.38. E+00	8.21. E−01	1.19. E−01	2.46. E−05	6.90. E−02
	Window	Glass	ton	11.97	1.23. E+04	1.10. E+02	5.71. E+01	8.15. E−01	4.72. E−03	1.39. E+01
	Column	Concrete	m^3	71.26	2.92. E+04	1.33. E+02	4.87. E+01	5.69. E+00	3.32. E−03	7.27. E+01
		Steel	ton	6.18	2.18. E+04	1.81. E+02	1.43. E+02	2.15. E+01	6.44. E−04	2.11. E+01

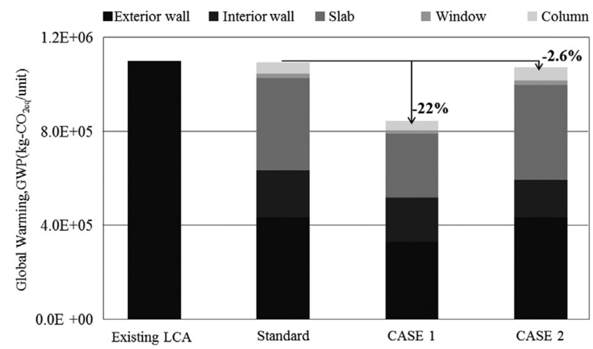


Fig. 3. Evaluation results using the integrated building LCA model at the building-component.

components.

Although the passive apartment building studied for the case analysis was built with various green building materials, the existing LCA method cannot reflect their environmental performance because uniform national LCI DBs were applied in this method. Therefore, if the user employs green building materials at the construction planning stage, discrepancies will likely occur between the results of the environmental impact evaluation performed at the planning stage using the existing LCA model and those of the building LCA constructed with the building materials.

5.3.2. Integrated building LCA model

The case analysis using the integrated building LCA model revealed that the results of the environmental impact evaluation of the whole building could be analyzed in terms of the building component unit, as listed in Table 7 and shown in Fig. 3. In Case 1, which used the carbon labeled concrete per-unit value, reduction rates of 22.8%, 2.8%, 0.7%, 0.4%, 2.5%, and 4.0% were achieved in the environmental impact categories of GWP, ADP, AP, EP, ODP, and POCP, respectively. In Case 2, which used the green gypsum board, reduction rates of 2.56%, 8.5%, 9.5%, 9.6%, 9.3%, and 9.0% were achieved in the same respective order of categories.

5.4. Application of integrated building LCA model

According to aforementioned analysis results using the integrated building LCA model, the exterior wall comprises concrete, steel, rebar, and insulation. Among them, the environmental performance can be more efficiently enhanced by changing to concrete, which is a high GWP building material, than changing to finishing materials such as the gypsum board. This result can also be interpreted as that the slab exterior wall with high proportion of concrete greatly influences the environmental performance of a building. Consequently, in order for the user to obtain points for the building LCA items in G-SEED, suitable building materials should be selected according to the evaluation results at the building component in which the following support may be considered.

Cases 3–5 were configured under different evaluation conditions for different building components, as listed in Table 8, in the same manner as in Cases 1 and 2 in which green concrete and gypsum board were applied, respectively. Comparative analyses were performed to obtain a G-SEED green certification. The conditions for Case 3 (exterior wall with eco concrete), Case 4 (slab with green concrete), and Case 5 (components with green concrete and gypsum board) were designed to minimize the environmental load of the building.

As a result, if a reduction of 10% or more is achieved relative to the reference Grade 1 condition in the aforementioned Phase 2 LCA items of the G-SEED, Cases 1, 4, and 5 can be considered to be eligible for Grade 1, as listed in Table 8 and shown in Fig. 4. However, in Cases 1 and 5, green concrete should be used in all components containing concrete, whereas changing only the slab would be sufficient to achieve Grade 1 in Case 4.

Table 8
Application conditions of different members depending on evaluation conditions.

Items	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
Slab	▮			▮	▮
Outer wall	▮		▮		▮
Inner wall		◌			◌
Window					
Column	▮				▮

▮: Carbon-labeled concrete, ◌: Green gypsum board

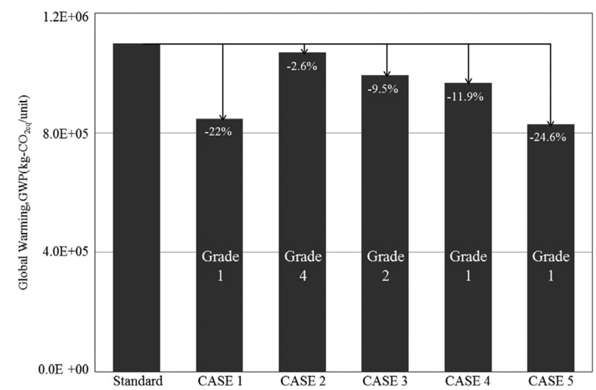


Fig. 4. Results of GWP evaluation in all evaluation conditions.

From these results, the integrated building LCA model proposed in this study can be inferred to be efficiently useful in predicting the contribution of individual building materials to the overall environmental impact of the building according to the evaluation results of the building components that reflect the environmental performance of the building materials. Hence, rapid and adequate choice of building materials are expected to be made at the design stage to obtain the target grade in G-SEED using the proposed integrated building LCA model.

6. Discussion

Worldwide, an increasing number of countries have introduced LCA based environmental performance evaluation of a building into their green building certification systems [41]. However, whereas they use methods adapted in compliance with the LCA guidelines, their green building certification systems employ different evaluation methods and lack interoperating linkage between the building materials and the buildings themselves. G-SEED does not implement quantitative LCA for buildings containing green building materials [42].

Using the integrated building LCA model proposed in this study, a user (architectural designer or green consulting specialist) can predict the contribution of individual building materials to the overall environmental impact of a building according to the evaluation results at the building component level, which reflect the environmental performance of the building materials used. The integrated building LCA model can also help the user set up an optimal plan to obtain the target grade of G-SEED by making rapid and precise choices of building materials at the design stage. Each user can thus contribute to reducing environmental load by providing support in reducing the environmental impacts of a building. Creation of individual LCI DBs for major building materials will greatly contribute to an optimal evaluation of the environmental performance of a building according to the major building components. Furthermore, the applicability of the integrated building LCA model proposed in this study to the quantitative evaluation of the environmental performance of a building suitable for Korean conditions was verified by implementing the stepwise evaluation method proposed in this study with linkage to G-SEED.

7. Conclusion

This study was aimed to develop an integrated building LCA model that allows interoperable linkage of LCA results among building materials used for construction, building components, and the whole building. The following summarizes the conclusions of this study.

1. An integrated building LCA model has been proposed in which green building evaluation is performed with interoperating linkage at the building, building component, and whole building levels, certification system, and green certification level.
2. At the building material level, LCA DBs were created for the environmental impacts of major building materials with high environmental loads in six environmental impact categories.
3. At the building component level, a classification system for building components was established tailored for the Korean conditions, and DBs were created for the environmental impacts of the building components under six environmental impact categories.
4. At the building level, a comparative analysis method was proposed by setting a reference building and a stepwise building LCA model that is interoperable with G-SEED.
5. The case analyses confirmed the feasibility of applying the results of the environmental performance evaluation of the building materials and building components to the environmental performance evaluation of the whole building using the proposed integrated building LCA model.

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