Renewable and Sustainable Energy Reviews 73 (2017) 265–275

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An integrated assessment system for managing life cycle CO_2 emissions of a building

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ARTICLE INFO

Keywords:
Integrated assessment system
Building
Life cycle CO_2 emission

ABSTRACT

Since the early 2000s, systems for evaluating the life cycle CO_2 ($LCCO_2$) emissions of buildings have been developed in order to reduce emissions and help prevent global warming caused by greenhouse gases. However, existing systems have limitations in that they only support a one-time evaluation of CO_2 emissions during the early planning or progress phase and cannot effectively provide feedback on evaluation results. Hence, this study aimed to develop an integrated assessment system that periodically evaluates and manages $LCCO_2$ emissions of a single building according to project processes, consisting of the early planning, progress, and construction phases. To this end, requisite factors for the integrated assessment system were analyzed, and the concept of this system was designed, including models for simple assessment, detailed assessment, construction site assessment, and result analysis. Further, the life cycle stages of buildings were classified into the production, construction, operation, and end-of-life stages, and a CO_2 emissions evaluation method and database were established to implement the evaluation model. Through this process, the web-based integrated assessment system was developed, and its practical applicability was verified through a case study.

1. Introduction

With the emergence of global warming caused by greenhouse gases as a serious problem in the world, carbon dioxide (CO_2) emissions have been strictly regulated at the international level [1–3]. The evaluation and management of CO_2 emissions generated by buildings are crucial [4–6] in addressing this problem because buildings are the main source of global CO_2 emissions, of which they account for more than one-third. Additionally, buildings exhibit the highest abatement potential (the reduction efficiency of CO_2 emissions for the static investment costs) [7–9].

CO_2 is emitted both directly and indirectly throughout the life cycle of buildings, including during the production, construction, operation, and end-of-life stages [10–12]. Hence, many countries have been developing systems to evaluate life cycle CO_2 ($LCCO_2$) emissions from buildings that incorporate the unique characteristics of their own construction industries [13,14]. In particular, in North America and Europe, where a bill of quantities (BOQ) is calculated based on the building assembly unit, simple $LCCO_2$ emissions evaluation systems have been developed; these systems primarily use data on the area of each building assembly in the early planning phase of buildings [15,16]. For instance, Athena EcoCalculator in Canada, a spreadsheet-based Life Cycle Assessment (LCA) system, can evaluate $LCCO_2$ emissions, embodied primary energy, air pollution, water pollution, and weighted resource use. Architects, engineers and other design professionals can instantly access to $LCCO_2$ emissions results for hundreds of common building assemblies. This system enables easy access to $LCCO_2$ emissions result in real time and comparison of different assemblies. However, it is available only in custom assembly options because column and beam sizes are fixed [17,18]. LISA in Australia, a stand-alone LCA system, is intended for all types of buildings and simple civil engineering facilities. Composed of a simplified input and output interface, and intended to be used in the evaluation of $LCCO_2$ emissions generated with using LCI DB of building materials, this system offers outstanding performance in the analysis of material production. However, it is difficult to interpret the evaluation results, and the results are of low accuracy [19]. Envest 2 in the UK is a web-based LCA system that simplifies the complex process of designing buildings with low environmental impact and whole life costs. This system is mainly intended for analyses of office buildings. It can evaluate $LCCO_2$ emissions, ozone depletion, human toxicity, and ecotoxicity, among others. The assessment and results of this system

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http://dx.doi.org/10.1016/j.rser.2017.01.139
Received 1 October 2015; Received in revised form 3 January 2017; Accepted 20 January 2017
Available online 27 January 2017
1364-0321/

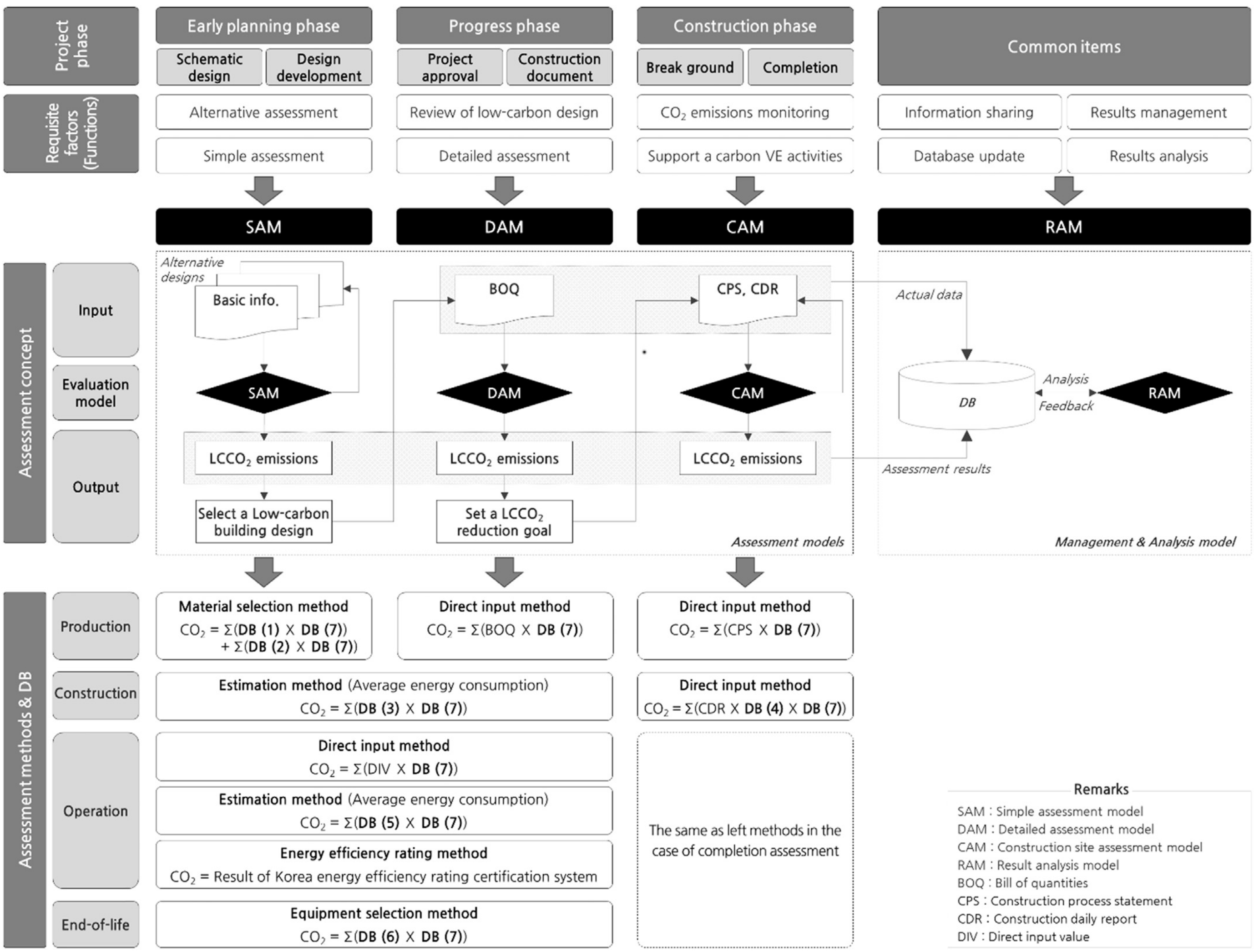

Fig. 1. Evaluation framework of the integrated assessment system.

are expressed as Ecopoint, the unique indicator of Building Research Establishment (BRE). Using this system, $LCCO_2$ emissions results can be easily exchanged in real time [20]. In South Korea and Japan, where the BOQ of buildings is generated based on the unit of building material for tasks, more detailed $LCCO_2$ emissions evaluation systems using the BOQ at the progress phase have been developed. For instance, SUSB-LCA in Korea, a stand-alone LCA system, calculates the amount of $LCCO_2$ emissions and life cycle cost, and energy consumption of buildings. Major functions of this system include evaluations of $LCCO_2$ emissions, comparisons of $LCCO_2$ emissions evaluated by the application of individual green building techniques. However, to evaluate $LCCO_2$ emissions using this system, the amounts of materials used in the construction of a building, and the amount of energy consumed during its operation stage must be taken into consideration. In addition, it is difficult to interpret the evaluation results [21]. BEGAS, a web-based LCA system, was developed for supporting the Korea Green Building Certification System (G-SEED). This system supports convenient assessment of CO_2 emission by developing an automatic quantity input technique not available in other systems. However, it can evaluate CO_2 emissions of only four building materials used during the production stage, and does not consider the life cycle of buildings [22]. In Japan, AIJ-LCA, a spreadsheet-based LCA system, is used to evaluate $LCCO_2$ emissions and level of energy consumption during the construction stage by considering building materials and measuring the energy consumed during the building's operation stage through the use of simulation results. The amount of emissions and the level of energy consumption of a standard building and the building to be assessed can then be compared during each stage as well as throughout the life cycle [23]. These evaluation systems are generally used as tools for estimating $LCCO_2$ emissions in the early planning and progress phases of buildings and application of the evaluation results to green building certification systems [24–27].

However, to reduce $LCCO_2$ emissions of buildings more effectively through these evaluation systems, the following three improvements should be made. (i) $LCCO_2$ emissions should be periodically evaluated and managed throughout building project processes beyond a one-time evaluation in the early planning or progress phase. $LCCO_2$ emissions should be evaluated during both the design process and construction stage, and carbon value engineering (VE) activities for reducing $LCCO_2$ emissions should be carried out. In addition, given that the early planning and progress phases exhibit the highest abatement potential of $LCCO_2$ emissions, emissions should be evaluated during the design process of low-carbon buildings [10,28]. (ii) To increase the accuracy of evaluation systems, input characteristics of resources (i.e., building materials and energy sources) and $LCCO_2$ emissions evaluation results of existing buildings should be continually managed and analyzed. Most existing evaluation systems provide only the function of evaluating $LCCO_2$ emissions of projects, while various data that are input or accumulate during emissions evaluations of other similar buildings are mostly unused. (iii) Open exchange of opinions and information between the main construction agents and experts in each field should occur. Existing evaluation systems have been developed primarily based on applications such as Microsoft Excel, limiting the swift exchange of information essential to reducing LCCO$_2$ emissions [15]. This study therefore aimed to develop an integrated assessment system that periodically evaluates and manages LCCO$_2$ emissions according to building project processes within the early planning, progress, and construction phases.

2. Material and methods

In this study, requisite factors for the integrated assessment system were analyzed according to each building project process, and the concept of the system, which consists of three evaluation models and an analysis model, was developed. To implement each model, a CO_2 emissions evaluation method and databases (DBs) were also established based on the life cycle stages of buildings, including the production, construction, operation, and end-of-life stages, as classified by ISO 21931-1 [29]. Fig. 1 shows the evaluation framework of the system developed in this study.

2.1. Analysis of requisite factors

Requisite factors for the integrated assessment system were analyzed based on building project processes after existing literature was reviewed and managers of architectural design offices and construction firms were interviewed. The analytic results confirmed that a model enabling an architect to evaluate LCCO$_2$ emissions of several design alternatives easily and then select a low-carbon option to reduce emissions is needed in the early planning phase involving schematic design and design development [30–32]. The results also indicated that because information on buildings to be evaluated is very limited in the early planning phase, a simple LCCO$_2$ emissions evaluation model using only the basic information about a building is required. A detailed model was, however, found to be necessary in the progress phase, during which project approval occurs, construction documents are drafted, and a large amount of information on the building becomes available.

In the construction phase, a construction process statement (a record of construction payment details according to construction progress) and construction record (a daily record of construction work progress) are generated. Thus, an evaluation model for measuring, assessing, and monitoring LCCO$_2$ emissions according to practical building construction processes (e.g., building tasks and percentage of completion) that includes support for VE activities to reduce emissions was deemed necessary [33,34]. Furthermore, at the completion of building construction, a function for the final evaluation of LCCO$_2$ emissions based on the completion statement (a document with information on building materials actually used), was found to be a requisite element. Finally, because of active cooperation between the main construction agents and experts in each field, a function facilitating quick exchange of information on the evaluated buildings and CO_2 emissions evaluation results and supporting decision-making was considered necessary.

2.2. Establishment of the assessment concept

Based on the above requisite elements, the integrated assessment system concept, consisting of a simple assessment model (SAM), detailed assessment model (DAM), construction site assessment model (CAM), and result analysis model (RAM), was established. The SAM was defined as a model for evaluating LCCO$_2$ emissions and then selecting a low-carbon building using only limited information (e.g., construction scheme, a site plan, a floor plan, and basic design documents) in the early planning phase of evaluated buildings. The DAM is a model for evaluating LCCO$_2$ emissions in the progress phase in detail and establishing an emissions reduction goal during the construction phase. The CAM is a model for periodically evaluating and managing LCCO$_2$ emissions of buildings throughout the construction phase. Finally, the RAM is a DB management model that compares and analyzes the emissions evaluation results based on the data of resources input into the SAM, DAM, and CAM and helps improve the accuracy of LCCO$_2$ emissions evaluation.

2.3. Construction of the assessment models

2.3.1. SAM

The early planning phase occurs before calculation of the BOQ required for evaluating the production stage. This study used a materials selection method that evaluates CO_2 emissions by selecting types of building materials to be used for each building part based on the DB of average input quantity of building material in similar previously constructed buildings. Moreover, because of limitations during the early planning phase in estimating the energy consumption required for the construction phase, an estimation method using average energy consumption from previous studies was proposed [35,36]. In the early planning phase, it is also difficult to estimate energy consumption required for the operation stage with accuracy. Thus, to evaluate CO_2 emissions effectively using only the available information in the early planning phase, the evaluation methods were classified into a direct input method, an estimation method, and an energy efficiency rating method. For the end-of-life stage, an equipment selection method that evaluates CO_2 emissions through the selection of demolition and landfill equipment, was also applied.

2.3.2. DAM

Typically, the BOQ of the evaluated building is prepared in the progress phase, which is evaluated using the DAM. For this reason, this study used a direct input method that evaluates CO_2 emissions in detail after input of the types and quantities of building materials based on the BOQ. Furthermore, because it is just as difficult in the progress phase as in the early planning phase to obtain detailed information on energy consumption for evaluating CO_2 emissions in the construction, operation, and end-of-life stages, the evaluation method applied to the SAM was also used for the DAM.

2.3.3. CAM

In this study, the CAM included a method of directly inputting information on building materials, vehicles used to transport these materials, construction equipment, and the amount of energy consumed in field offices. In addition, a completion assessment function was added to evaluate CO_2 emissions in the production and construction stages based on the completion statement and construction record. The LCCO$_2$ emissions assessment method was the same as that of DAM.

2.3.4. RAM

The RAM was developed to supplement the DB of the integrated assessment system by efficiently analyzing measurement data accumulated through the CO_2 emissions evaluations of various buildings. For example, data on building materials actually used in buildings, which are input into the DAM or CAM, can be applied to research on improving the DB used in the SAM for evaluating the production stage. Furthermore, data on actual energy consumption of the construction phase input into the CAM can be used in research on improving the DB that evaluates the construction stage in the SAM and DAM.

2.4. Construction of the assessment DBs

2.4.1. DB (1): Average quantity of structural materials

Structural materials, which lead to more than 80% of all CO_2 emissions generated in the production stage of buildings, are the main

Table 1
Average supply quantity of the residential building.

Division	Structure type	Structure form	Plane type	Ready-mixed Concrete (m^3/m^2)	Rebar (kg/m^2)
Residential building	Reinforced concrete (RC)	Wall	Flat	0.66	60.00
			Tower	0.59	62.20
			Mixed	0.63	61.10
		Column	Flat	0.65	63.52
			Tower	0.57	75.56
			Mixed	0.61	69.54
		Flat slab	Flat	0.62	82.34
			Tower	0.56	77.50
			Mixed	0.58	79.92

evaluated element [37]. The DB of the average quantities of structural materials used in buildings similar to those being evaluated is required by the SAM before the BOQ calculation occurs. Thus, this study analyzed the BOQ of 60 buildings recently constructed in Korea to obtain the average quantities of the main structural materials, such as ready-mixed concrete, rebar, and steel frames, based on unit area.

The quantities of structural materials used in buildings vary greatly based on the specific building purpose. Accordingly, buildings were classified into apartment complexes, office buildings, and mixed-use buildings, and the DB of building material quantities was established according to the individual structures of such building types. Specifically, the apartment complex category included a residential building, an annexed building, and an underground parking lot; the office building category included an office building, annexed building, and underground parking lot; and the mixed-use building category was divided into a residential building, an office building, an annexed building, and an underground parking lot.

Table 1 partially shows the DB of the average quantities of structural materials established in this study. To evaluate CO_2 emissions of these structural materials, this DB is used, along with the gross area of evaluated buildings input in the first stage of the SAM and the CO_2 emission factor of each building material selected in the production stage.

2.4.2. DB (2): Area of finishing materials

The area into which finishing materials are input varies according to the shapes and parts of buildings. This study constructed a simple equation to calculate the finishing area by analyzing the plans of 60 buildings with various shapes, as shown in Table 2. According to a schedule of typical interior and exterior finishing materials in Korea, building parts were classified into exterior walls, openings, roofs, inner walls, interior floor, and interior ceiling. The finishing area were multiplied by the CO_2 emission factors of building materials selected

Table 2
Provisional finished area formulas for flat-type buildings.

Division		Flat-type
Exterior wall	Front and back	$A = S \times H \times \alpha \times (2U + C)\sqrt{F}$
	Side wall	$A = S \times H \times \alpha \times 2\sqrt{F}$
Interior wall	Exclusive space	$A = S \times H \times (4U + C)\sqrt{E}$
	Core	$A = S \times H \times 4C)\sqrt{E}$
Opening		$A = S \times H \times \beta \times (2U + C + 2)\sqrt{F}$

A: Finished area (m^2); S: Number of stories; H: Story height (m); U: Number of units; C: Number of cores; F: Floor area (m^2); E: Exclusive area (m^2); α: wall surface rate; β: window surface rate

Table 3
Average energy consumption of the construction stage.

Energy source	Energy consumption	Unit
Diesel	5.24	ℓ/m2
Gasoline	0.05	ℓ/m2
Electricity	10.47	kWh/m2

in the production stage to determine the total emissions of finishing materials.

2.4.3. DB (3): Average energy consumption in the construction stage

The DB of average energy consumption in the construction stage can be effectively used in the SAM and DAM before the construction plan of the building is generated. In this study, the DB of average energy consumption per unit area in the construction stage, which was determined by a previous study [35] (Table 3), was used in conjunction with the gross area of the building and the CO_2 emission factor of each energy source to evaluate the CO_2 emissions of the construction stage.

2.4.4. DB (4): Mileage of construction equipment

A DB of mileage by the types and standards of construction equipment is needed both to calculate CO_2 emissions from the use of equipment in the construction stage and to estimate emissions for reduction using the CAM. Thus, this study established the DB of construction equipment mileage based on the Korean Construction Standard Production Unit System [38,39], as shown in Table 4. CO_2 emissions from the use of construction equipment can be calculated using this DB along with data (i.e., input time by construction equipment) on the amount of equipment used in the actual construction stage and the CO_2 emission coefficient of each energy source.

2.4.5. DB (5): Average energy consumption in the operation stage

The DB of average energy consumption in the operation stage comprises analysis results of the amount of energy consumed by existing buildings. It is used in the estimation modeling method by the evaluation methods for CO_2 emissions of the operation stage in the SAM, DAM, and completion assessment.

To establish a highly reliable DB of average energy consumption in the operation stage, this study used data on the average energy consumption of apartment complexes by unit area according to heating type and that of office buildings by unit area from the Energy Consumption Survey [40] published by the Ministry of Trade, Industry, and Energy in Korea. The mixed-use building type, which was not included in the final energy survey, was classified as both residential and commercial space according to space usage and then

Table 4
Mileage of the construction equipment.

Equipment	Size	Energy source	Mileage (ℓ/h)
Bulldozer	10ton	Diesel	12.5
	19ton	Diesel	25.0
	32ton	Diesel	41.6
Excavator	0.4 m^3	Diesel	9.9
	1.0 m^3	Diesel	19.5
	2.0 m^3	Diesel	32.8
Crane	50 ton	Diesel	12.0
	150 ton	Diesel	24.4
	300 ton	Diesel	28.0
Concrete mixer	0.1 m^3	Gasoline	1.3
	0.3 m^3	Gasoline	2.0
	0.45 m^3	Gasoline	3.9
Concrete pump car	80 m^3/h	Diesel	16.5

Table 5
Average energy consumption of the operation stage.

Energy source	Unit	Individual heating				Central heating			District heating
		Petroleum	LPG	Electricity	City Gas	Ordinary	Petroleum	City Gas	Ordinary
Kerosene	ℓ/yr/m^2	6.801	–	0.045	–	–	–	–	–
Heavy oil	ℓ/yr/m^2	–	–	–	–	2.567	10.492	–	–
Propane	kg/yr/m^2	1.189	5.529	1.346	0.013	0.181	0.649	0.03	0.054
City gas (Cooking)	Nm^3/yr/m^2	0.008	–	0.021	1.141	1.039	0.567	1.191	1.376
City gas (Heating)	Nm^3/yr/m^2	–	–	–	7.934	5.793	–	7.67	–
Electricity	kWh/yr/m^2	30.785	31.355	37.099	35.287	33.458	29.277	34.813	37.99
Heat energy	Mcal/yr/m^2	–	–	–	–	–	–	–	94.36
Hot water	Mcal/yr/m^2	–	–	–	–	0.587	0.484	0.621	0.75

divided into the apartment complex and office building categories, respectively.

Table 5 shows the DB of average energy consumption in the operation stage of apartment complexes created in this study. The CO_2 emissions of the operation stage can be evaluated using this DB along with the gross area and life of the evaluated building and the CO_2 emission coefficient of each energy source.

2.4.6. DB (6): mileage of disposal and landfill equipment

When the SAM, DAM, and completion assessment are applied, information on the demolition and disposal of the evaluated building and its materials is necessary. Thus, this study established a DB of the amount of waste materials generated during deconstruction according to the type of use and structure of buildings based on the Korean Construction Standard Production Unit System [38,39], as shown in Table 6.

A DB of mileage (i.e., the amount of diesel used for building deconstruction and disposal of waste materials) of the equipment used in this stage was also created by analyzing a previous study [35] on demolition and landfill equipment, as shown in Table 7. Using this DB, the quantity of waste materials can be calculated according to the purpose and structure of the evaluated building. The CO_2 emissions of the end-of-life stage can be evaluated based on the mileage of equipment used to dispose of this quantity of waste and the CO_2 emission factor of diesel.

2.4.7. DB (7): CO_2 emission factors of building materials and energy sources

According to the DB selection standard of the LCA, the CO_2 emission factor should be selected based on, in order, regional, temporal, and technological relationships [41–43]. Thus, in this study, a carbon emission factor [44] proposed by the Korean government and the carbon emission factors of concrete in Korea from previous studies [45,46] were applied, as shown in Table 8.

In addition, the CO_2 emission factors of energy sources were determined using the Intergovernmental Panel on Climate Change's (IPCC) 2006 Guidelines for National Greenhouse Gas Inventories [47], as shown in Table 9. Because country-specific CO_2 emission factors are recommended for electricity and local heating, the official CO_2 emission factors proposed by the Korea Power Exchange and Korea District Heating Corporation were applied [48,49]. For city gas and kerosene, the CO_2 emission factors derived by the Korea Energy Management Corporation from the IPCC's 2006 Guidelines for National Greenhouse Gas Inventories were used [50].

Table 6
Amount of wasted building materials.

Purpose	Structure	Wasted concrete (ton/m^2)	Wasted steel (ton/m^2)	Mixed wastes (ton/m^2)	Total (ton/m^2)
Apartment building	RC	1.566	0.061	0.169	1.796
Office building	RC	1.488	0.073	0.135	1.696
	S	0.937	0.055	0.135	1.127
	SRC	1.644	0.122	0.152	1.918

Table 7
Mileage of the disposal and landfill equipment.

Division	Equipment combination	Mileage (ℓ/ton)
Deconstruction	Backhoe (1.0 m^3)+Giant Breaker(0.7 m^3)	3.642
	Pavement Breakers (25 kg) 2 units+Air Compressor (3.5 m^3/min)	2.385
	Backhoe (1.0 m^3)+Hydraulic Breaker (1.0 m^3) + Giant Breaker (0.7 m^3)	4.286
	Backhoe (0.4 m^3)+Breaker(0.4 m^3)	4.760
Landfill	Dozer (D8N, 15 PL, 6 PL)+Compactor (32ton)	0.150

3. Results

3.1. Integrated assessment system

A web-based integrated assessment system was developed by applying both the $LCCO_2$ emissions evaluation methods and DBs established in Section 2. Unlike other existing evaluation systems, this system can provide periodical evaluation and management of $LCCO_2$ emissions through the SAM, DAM, and CAM according to a series of project processes including the schematic design, design development, construction document, and construction phases of a single building. This systematic evaluation structure enables evaluation and management of $LCCO_2$ emissions from buildings. In addition, in RAM, $LCCO_2$ emissions evaluation results from SAM, DAM, and CAM can be analyzed, and the DB is managed and updated.

Because the integrated assessment system is web-based, it can be connected to user terminals, such as PCs and smartphones, facilitating real-time $LCCO_2$ emissions evaluation and the exchange of evaluation results between construction project managers. The composition of the integrated assessment system is shown in Table 10 and its main display screen in Fig. 2.

3.1.1. SAM

SAM is an evaluation model that improved the existing simple $LCCO_2$ emissions assessment systems using the area of each building assembly. The existing systems were evaluated the $LCCO_2$ emissions through calculation and direct input of the area in accordance with the each building assembly. On the other hand, SAM improved the user's satisfaction by the construction of the DB of average input quantity of building material, the equations for the area of finishing materials, and a list of the various building materials used in the each building assembly in similar previously constructed buildings. This model can

Table 8
CO_2 emissions factor of the building materials.

Building materials	CO_2 emissions factor	Unit	Source
Ready-mixed concrete 21 MPa	346.000	kg-CO_2/m^3	DPS
Ready-mixed concrete 24 MPa	346.000	kg-CO_2/m^3	
Ready-mixed concrete 27 MPa	364.000	kg-CO_2/m^3	
Ready-mixed concrete 30 MPa	389.100	kg-CO_2/m^3	
Ready-mixed concrete 35 MPa	425.400	kg-CO_2/m^3	
Ready-mixed concrete 40 MPa	465.900	kg-CO_2/m^3	
Electric arc furnace rebar	0.760	kg-CO_2/kg	KCF
H section steel	0.405	kg-CO_2/kg	
Water-based paint	0.360	kg-CO_2/m^2	
Silicone-based paint	0.322	kg-CO_2/m^2	
Stone coat	11.221	kg-CO_2/m^2	
Granite with stone molding	13.431	kg-CO_2/m^2	
Plate glass	9.859	kg-CO_2/m^2	
Insulating glass	22.425	kg-CO_2/m^2	
Tempered glass	13.351	kg-CO_2/m^2	

DPS: CO_2 emissions DB from previous study; KCF: Korea carbon emission factor

Table 9
CO_2 emissions factor of the energy source.

Energy source	CO_2 emissions factor	Unit	Source
Kerosene	2.441	kg-CO_2/ℓ	IPCC
Medium quality heavy oil	3.003	kg-CO_2/ℓ	
Propane	2.889	kg-CO_2/kg	
City gas	2.200	kg-CO_2/Nm^3	
Diesel	2.580	kg-CO_2/ℓ	
Gasoline	2.080	kg-CO_2/ℓ	
Electricity	0.495	kg-CO_2/kWh	KPX
District heating	0.051	kg-CO_2/MJ	KDHC

PCC: IPCC 2006 guidelines; KPX: Korea Power Exchange; KDH: Korea District Heating Corporation

be used as a useful alternative evaluation model to reducing the $LCCO_2$ emissions of a building in the early design stage that cannot obtain detailed information.

The purpose, structure, area, life, and plane information of the evaluated building are input as the basic information used in the SAM. In the production stage, the quantities of structural and finishing materials to be used in the evaluated building are calculated based on the basic information values. Evaluation is performed by selecting materials by building part. In the operation stage, one method is chosen for evaluation from the direct input, estimation, and energy efficiency rating methods, depending on the amount of collected available information. In the end-of-life stage, the amount of waste matter generated is input based on the basic information and DB (Table 6), and evaluation is performed by selecting demolition and landfill equipment for waste disposal. The CO_2 emissions evaluation result for each stage is produced, and comprehensive evaluation results can be printed.

3.1.2. DAM

DAM is the $LCCO_2$ emissions assessment model using the BOQ at the progress phase. It is similar to the existing evaluation systems developed in Korea and Japan. This model enables reviewing the $LCCO_2$ emissions assessment results of SAM and setting the goal of $LCCO_2$ emissions at CAM.

The evaluation method of the DAM is similar to that of the SAM, except in the production stage. In the DAM, CO_2 emissions are evaluated using directly input data on the quantity of building materials stated in the BOQ according to building tasks.

Table 10
Configuration of the integrated assessment system.

Division	Methods	SAM	DAM	CAM	RAM	Configuration	Note
Assessment list	–	■	■	■	·	Creation and management of evaluated buildings	–
Basic information	–	■	■	■	·	Input of data on the purpose, structure, area, life, and plane information of buildings	(a)
Production stage	Material selection	■	·	·	·	Selection of finishing material types by building assembly and structural material type (Ready-mixed concrete, rebar, and steel frame)	(b)
	Direct input	·	■	■	·	Direct input of the amount of building materials used	–
Construction stage	Estimation	■	■	·	·	Suggestion of a default value for energy consumption based on the unit area	–
	Direct input	·	·	■	·	Input of data on transportation vehicles and construction equipment used and energy consumption in the field office	(c)
Operation stage	Estimation	■	■	·	·	Selection of the heating system for the building	–
	Direct input	■	■	·	·	Input of values derived by energy consumption simulation	–
	Energy efficiency rating	■	■	·	·	Input of the evaluation result from preliminary certification of energy efficiency rating	–
End-of-life stage	Equipment selection	■	■	·	·	Selection of demolition and disposal equipment	–
Assessment result	–	■	■	■	·	Confirmation of the $LCCO_2$ emissions evaluation method and results and printing of the comprehensive evaluation results	(d)
Result comparison	–	·	·	·	■	Comparison of evaluation results and confirmation of the average value of $LCCO_2$ emissions	–
Data analysis	–	·	·	·	■	DB analysis based on the production stage, main construction materials, construction stage, and operation stage	–

■: Applied;·: Not applied

Fig. 2. Configuration of the integrated assessment system.

3.1.3. CAM

CAM is the $LCCO_2$ emissions assessment model in the construction phase that was not normally covered by the existing evaluation system. In addition, it can be utilized as a useful evaluation model for reducing and managing $LCCO_2$ emissions of real buildings, as periodically measured by the construction phase, and for supporting the carbon VE activities.

In the CAM, CO_2 emissions can be evaluated and managed according to building tasks or percentage of completion of the evaluated building. CO_2 emissions are calculated in real time with the direct input of information on the quantity of building materials used through the point of evaluation, transportation vehicles and construction equipment used, and energy consumption measured at the field office.

3.1.4. RAM

RAM is the result analysis model that was not implemented in existing evaluation systems. In the RAM, $LCCO_2$ emissions of a building can be compared according to different building project processes. Moreover, the building evaluation results and main management data that obtained from SAM, DAM, and CAM (e.g., CO_2 emissions of the production stage, quantity of main building materials, and energy consumption in the construction and operation stages) can be analyzed and extracted. Using RAM, this system can build actual DBs required for $LCCO_2$ emissions assessment of buildings, enabling accurate estimations of building $LCCO_2$ emissions by applying the DB of RAM to the DB of this system.

3.2. Case study

To confirm the applicability of the integrated assessment system developed in this study, $LCCO_2$ emissions were evaluated using the SAM, DAM, and CAM for the construction project processes of an apartment complex. Table 11 shows an overview of the evaluated building selected for the case study.

3.2.1. Evaluation method

Based on the design documents and performance data of the evaluated buildings, virtual scenarios for evaluating $LCCO_2$ emissions according to construction project processes were divided into three cases, as shown in Fig. 3.

In Case 1, the $LCCO_2$ emissions of three design alternatives (Alternatives 1, 2, and 3) were evaluated in the early planning phase, and a low-carbon building that generated the lowest level of emissions was selected. Alternative 1 was a building with 27-MPa concrete on all floors and insulating glass. Its heating system was based on local

Table 11
Overview of the evaluated building.

Project name		L apartment complex zones 4, 5
Site area		87,556.90 m^2
Zoning district		Ordinary residential zone
Purpose		Apartment building
Structure		Reinforced concrete structure
Number of buildings		21
Gross area	Above ground	211,074.89 m^2
	Underground	72,756.91 m^2
	Total	283,831.80 m^2
Heating system		Local heating
Service life		40 years

heating, and the CO_2 emissions of the operation stage were evaluated using the direct input method based on the annual energy consumption calculated through an energy simulation. The combination of a backhoe (1.0 m^3) and a giant breaker (0.7 m^3) was used as demolition equipment. Alternative 2 was a building with 27-MPa concrete in the lower floors and 21-MPa concrete in the upper floors, as well as plate glass. The CO_2 emissions of the operation stage were evaluated using the estimation method of local heating developed in this study, and two pavement breaker units (25 kg) and an air compressor (3.5 m^3/min) were used for demolition. Alternative 3 was a building also equipped with 27-MPa concrete in the lower floors and 21-MPa concrete in the upper floors, but instead containing insulating glass. As with Alternative 1, the CO_2 emissions of the operation stage were evaluated using the direct input method based on an energy simulation. For demolition equipment, two pavement breaker units (25 kg) and an air compressor (3.5 m^3/min) were used.

In Case 2, $LCCO_2$ emissions of the selected low-carbon design alternative from the SAM, Alternative 3, were evaluated in detail using the DAM. This study evaluated emissions using an actual BOQ of Alternative 3.

In Case 3, CO_2 emissions of the production and construction stages and $LCCO_2$ emissions at the point of building completion were evaluated (completion assessment).

3.2.2. Evaluation results

3.2.2.1. Case 1. Fig. 4 shows the results of evaluating the $LCCO_2$ emissions of the three design alternatives from Case 1. As shown in this figure, the emissions of Alternatives 1, 2, and 3 were 1977.67, 2204.80, and 1963.89 kg-CO_2/m^2, respectively. Based on this result, Alternative 3 was selected as the low-carbon building in this study.

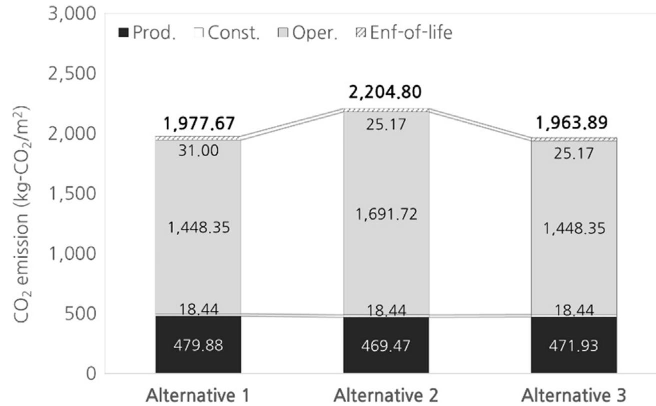

Fig. 4. Assessment result of case 1.

Because low-strength (21-MPa) concrete was used in the upper floors above the seventh floor of Alternative 3, the CO_2 emissions of the production stage were 7.95 kg-CO_2/m^2 lower than those of Alternative 1. CO_2 emissions of the end-of-life stage were also 5.83 kg-CO_2/m^2 lower than those of Alternative 1 because of the selection of high-mileage demolition equipment. The use of insulating glass in Alternative 3 resulted in 2.46 kg-CO_2/m^2 greater CO_2 emissions in the production stage than in Alternative 2, which instead used plate glass. However, because of insulation, the CO_2 emissions of the operation stage in Alternative 3 were lower than those of Alternative 2 by 243.37 kg-CO_2/m^2. (In this analysis, it was assumed that there was no error between the estimation and direct input methods, which were used to evaluate CO_2 emissions of the operation stage in Alternatives 2 and 3, respectively).

3.2.2.2. Case 2. Fig. 5 shows the results of evaluating $LCCO_2$ emissions in Alternative 3, selected as the low-carbon building in the study. According to the DAM evaluation result in Fig. 5, $LCCO_2$ emissions of Alternative 3 were 1975.18 kg-CO_2/m^2.

Specifically, the CO_2 emissions of the production stage, evaluated by the DAM, were 483.22 kg-CO_2/m^2, slightly higher than the value of 471.93 kg-CO_2/m^2 obtained by the SAM in Case 1. This finding is due to the difference between the quantity of building materials estimated by the SAM in the early planning phase and that stated in the BOQ generated in the progress phase. Furthermore, because the difference in results for the production stage between the SAM and DAM was insignificant at 2.34% (with an error rate for $LCCO_2$ emissions of

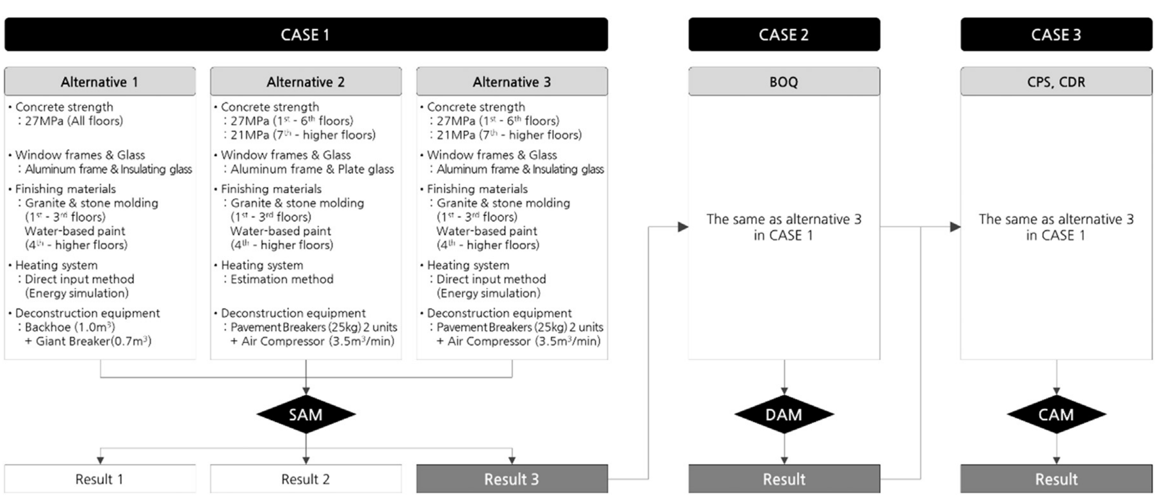

Fig. 3. Scenario for this case study.

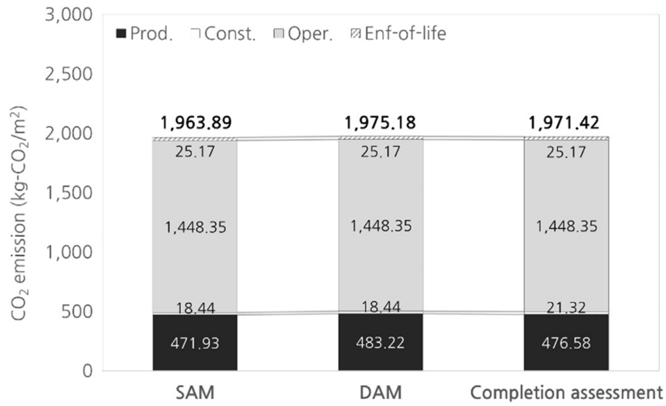

Fig. 5. Assessment result of the alternative 3.

0.57%), the SAM was verified as an effective tool to evaluate $LCCO_2$ emissions in the early planning phase.

3.2.2.3. Case 3. Fig. 6 describes the CO_2 emissions from the construction processes according to building tasks and percentage of completion in Alternative 3, derived by the CAM. As shown in the figure, the total CO_2 emissions from the construction processes of Alternative 3 were 497.90 kg-CO_2/m^2, of which 476.58 kg-CO_2/m^2 were from the production phase and 21.32 kg-CO_2/m^2 were from the construction phase. Specifically, until reinforced concrete work generated 82.60% (production stage: 84.21%, construction stage: 46.58%) of the CO_2 emissions from all construction processes. Thus, it was confirmed that carbon VE activities to reduce CO_2 emissions will be important in reinforced concrete work.

Moreover, $LCCO_2$ emissions (refer to Fig. 5) at the point of building completion, derived by applying the evaluation results, were found to be 1971.42 kg-CO_2/m^2. This value differs by 1.39% and 13.51% from the DAM results for the production and construction stages, respectively, in Case 2. The slight difference in the results for the production stage between the DAM and CAM was because of the difference between the quantity of building materials stated in the BOQ generated in the progress phase and those actually used during construction. On the other hand, the relatively significant difference in results for the construction phase between the DAM and CAM indicates a difference between energy consumption from the DB selected in this study and actual energy consumption during construction. This problem can be solved in the RAM by analyzing measured data on energy consumption by building construction processes input into the CAM.

Furthermore, because CO_2 emissions of actual construction processes can be quantitatively evaluated according to building tasks and percentage of completion of the evaluated building, as shown in the case study, the CAM was verified as an effective evaluation tool for reducing CO_2 emissions during construction.

4. Discussion

Many industries and sectors have conducted various studies on the $LCCO_2$ emissions evaluation, and environmental labeling systems based on LCA method are being widely implemented [51]. Studies have also been actively conducted on the building $LCCO_2$ emissions assessment methods from the mid-1990s to the present day, and many countries have developed their evaluation systems to support building $LCCO_2$ emissions assessment [52–54]. These evaluation methods were developed in order to quantitatively evaluate the $LCCO_2$ emissions of buildings in the early planning stage and to reduce the emission; Athena EcoCalculator and Envest 2 can evaluate various environmental impact categories, including the CO_2 emissions, and support green building certification systems such as LEED and BREEAM [55–57]. Since LCA was introduced in Korea as a method for evaluating $LCCO_2$ emissions of buildings in the late 1990s, various studies have been actively conducted on the evaluation technology of building $LCCO_2$ emissions assessment, and establishment of databases for $LCCO_2$ emissions assessment. Furthermore, SUSB-LCA developed in 2007 by the Sustainable Building Research Center of Hanyang University is considered the most representative $LCCO_2$ emissions evaluation system for buildings in Korea. Since then, various evaluation systems such as BEGAS have been developed. However, because most of the evaluation systems only provide a one-time evaluation of $LCCO_2$ emissions or are connected to the green building certification system, continual management and analysis of the $LCCO_2$ emissions evaluation results of existing buildings cannot be maintained. Consequently, they are insufficient for the effective reduction of $LCCO_2$ emissions of buildings. Therefore, there is a growing necessity for studies on evaluation systems that can provide periodical evaluation and management of quantitative analyses of $LCCO_2$ emissions of buildings according to building project processes within the early planning, progress, and construction phases.

This study developed an integrated assessment system consisting of the SAM, DAM, CAM, and RAM that can contribute more effectively to reducing $LCCO_2$ emissions generated by buildings. The SAM requires less time and work than existing evaluation systems, which require the manual input of data on various building materials and CO_2 emission factors. Using the SAM, various design alternatives can be evaluated within a short timeframe, and the design and selection of a low-carbon building are more effectively supported. The DAM calculates CO_2 emissions of the evaluated building more accurately than does the SAM. It can also calibrate CO_2 emissions according to the conditions and environment of the evaluated building and estimate the amount of CO_2 emissions reduced through the application of green construction technology. The CAM was developed for periodic evaluation and management of CO_2 emissions from the actual construction processes of a low-carbon building. It can be used effectively to improve the construction of a low-carbon building established in the SAM or DAM. The RAM compares data on $LCCO_2$ emissions produced by the SAM, DAM, and CAM according to building project processes. In addition, the DB of the integrated system can be constantly managed and updated by analyzing measurement data accumulated through $LCCO_2$ emissions evaluations of buildings.

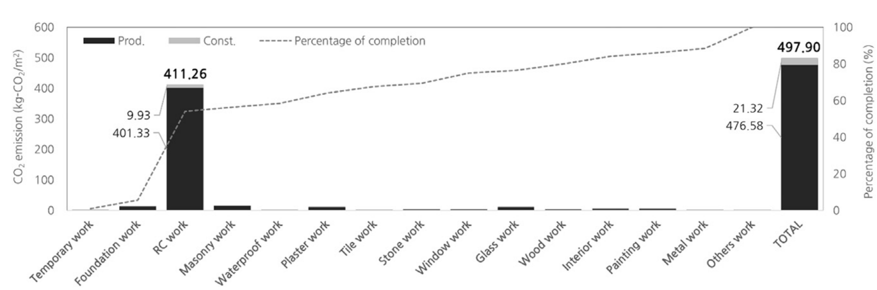

Fig. 6. Assessment result by building task and percentage of completion.

Therefore, it is expected that the integrated assessment system developed in this study will be effectively used in the practical design and construction of a low-carbon building from the early planning phase.

5. Conclusions

This study developed an integrated assessment system for periodically evaluating and managing $LCCO_2$ emissions of buildings according to project processes. The conclusions of this research are as follows.

1. A web-based integrated assessment system consisting of the SAM, DAM, CAM, and RAM was developed to evaluate $LCCO_2$ emissions according to construction project processes.
2. To develop the SAM, which evaluates $LCCO_2$ emissions in the early planning phase, design data of 60 buildings were analyzed, and a DB of structural materials and a simple equation for calculating the finishing area were constructed. In addition, evaluation methods for the operation stage were classified into the direct input, estimation, and energy efficiency rating methods.
3. The $LCCO_2$ emissions evaluation method using the BOQ was established to develop the DAM, which evaluates $LCCO_2$ emissions in the progress phase.
4. A DB of construction equipment mileage was established to develop the CAM, which evaluates CO_2 emissions during construction, and a completion assessment for evaluating $LCCO_2$ emissions at the point of building completion was proposed.
5. The RAM, which can constantly manage and update the integrated assessment system's DB by analyzing data accumulated through $LCCO_2$ emissions evaluations, was established.
6. A study of three cases using the integrated assessment system to evaluate $LCCO_2$ emissions according to building project processes verified the applicability of the SAM, DAM, and CAM. Specifically, in comparing the $LCCO_2$ emissions of a selected low-carbon building and the CO_2 emissions of the production stage, the maximum errors were found to be insignificant at 0.57% and 2.34%, respectively. Therefore, it is expected that the integrated assessment system developed in this study will be effectively used in the practical design and construction of a low-carbon building from the early planning phase.

Acknowledgments

"This research was supported by a grant (16CTAP-C114806-01) from Technology Advancement Research Program (TARP) funded by Ministry of Land, Infrastructure and Transport of Korean government".

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