

Article

Development of a Streamlined Environmental Life Cycle Costing Model for Buildings in South Korea

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Abstract: In the building construction industry, simultaneous and integrated evaluation of a building's environmental and economic performance in the early planning stage greatly facilitates stakeholders' decision-making for sustainable building construction. This study aimed to develop a streamlined Environmental Life Cycle Costing (ELCC) model for buildings, applicable to the early planning stage of construction projects. To this end, we selected three of the private cost-related life cycle cost categories that are determinants of stakeholders' decision-making in the early planning stage of construction and extracted 10 major building materials that account for over 95% of the total direct construction cost. Then, we developed a streamlined ELCC model for buildings by combining the monetary value-based life cycle analysis model, KOLID (Korean Life Cycle Impact Assessment Method Based on Damage-Oriented Modeling), and the present worth method. Finally, we conducted a case study to empirically verify the applicability of the proposed model.

Keywords: streamlined environmental life cycle costing; life cycle sustainability assessment; building; private cost; external cost

1. Introduction

Sustainable development has become necessary in all industries [1–5]. Sustainable development is an ideology that strives to solve environmental problems and to pursue balanced social development simultaneously. Its core aspects are environmental, economic, and social [6–8]. In the pursuit of this ideology, an increasing number of businesses, industries, and sectors are stepping up their efforts to assess and improve the environmental, economic, and social performance of their products and services, drawing upon a technological framework known as Life Cycle Sustainability Assessment (LCSA). [9–11]. LCSA is a technique for sustainable assessment based on the concepts and practices of Life Cycle Assessment (LCA); specifically, it assesses the sustainable core area of LCA, which is composed of Environmental LCA (ELCA), Environmental Life Cycle Costing (ELCC), and Social Life Cycle Assessment (S-LCA), taking into account the lifespan of a product or service (e.g., production, use, and end-of-life) [12,13].

Of these components of LCA's core area, ELCC evaluates the economic performance of a product or service. This concept came to the fore with a paper published in 2008 by the Society of Environmental Toxicology and Chemistry (SETAC), entitled "Environmental Life Cycle Costing" [14]. Unlike conventional life cycle costing, ELCC assesses both private costs directly incurred throughout the life cycle of a product or service and external costs related to environmental impacts, and presents

the sum of all direct costs and at least one external cost. Owing to its advantage of integrated computation of all the costs related to the environmental and economic performance of a product or service, ELCC has been extensively studied and applied in many industries [14,15].

The building construction industry is also keenly interested in ELCC [16–20]. Unlike other products and services, buildings are characterized by the huge space required, cost-intensive construction and operation/maintenance over a long utilization period, and enormous environmental impacts [21,22]. Therefore, if the costs for a building's economic performance and environmental performance, which are usually inversely proportional, can be estimated in an integrated and equally weighted manner, all stakeholders can use the results in their decision-making for sustainable building construction. Since the mid-1980s, the building construction industry, spurred by this necessity, has been extensively researching the development of building-level ELCC methods in which carbon emission trading prices are regarded as external costs and are integrated into the conventional life cycle costing applied to long lifespan buildings and infrastructures [18,23,24]. However, this endeavor is hampered by the fact that carbon credits are not generally traded on a scale of a single building unit and because their prices are extremely sensitive to national policies, economic situations, and business fluctuations [22,25–28]. Moreover, despite various types of environmental impact stemming from a building throughout its life cycle, carbon pricing considers only the indirect economic value of carbon emissions that cause global warming, which makes it difficult to apply emission trading prices to the external costs for ELCC for buildings. Therefore, research is needed to develop a method for computing reasonable external costs on the scale of a single building unit as well as an ELCC model for buildings containing such a scheme.

In the building construction industry, the early planning stage is the stage with the highest life cycle cost reduction potential, and the estimation of the life cycle cost required in this stage plays a pivotal role in the success or failure of the whole building construction industry [23,29–31]. It is thus of crucial importance to enhance the efficiency of ELCC for buildings, focusing on the major cost categories in the early planning stage that are determinants of stakeholders' decision-making and simplifying the related assessment data.

Against this background, this study aims to develop a streamlined ELCC model for buildings, applicable to the early planning stage of construction projects.

2. Environmental Life Cycle Costing

Life Cycle Costing (LCC) is classified into conventional, environmental, and societal life cycle costing depending on the cost category and scope of assessment [14]. Figure 1 illustrates these three types of LCC by category and scope. Conventional life cycle costing assesses all costs incurred directly from the production to the utilization and end-of-life stages. ELCC considers at least one external cost in addition to those assessed by conventional life cycle costing. Thus, it consists of private costs corresponding to conventional life cycle costing and external costs related to environmental impacts. Societal life cycle costing considers all present and future external costs that are considered by the ELCC. At present, only its conceptual definition and scope are presented.

On the other hand, the term ELCC, which was first used in 2005 by Reich [32], began to be known and gradually accepted after the publication of "Environmental Life Cycle Costing" [14] in 2008 by the SETAC. The concept of ELCC emerged by extending the related concepts presented in earlier works, such as "Integrating Life Cycle Cost Analysis and Life Cycle Assessment Presented" by Norris [33,34], "LCA-based Life Cycle Costing" by Rebitzer et al. [35], and "Life Cycle Costing as Part of Design for Environment" by Schmidt [36]. Its detailed and standardized assessment method was released in "Environmental Life Cycle Costing: A Code of Practice" [15] in 2011, which was published by the SETAC.

A standard ELCC assessment system includes four phases: goal and scope definition, Life Cycle Inventory (LCI) analysis, life cycle interpretation, and reporting and review [14,15]. In the goal and scope definition phase, the study's goal and the target system's scope are defined, specifying

the study's rationale, intended application, subject function, system boundaries, functional units, allocation procedure, data requirements, hypotheses, and limitations. In the LCI analysis phase, data collection and allocation should be carried out concretely within the system boundaries specified in the definition phase, and the future values should be converted into present values using the present worth method, thereby applying an appropriate discount rate for the conversion. In the life cycle interpretation phase, the ELCC evaluation results derived from the LCI analysis phase are evaluated, and the final results are derived by determining the principal factors of ELCC and subjecting the ELCC evaluation results to consistency, completeness, and sensitivity analyses. In the reporting and review phase, expert review is performed to determine the validity of the ELCC evaluation results by examining the goal and scope, functional units, system boundaries, allocation procedure and method, discount rate application method, and conclusion.

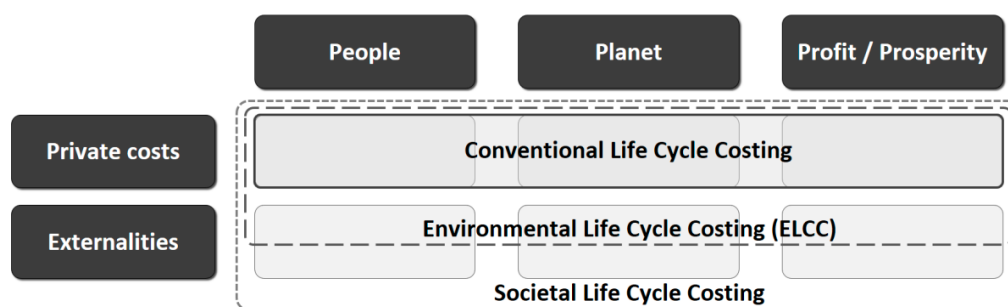


Figure 1. Scope of three kinds of life cycle costing [14].

3. Model Development

In this study, we developed a streamlined ELCC model for buildings, applicable to the early planning stage of construction projects, by drawing upon the ELCC method provided by the SETAC [14, 15]. First, we investigated the cost categories related to the private costs for construction from the LCA perspective and selected major cost categories involved in the early planning stage that are determinants of stakeholders' decision-making. Then, we extracted the major building materials that account for a high proportion of the direct construction costs in terms of economic importance and developed a streamlined ELCC model for buildings, consisting of private external construction costs, by combining the monetary value-based life cycle analysis model, KOLID (Korean Life Cycle Impact Assessment Method Based on Damage-Oriented Modeling) [37] and the present worth method.

3.1. Selection of Major Cost Categories

As outlined in Table 1, the private costs for construction in LCC were broken down into initial investment, operation costs, destruction, and other costs. Initial investment costs were subdivided into planning and design costs and direct construction costs, and operation costs were subdivided into operation energy, maintenance, and general management costs [38].

To simplify the ELCC method, we selected the major cost categories that are determinants of stakeholders' decision-making in the early planning stage of construction. In the selection process, we excluded the categories that do not directly incur material costs but are only related to business operation and management, such as planning and design costs, general management costs, and support funds. Destruction costs were also excluded from the major cost categories because they cannot be accurately estimated in the early planning stage of construction, and their contribution is negligible from the LCC perspective. Direct construction, operation energy, and maintenance costs were thus selected as the major cost categories.

3.2. Selection of Major Building Materials

Simplifying the input data list for the LCI stage helps in simplifying the LCC assessment process conducted in the early planning stage of construction. The construction work process is more complicated than the production process of general products. In general, more than 1000 building materials are required, and an LCC assessment that considers all items is excessively time- and work-intensive [39]. Therefore, we analyzed the itemized direct construction costs using a bill of materials, and extracted major building materials in terms of economic importance—specifically, materials for which the total contribution to the direct construction costs for a construction project exceeded 95%.

Table 2 presents an overview of the buildings selected for the direct construction cost analysis in this study. They were all apartment building complexes with reinforced concrete structures (RC structure) in Seoul, Korea. To reflect various structure types in the cost analysis, we selected three structure types (wall type, rigid-frame, and flat plate) and two target buildings per type. Based on the quantities of building material specified in each building's bill of materials and the 2017 H2 price information for construction costs released by the Korean Public Procurement Service [40], we estimated the direct construction costs, including material costs, labor costs, and miscellaneous expenses, and analyzed the mean contribution of each type of building to each building material. It was assumed that all building materials were used for construction as specified in the bill of materials in terms of type and quantity, and the waste disposal costs related to discount rate application were not considered. Equation (1) is the formula for the direct construction cost calculation.

Table 1. Life cycle cost categories.

Classification		Items	
Initial investment costs	Planning & design costs	Planning costs Design costs	Basic design costs Execution design costs
	Direct construction costs	Material costs Labor costs Miscellaneous expenses	Materials, equipment, others Labor costs included in construction costs Various indirect costs, supervision costs, etc.
	Operation energy costs	Electricity bills Gas bills District heating & cooling bills Water & sewage bills	Electricity bills for air conditioning/hot water supply Gas bills for air conditioning/hot water supply District heating & cooling bills Water & sewage bills
Operation costs	Maintenance costs	Repair parts costs Replacement costs	Repair & consumable parts costs Replacement costs, such as equipment & piping
	General management costs	Taxes Insurance premiums Labor costs	Acquisition & registration taxes on buildings Fire insurance premium Labor costs for general management
	Destruction costs	Destruction costs Residual values	Destruction costs of a building Residual values of a building
Other costs	Support funds	Various support funds	Support funds for electricity provider, etc.

Table 2. Evaluation targets.

Classification	Building "A"	Building "B"	Building "C"	Building "D"	Building "E"	Building "F"
Location	Seoul, Korea	Seoul, Korea	Seoul, Korea	Seoul, Korea	Seoul, Korea	Seoul, Korea
Break ground	Jan. 2009	Oct. 2009	Jan. 2012	Jan. 2012	Oct. 2011	Jun. 2011
Completion	Jan. 2011	Sep. 2011	Jun. 2014	Jun. 2014	Jun. 2014	Dec. 2013
Structure	Reinforced concrete (RC) structure, (Wall type)	RC structure, (Wall type)	RC structure, (Rigid-frame)	RC structure, (Rigid-frame)	RC structure, (Flat plate)	RC structure, (Flat plate)
Lot area	10,780 m ²	40,424 m ²	75,115 m ²	56,336 m ²	72,608 m ²	108,163 m ²
Building area	2513 m ²	10,210 m ²	19,480 m ²	16,320 m ²	14,172 m ²	18,658 m ²
Gross floor area	83,883 m ²	68,612 m ²	227,466 m ²	208,393 m ²	190,866 m ²	267,015 m ²
Building coverage ratio	23%	25%	26%	29%	20%	17%
Floor area ratio	564%	169%	201%	239%	185%	172%

$$DCC = \sum_{i=1}^n (Q_i \times C_i \times UP_i), \quad (1)$$

where DCC denotes the direct construction cost, Q_i denotes the quantity of building material (i), C_i denotes the unit conversion coefficient applied to quantity of building material and unit direct construction cost, and UP_i denotes the unit direct construction cost of building material (i).

Figure 2 presents the results of the analysis of the major building materials for each structure type in terms of economic importance. The results show that the percentages of rebar and ready-mixed concrete slightly varied according to structure type, but the major building materials for which the total contribution exceeded 95% of the direct construction costs were ready-mixed concrete, rebar, glass, concrete brick, insulation, gypsum board, window frame, stone, tile, and paint in all three structure types.

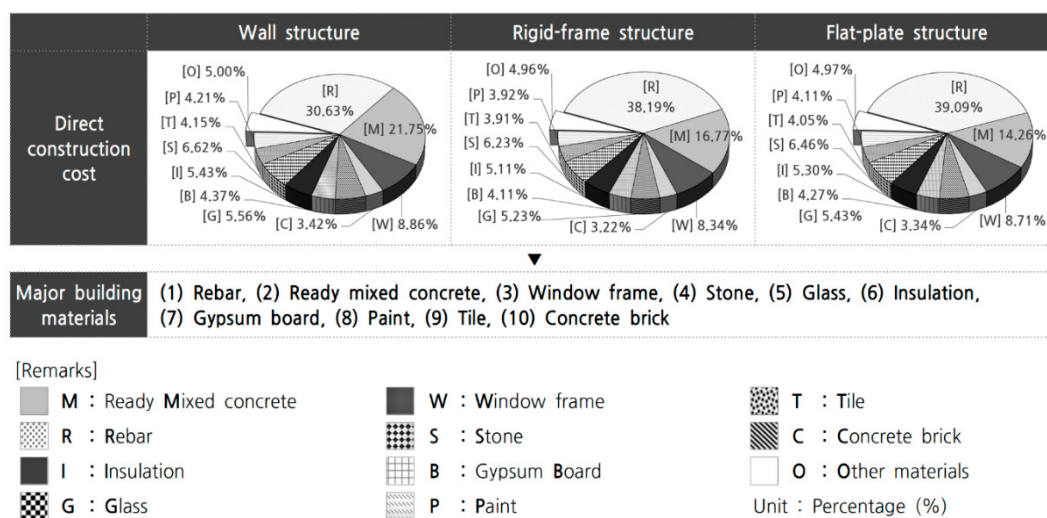


Figure 2. Results of the analysis of major building materials.

According to Roh et al. [41], the six major building materials for which the total contribution exceeded 95% in terms of environmental impact were ready-mixed concrete, rebar, glass, concrete brick, insulation, and gypsum board, which were also included in our 10 major building materials in terms of economic importance.

3.3. Development of ELCC Model

An ELCC model should consider at least one external cost in addition to the private costs considered in conventional life cycle costing [14]. To meet this requirement, we defined the major cost categories selected above (i.e., direct construction, operation energy, and maintenance costs) as pertaining to private costs, and the corresponding costs in the construction (building material production and construction work) and operation energy consumption stages and the Marginal Willingness To Pay (MWTP) for environmental impacts incurred in the maintenance stage as external costs. Then, we constructed a streamlined ELCC model for buildings which combined the private and external costs using the present worth method. Figure 3 is a schematic representation of the streamlined ELCC model for buildings developed in this study.

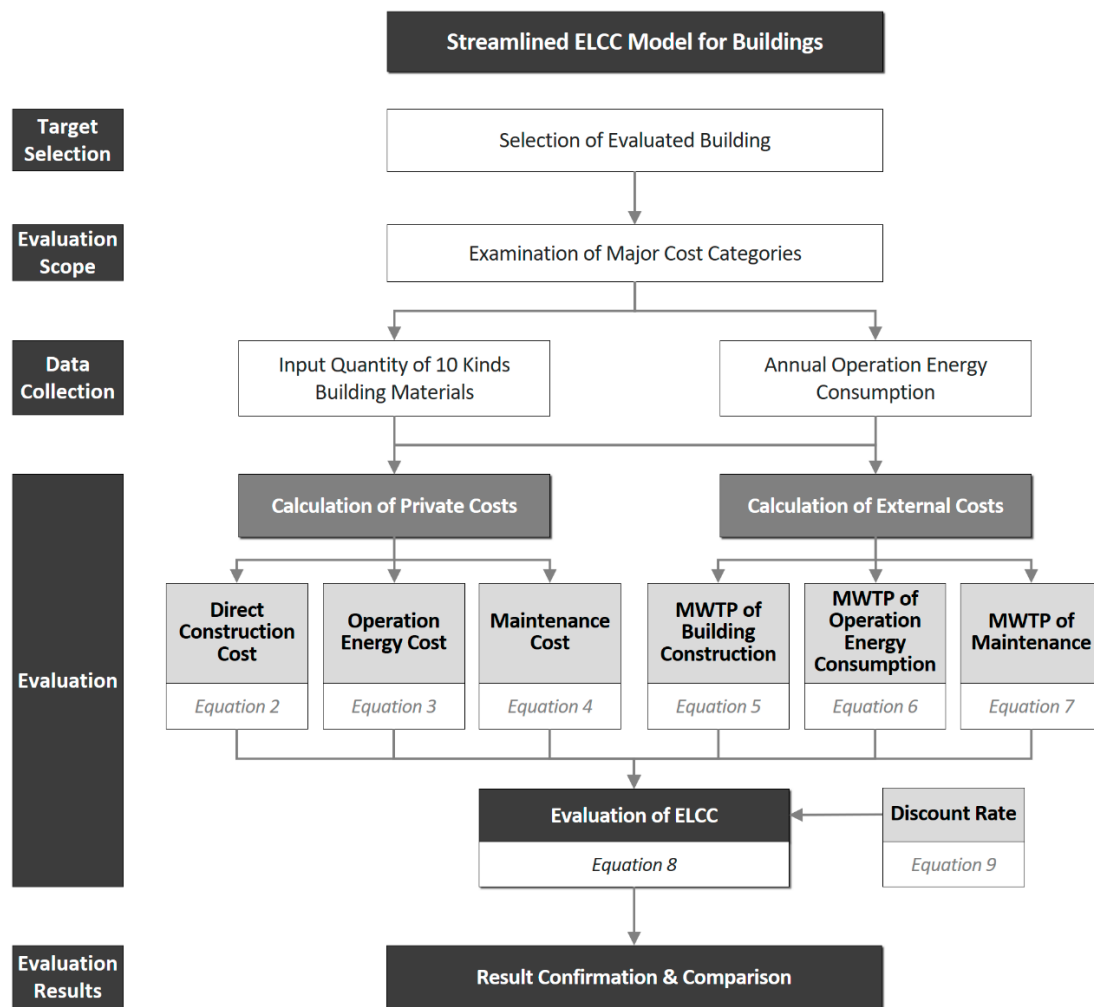


Figure 3. Streamlined ELCC model for buildings.

3.3.1. Calculation of Private Costs

The private costs, consisting of direct construction, annual operation energy, and maintenance costs, were calculated in a similar way as conventional life cycle costing. That is, direct construction costs were calculated by multiplying the input quantity of the 10 major building materials (ready-mixed concrete, rebar, glass, concrete brick, insulation, gypsum board, window frame, stone, tile, and paint) and the unit price of each building material. Annual operation energy costs were calculated by multiplying the annual energy consumption and energy unit price, and maintenance costs by calculated by multiplying the input quantity of the building materials, repair rate, and unit prices. Equations (2)–(4) are the formulas for calculating the private costs for direct construction, annual operation energy, and maintenance costs, respectively.

$$PC_I = \sum_{i=1}^{10} (Q_{m,i} \times UP_{m,i}), \quad (2)$$

$$PC_R = \sum_{i=1}^n (Q_{e,i} \times UP_{e,i}), \quad (3)$$

$$PC_N = \sum_{i=1}^{10} (Q_{m,i} \times UP_{m,i} \times R_{m,i}), \quad (4)$$

where PC_I denotes the direct construction costs (private costs), $Q_{m,i}$ denotes the input quantity of major building materials (i), and $UP_{m,i}$ denotes the unit price of major building materials (i). PC_R denotes the operation energy costs (private costs), $Q_{e,i}$ denotes the annual consumption of energy sources (i), and $UP_{e,i}$ denotes the unit prices of energy sources (i). Meanwhile, PC_N denotes the maintenance costs (private costs), and $R_{m,i}$ denotes the repair rate of the major building materials (i).

3.3.2. Calculation of External Costs

As methods for reflecting external costs in ELCC, SETAC [14] presented the concepts of “Willingness To Pay” (WTP) and “damage cost” at the endpoint level. WTP is a contingent valuation method reflecting the threshold price that consumers are willing to pay in a virtual market for a given material type, and the damage cost at the endpoint level is an approach to monetizing environmental impacts by integrating the economic valuation theory established in environmental economics into the ELCA. We applied the economic valuation costs of the KOLID, calculated by analyzing the values of the four safety guards (human health, social assets, biodiversity, and primary production) against environmental impacts, using the MWTP based on the damage cost at the endpoint level. Figure 4 is the conceptual diagram of the KOLID [37]. The KOLID quantifies 16 types of endpoint damage, including cancer, infectious disease, and cataracts, which are attributable to six environmental impact categories (global warming, ozone layer depletion, acidification, eutrophication, photochemical oxidation, and abiotic depletion) triggered by products and services. The four safety guard objects are also evaluated and can be monetized using the MWTP for each safety guard established by the questionnaire survey.

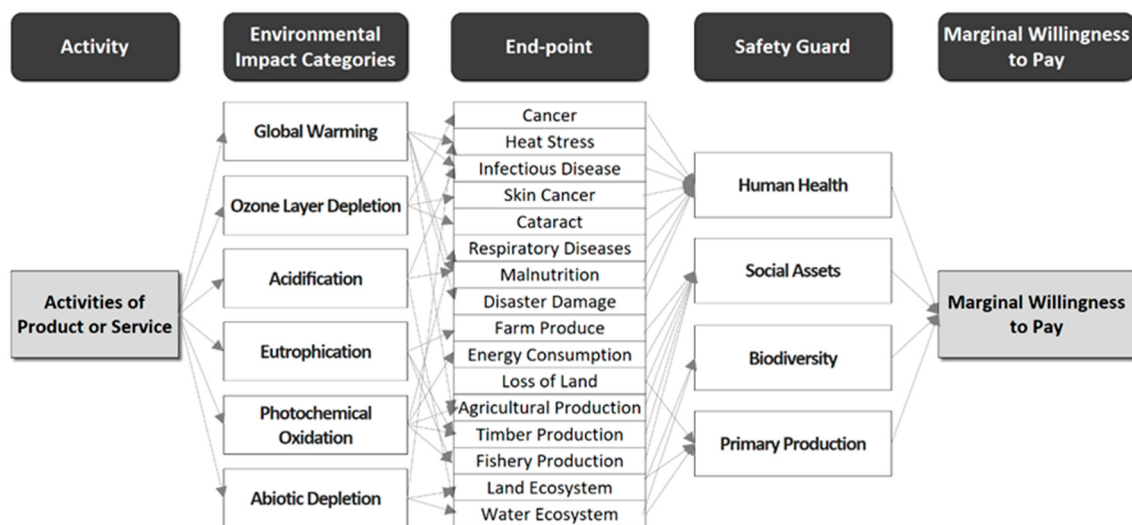


Figure 4. Conceptual diagram of Korean Life Cycle Impact Assessment Method Based on Damage-Oriented Modeling (KOLID).

To put it differently, the MWTP in the construction, operation energy consumption, and maintenance stages can be calculated by multiplying the input quantities of the major building materials or the energy consumption of each energy source, factor of each safety guard, and MWTP of each safety guard. Equations (5)–(7) are the formulas for calculating the MWTP in the construction, operation energy consumption, and maintenance stages, respectively. Table 3 outlines the safety guard factors of major building materials and energy sources based on the Korean LCI database, and Table 4 outlines the MWTP for the safety guards provided by the KOLID.

$$EC_I = \sum_{i=1}^{10} (Q_{m,i} \times SF_{m,i,j} \times MW_j), \quad (5)$$

$$EC_R = \sum_{i=1}^n (Q_{e,i} \times SF_{e,i,j} \times MW_j), \quad (6)$$

$$EC_N = \sum_{i=1}^{10} (Q_{m,i} \times SF_{m,i,j} \times MW_j \times R_{m,i}), \quad (7)$$

where EC_I denotes the MWTP in the construction stage (external cost), $Q_{m,i}$ denotes the input quantity of major building material (i), $SF_{m,i,j}$ denotes the factor for safety guard (j) with respect to major building material (i), and MW_j denotes the MWTP for safety guard (j). Meanwhile, EC_R denotes the MWTP in the operation energy consumption stage (external cost), $Q_{e,i}$ denotes the annual energy consumption of energy source (i), and $SF_{e,i,j}$ denotes the factor for safety guard (j) with respect to energy source (i). EC_N denotes the MWTP in the maintenance stage (external cost), and $R_{m,i}$ denotes the repair rate for major building material (i).

Table 3. Safety guard factors of major building materials and energy sources.

Classification	Unit	Safety Guard			
		Human Health (DALY/Unit)	Social Assets (USD/Unit)	Biodiversity (EINES/Unit)	Primary Production (NPP/Unit)
Ready-mixed concrete	m ³	2.47×10^{-4}	5.31×10^0	1.48×10^{-13}	4.63×10^1
Rebar	kg	3.98×10^{-7}	8.47×10^{-3}	2.48×10^{-16}	4.62×10^{-2}
Glass	kg	1.44×10^{-6}	3.00×10^{-2}	7.01×10^{-16}	1.74×10^{-1}
Gypsum board	kg	2.09×10^{-7}	4.52×10^{-3}	9.70×10^{-17}	2.57×10^{-2}
Electricity	kWh	2.72×10^{-7}	5.92×10^{-3}	2.86×10^{-16}	3.26×10^{-2}

DALY: disability adjusted life year; USD: United States dollar; EINES: expected increase in number of extinct species; NPP: net primary production; KRW: Korean Won; 1 USD = 1070 KRW.

Table 4. Marginal willingness to pay (MWTP) according to safety guard of KOLID.

Safety Guard	Description	Unit	MWTP (USD/Unit)
Human health	Mortality, or diseases or disorders leading to mortality	DALY (disability adjusted life year)	26,355.14
Social assets	Agricultural products, fishery resources, forestry resources, mineral resources, fossil fuel resources	KRW (Korean Won, economic costs)	0.000935
Biodiversity	Extinction of vascular plant species water-borne plants	EINES (expected increase in number of extinct species)	531.78
Primary production	Land plants and marine plankton	NPP (net primary production)	46.07

1 USD = 1070 KRW.

3.3.3. Application of the ELCC Model Equation

The primary goal of LCC is the identification of an economically advantageous design option by computing the total costs of various design options in the early planning stage of a construction project. During the computation process, it is of crucial importance to use an appropriate method to ensure the temporal synchronization of current and future costs, given that costs change over time. In this study, we applied the present worth method to convert all costs into current values using discount rates.

In the present worth method, costs are categorized into initial, recurring, and non-recurring costs [38]. Initial costs are the costs required in the initial business stage, recurring costs are the costs incurred in an annual cycle during the utilization period of a project, and non-recurring costs are the costs incurred sporadically during the utilization period of a project. Therefore, we set up an equation for the streamlined ELCC model for buildings, in which the direct construction costs required for construction work were applied as initial costs, the annually occurring operation energy costs as

recurring costs, and the maintenance costs for repair as non-recurring costs (Equation (8)). Additionally, we used the real interest rate, which represented the actual monetary value change by combining the fixed deposit interest rate and the inflation rate (Equation (9)), as the discount rate to convert the costs incurred at different points in time into the same-criteria values:

$$ELCC = (PC_I + EC_I) + \sum_{n=1}^n \frac{(PC_R + EC_R) \times (1+i)^n - 1}{i \times (1+i)^n} + \sum_{k=1}^k \frac{(PC_N + EC_N)}{(1+i)^{ak}}, \quad (8)$$

$$i = \frac{1+j}{1+k} - 1. \quad (9)$$

In Equation (8), ELCC represents the environmental life cycle cost; PC_I and EC_I denote direct construction costs (private costs) and the MWTP (external costs) for the environmental impacts incurred in the construction stage, respectively; PC_R and EC_R denote the annual operation energy costs (private costs) and the MWTP (external costs) for the environmental impacts incurred in the operation energy consumption stage, respectively; and PC_N and EC_N denote the maintenance costs (private costs) and the MWTP (external costs) for the environmental impacts incurred in the maintenance stage, respectively. i , n , k , and a denote the real interest rate lifespan of the building, the repair frequency during the building lifespan, and the repair cycle of building materials, respectively. Meanwhile, in Equation (9), i , j , and k denote the market interest (fixed deposit interest rate), and inflation rate, respectively.

4. Case Study

To investigate the applicability of the streamlined ELCC model for buildings developed in this study, we performed ELCC on two apartment buildings with different structure types using the evaluation model shown in Figure 3, and we compared the results of the evaluation.

4.1. Target Selection

Table 5 presents the basic characteristics of the buildings in the case study. The building selected for evaluation (evaluated building) was a 15-story, plate-type, flat plate, RC structure apartment building with four units per story, located in Seoul. The building selected for comparison with the ELCC evaluation results (referenced building) was a 15-story, plate-type, wall-type, RC structure apartment building with four units per story. The per unit exclusive areas of the evaluated and referenced buildings were 59.77 m² and 59.99 m², respectively. The wall-type RC structure is the most widely applied building type in Korea. It was assumed that these two buildings were identical in conditions and functions except for the structure type (flat plate vs. wall type).

Table 5. Targets of case study.

Classification	Evaluated Building	Referenced Building
Purpose	Apartment building	Apartment building
Structure	RC structure, flat plate	RC structure, wall type
Plane form	Plate-type, 4 units per story	Plate-type, 4 units per story
Exclusive area per unit	59.77	59.99
Total exclusive area	3108.04	3119.48
Gross floor area	4024.17	4039.56
Number of stories	15	15

4.2. Evaluation Scope

The evaluation scope of the set for this case study was as follows: private costs, consisting of direct construction; operation energy; and maintenance costs, selected as major cost categories and external costs corresponding to the private costs in the construction, operation energy consumption,

and maintenance stage stages. Given that this case study aimed to perform a relative comparison of ELCC between two apartment buildings with different structure types, we excluded the construction processes from the scope of evaluation, which incurred direct construction costs but were not part of the construction work, such as infrastructure construction and machinery equipment construction.

4.3. Data Collection

For the application of the proposed streamlined ELCC model for buildings, it is necessary to obtain the data for the input quantities of the 10 major building materials selected previously and the annual operation energy consumption. Therefore, we collected the input quantities of the 10 major building materials per unit exclusive area based on the bill of materials for each building and estimated the annual operation energy consumption per unit exclusive area using the operation energy consumption estimation model equation suggested in a previous study [42] by statistically analyzing the typical energy consumption patterns of Korean apartment buildings. Table 6 presents the collected input quantities of the major building materials and the estimated annual operation energy consumption of the evaluated and referenced buildings.

Table 6. Data collection.

Classification		Unit	Evaluated Building	Referenced Building
Input quantity of major building materials	Ready-mixed concrete	m ³ /m ²	0.68	0.92
	Rebar	kg/m ²	128.63	108.54
	Glass	kg/m ²	6.92	7.18
	Concrete brick	kg/m ²	88.87	86.24
	Insulation	kg/m ²	1.68	1.65
	Gypsum board	kg/m ²	2.51	2.74
	Window frame	kg/m ²	5.51	5.46
	Stone	kg/m ²	4.68	4.84
	Tile	kg/m ²	5.16	5.08
	Paint	kg/m ²	1.36	1.42
Annual operation energy consumption	Electricity	kWh/m ² , year	27.50	27.50
	City gas	kWh/m ² , year	99.40	99.40

4.4. Evaluation

We calculated the private and external costs of the evaluated and referenced buildings using the collected data. For the private cost calculation, we applied the unit of each of the major building materials released in the 2017 H2 price information for construction costs provided by the Korean Public Procurement Service [40], the unit prices for electricity and city gas provided by the Korea Energy Economics Institute [43], and the repair rate of each building material based on the long-term repair planning standards stipulated in the Enforcement Decree of the Housing Act [44] for direct construction, operation energy, and maintenance costs, respectively. External costs were evaluated by applying the safety guard factors and the MWTP for each safety guard, presented in Tables 3 and 4, respectively.

The private and external costs of the evaluated and referenced buildings evaluated were then subjected to ELCC evaluation using Equation (8). The lifespan of each building was set at 40 years, adapting the standards stipulated in the Enforcement Decree of the Corporate Tax Act [45], and the discount rate was set as the mean real interest rate of the preceding 10 years calculated on the basis of the market interest and inflation rates released by the Bank of Korea [46] (refer to Table 7).

Table 7. Real interest rates.

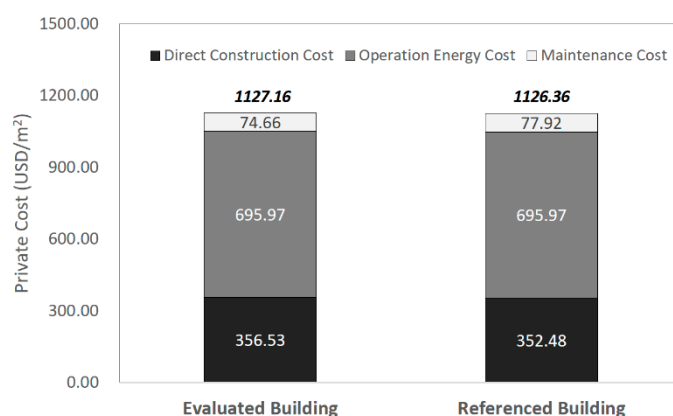
Year	Fixed Deposit Interest Rate (%)	Inflation Rate (%)	Real Interest Rate (%)
2008	5.67	4.70	0.93
2009	3.23	2.80	0.42
2010	3.18	3.00	0.17
2011	3.69	4.00	−0.30
2012	3.43	2.20	1.20
2013	2.73	1.30	1.41
2014	2.43	1.30	1.12
2015	1.74	0.70	1.03
2016	1.48	1.00	0.48
2017	1.56	1.90	−0.33
Average	2.91	2.29	0.61

4.5. Evaluation Results

We analyzed the case study results of the evaluated and referenced buildings in terms of private costs, external costs, and ELCC.

4.5.1. Private Costs

Figure 5 illustrates the LCC evaluation results for the private costs of the evaluated and referenced buildings. The results show that the private costs per unit exclusive area of the evaluated and referenced buildings during their lifespan were 1127.16 USD/m² and 1126.36 USD/m², respectively, with the cost for the referenced building lower by about 0.8 USD/m² per unit area. In particular, the unit direct construction cost of the evaluated building was higher by about 4.0 USD/m² because of the higher input quantity of rebar, despite the lower input quantity of ready-mixed concrete due to the higher unit price of rebar compared with that of concrete. On the other hand, the referenced building had about 3.0 USD/m² higher unit maintenance cost, due to the higher input quantities of gypsum board and paint, which need to be replaced in the maintenance stage. From these private cost evaluation results, the referenced building is considered to have better economic performance than the evaluated building.

**Figure 5.** Evaluation results of private costs.

4.5.2. External Costs

Figure 6 illustrates the LCC evaluation results for the external costs of the evaluated and referenced buildings. The results show that the external costs for the environmental impacts per unit exclusive area of the evaluated and referenced buildings during their lifespan were 128.35 USD/m² and 131.41 USD/m², respectively, with the evaluated building showing a value lower by about 3.0 USD/m².

per unit area, due to the increased external costs in the construction stage from the high input quantity of ready-mixed concrete, which has a higher environmental impact than other materials, although the input quantity of rebar was lower than in the referenced building. On the other hand, the external costs in the maintenance stage were very similar for both buildings. Based on these external cost evaluation results, the evaluated building is considered to have a better economic performance than the referenced building.

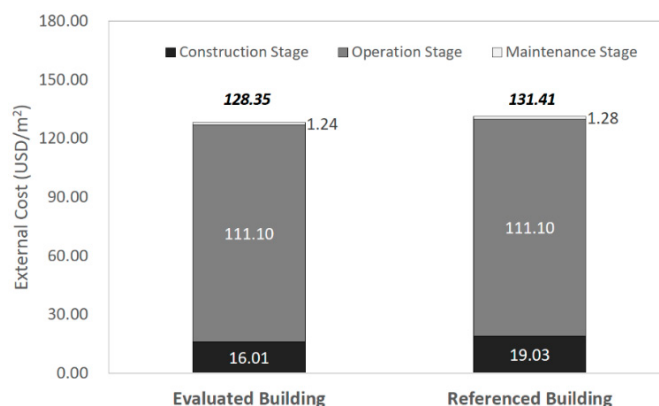


Figure 6. Evaluation results of external costs.

4.5.3. Environmental Life Cycle Cost

Figure 7 illustrates the ELCC evaluation results for the private and external costs of the evaluated and referenced buildings. It shows that the ELCC per unit exclusive area of the evaluated and referenced buildings during their lifespan were 1255.52 USD/m² and 1257.77 USD/m², respectively, with the evaluated building showing a value lower by about 2.0 USD/m² per unit area. Above all, although the LCC evaluation results for the private and external costs of the evaluated and referenced buildings showed discrepancies, we were able to perform an analysis concurrently considering both economic and environmental performance through simple addition of these evaluation results to the same-criteria values, thus confirming the applicability of the proposed evaluation model along with the need for external cost evaluation. Furthermore, the external costs within the scope of this case study exceeded the ELCC calculated as the final result by slightly over 10%.

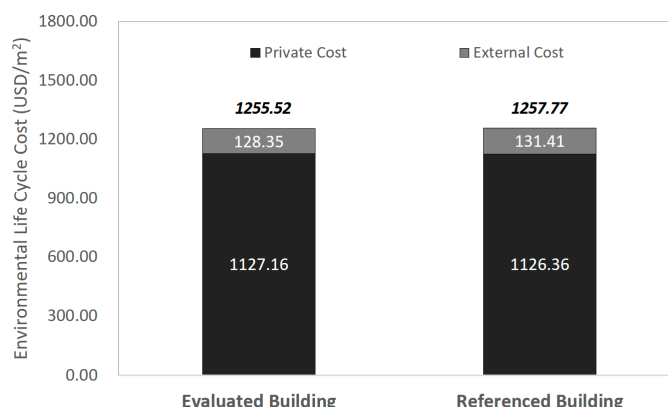


Figure 7. Evaluation results of environmental life cycle cost.

5. Discussion

Compared with general products, buildings require huge space and costs for construction and operation over a long period of time and have a large environmental impact. Therefore, evaluating the

economic and environmental performance simultaneously in the early planning stage, which has the greatest reduction potential in terms of life cycle cost and environmental impact, plays a pivotal role in the success or failure of the entire building construction industry.

This study aimed to present a technical option, capable of supporting stakeholders' decision-making for sustainable building construction by developing a streamlined ELCC model for buildings applicable to the early planning stage of a construction project. The significance of the streamlined ELCC model for buildings developed in this study lies in the fact that the simplified LCC assessment involves the extraction of major building materials that account for over 95% of the total direct construction costs, thus facilitating ELCC assessment and improving its applicability. Not only can the proposed model efficiently support stakeholders' decision-making to enhance the sustainability of buildings in the early planning stage of construction, it is also expected to serve as a reference model for judging sustainable buildings in government tender, for example, for a government that places a high value on buildings' environmental performances.

Furthermore, this case study is significant in that its results demonstrated that economic performance evaluation can change through the inclusion of external costs triggered by environmental impacts in the LCC evaluation, unlike the conventional life cycle costing which only consists of private costs. Although no statistically significant differences were observed in the ELCC between the evaluated and referenced buildings in this case study, the approach it adopted is expected to help extend the decision-making method and scope when judging a sustainable building's economic performance.

6. Conclusions

In this study, we developed a streamlined ELCC model for buildings applicable to the early planning stage of construction projects. The following is a summary the study's main achievements:

1. We established an equation for the systematic evaluation of ELCC in the early planning stage of a construction project by considering the MWTP of the KOLID as external costs, and developed a streamlined ELCC model for buildings.
2. As the major cost categories for the streamlined ELCC model for buildings in the early planning stage of a construction project, we selected direct construction, operation energy, and maintenance costs as the scope of the private cost evaluation, and the corresponding costs in the construction, operation energy consumption, and maintenance stages as the scope of the external cost evaluation.
3. By analyzing the direct construction costs of six buildings constructed in Korea, we extracted 10 building materials that accounted for over 95% of the total direct construction cost: concrete, rebar, glass, concrete brick insulation, gypsum board, window frame, stone, tile, and paint.
4. We verified the applicability of the streamlined ELCC model for buildings developed in this study by performing quantitative ELCC evaluations on two apartment buildings with different structure types and compared their private and external costs in a case study.

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