Sustainability **2014**, *6*, 158-174; doi:10.3390/su6010158

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Sustainability Life Cycle Cost Analysis of Roof Waterproofing Methods Considering $LCCO_2$

Sangyong Kim [1], Gwang-Hee Kim [2,*] and Young-Do Lee [3]

[1] School of Construction Management and Engineering, University of Reading, Whiteknights PO Box 219, Reading RG6 6AW, UK; E-Mail: rd026992@reading.ac.uk

[2] Department of Plant/Architectural Engineering, Kyonggi University, Suwon-si, Gyeonggi-do 443-760, Korea

[3] Department of Architecture and Civil Engineering, Kyungdong University, Gosung-Goon, Gwangwon-do 219-705, Korea; E-Mail: lyd@k1.ac.kr

***** Author to whom correspondence should be addressed; E-Mail: ghkim@kyonggi.ac.kr; Tel.: +82-31-249-9757; Fax: +82-31-244-6300.

Received: 27 September 2013; in revised form: 19 November 2013 / Accepted: 18 December 2013 / Published: 27 December 2013

Abstract: In a construction project, selection of an appropriate method in the planning/design stage is very important for ensuring effective project implementation and success. Many companies have adopted the life cycle cost (LCC) method, one of the methods for analyzing economic efficiency, for appropriate decision-making in the basic/detailed design stage by estimating overall costs and expenses generated over the entire project. This paper presents an LCC method for calculating the LCC of CO_2 ($LCCO_2$), based on materials committed during the lifecycle of a structure for each roof waterproofing method and adding this cost to the LCC for comparative analysis. Thus, this technique presents the LCC that includes the cost of CO_2 emission. The results show that in terms of initial construction cost, asphalt waterproofing had the highest CO_2 emission cost, followed by sheet waterproofing. $LCCO_2$ did not greatly influence the initial construction cost and maintenance cost, as it is relatively smaller than the LCC. However, when the number of durable years was changed, the LCC showed some changes.

Keywords: life cycle cost; life cycle cost of CO_2; roof waterproofing; CO_2 emission

---

1. Introduction

Construction projects have several standard stages, which the Project Management Institute categorizes as follows: initiation, planning, execution, and close [1]. In a construction project, these processes inevitably generate extra costs at every stage; therefore, a rigorous estimation procedure is necessary. In particular, it is crucial to adopt a suitable method for successful project delivery at process outset. In the construction industry, reasonable decisions are made by analyzing the economics of a project, using objectives and quantitative methods. This is done to ensure compliance with design regulations for safety, functionality, durability, and potential functions of the building by developing and adopting life cycle cost (LCC) and value engineering (VE) in their procedure. Simultaneously, project managers attempt to minimize extra expenses while meeting the structural and functional requirements of a project.

However, current economic analysis tools tend to have a limitation in terms of their applicable range as they merely focus on reducing direct costs for a project, such as labor, material, and site overhead cost. This implies that there is no consideration for the environment within these tools, which is a serious drawback. Among the harmful environmental effects of rapid industrial development, global warming is the most profound, and the solution to this problem demands extensive changes from the government, industry, and public [2]. This demand has resulted in the emergence of a paradigm globally, called 'sustainable development'. Sustainable development has become a common aspect in every activity owing to the environmental deterioration caused by aggressive human activity. This requires an active measure for considering the environmental impact caused by the construction industry in order to keep pace with global trends and respond to changes in domestic and foreign environmental policies. However, the LCC method, which is currently used in the initial stage of a project, considers only direct costs but not the environmental cost of CO_2 management. Therefore, it is important to develop an integrated instrument that can assess the socio-environmental aspects of a project. For LCC estimation, common procedures from design to demolition and disposal are considered and the cost of each step is calculated. However, the proportion of waterproofing work in the overall construction is so small that it is difficult to estimate the associated amount of disposal work. Therefore, the purpose of this research is to propose an LCC calculation method that includes the cost of CO_2 emission, LCC, and $LCCO_2$ during the demolition and disposal stages of a building. Sensitivity analysis related to alternatives and uncertain factors is omitted in this research.

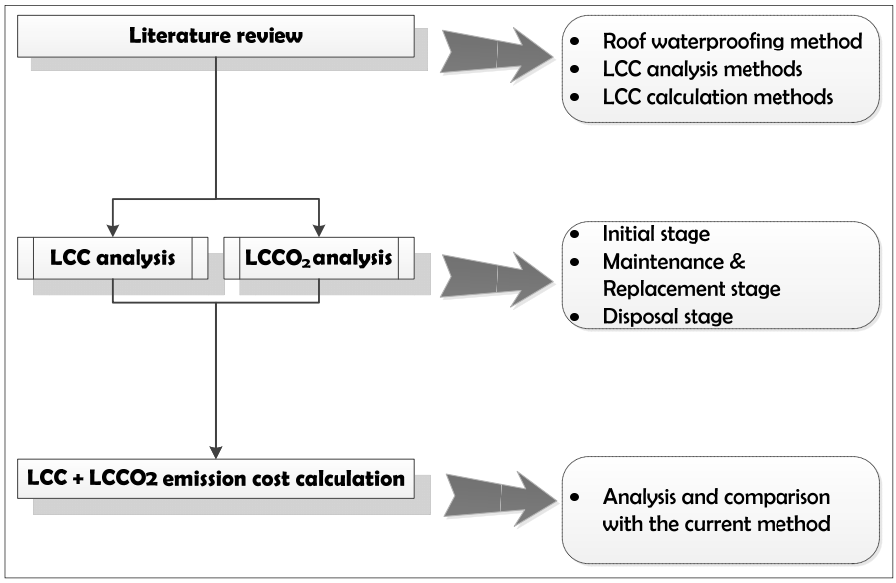
Thus, this research proposes a new LCC method that includes CO_2 emission cost by analyzing the entire LCC of different roof waterproofing methods by calculating the LCC of CO_2 ($LCCO_2$). Through conventional LCC analysis, it is possible to examine the economic feasibility of the new instrument, including the costs at the initial, operation and maintenance (O&M), disposal, and demolition stages. Moreover, the new method can provide a reasonable logic for choosing a suitable construction method by considering the environmental impact of a project by including $LCCO_2$ costs. Furthermore, this method can assist designers and engineers in systematic decision-making for selecting the most suitable alternative from economic and environmental viewpoints, which otherwise used to be based on their personal experience and knowledge.

2. Methodology

In this research, LCC, which reflects the initial cost and the cost O&M stages, such as labor, material, and disposal costs for replacement and maintenance, is calculated. The life cycle inventory (LCI) method, which is the data collection aspect of the LCA method, is used for tracking all flows in and out of the basic unit data of CO_2 emissions of each material [3]. The calculated data is used for estimating total project cost, including the cost of CO_2 emissions over the entire project life. It is ambiguous to stipulate standards for CO_2 emission costs related to disposal, transport distance, loads, and the type of delivery vehicle [4]. Therefore, the research proceeds under the assumption that the LCC and $LCCO_2$ are calculated at the demolition and disposal stage of a building, in compliance with the research purpose, which is to estimate the LCC including the CO_2 emission cost.

The research procedure is as follows (see Figure 1): analyze the current research mainstream and determine limitations of past studies by reviewing literature on waterproofing methods that perform LCC and $LCCO_2$ estimation; calculate the $LCCO_2$ and LCC according to stages, such as material manufacturing and maintenance (including disposal costs), and; compare and analyze the LCC, which includes the $LCCO_2$ of each roof waterproofing method.

Figure 1. Research procedure.



3. Literature Review

3.1. Selection of Waterproofing Methods by LCC

Conventionally, studies on waterproofing methods were focused on the assessment and improvement of the material functions by finding causes of defect and suggesting solutions to avoiding these causes. One study, conducted by Oh [5], suggested two solutions: to examine the liquid-applied membrane waterproofing method using recycled materials and the applicability of recycled materials to the liquid-applied membrane waterproofing. Kang [6] and An [7] analyzed the causes of waterproofing defects for developing desirable waterproofing design and methods. However, these studies tended to

face several difficulties in terms of choosing a suitable waterproofing method at the planning and design stage.

Recently, there has been focus on applying various academic standards for finding and proposing objective and economic waterproofing methods at the initial planning and design stage. A representative study, conducted by Oh [8], suggested the capability assessment method for deciding the suitability of waterproofing methods by analyzing causes of defects in roof waterproofing. Kim [9], who built the cost categorizing system for individual waterproofing methods proposed an LCC analysis model for each waterproofing method for underground apartment structures by using previous study and examined the proposed model. A study conducted by Choi [10] is related to desirable economic models for estimating roof waterproofing costs, including initial, O&M, and disposal costs. VE and LCC were adopted to devise a system for the analysis and application of VE procedures. A risk-based weighted LCC (RWLCC) cost estimate model [11] was also presented in that research.

3.2. Cost Estimation of CO_2 Emission

Several studies have attempted to devise a method for quantifying CO_2 emission and energy consumption of a certain building material, and subsequent conversion of the result into actual cost. Moreover, a number of studies have been conducted on constructing a database for calculating the CO_2 emission unit price using LCA. Estimation using an accumulate method and an industrial relation table was introduced by Lee [12], and the actual quantity was estimated using input-output tables 1990. The database of energy consumption and the basic unit price of CO_2 emission was built using 1995, input-output tables of 2000 for developing unit price data and a program for assessing the overall LCA process by the department of construction. Kim [13,14] and Lee [15] proposed a model for estimating energy consumption and the CO_2 emission basic unit price. The amount of energy consumed by the main construction materials was calculated in terms of CO_2 consumption units. Based on previous studies, CO_2 emissions for internal wall and floor components were estimated and compared in a quantitative manner. In addition, the emission quantity for each component of a masonry wall was calculated, and a method for converting the cost of trading CO_2 emission price was proposed by Lee *et al.* [16].

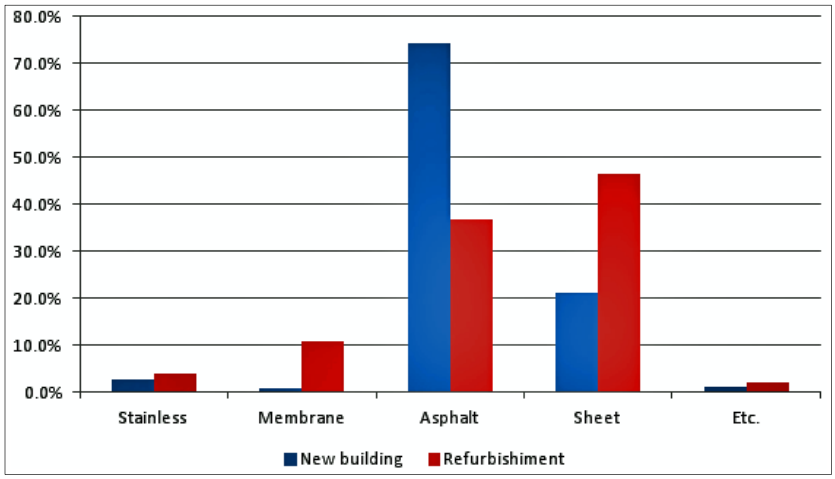
Previous studies have focused on evaluating the performance of waterproofing methods and improving the same by applying scientific methods at the initial planning stage to achieve objective decision-making. In particular, selection of a method for determining cost over the entire lifecycle using the LCC analysis method, which is an economic method, is being researched. Some studies have aimed to estimate the CO_2 emission of each construction method for determining the environmental impact, but no distinctive integrated study on economic and environmental factors has been conducted thus far.

4. LCC Estimation

4.1. Selection of Roof Waterproofing Method

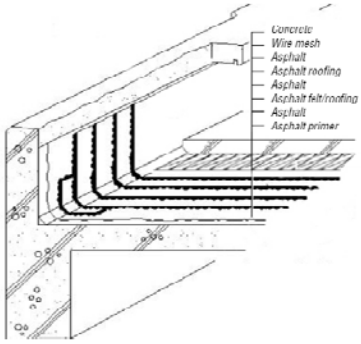
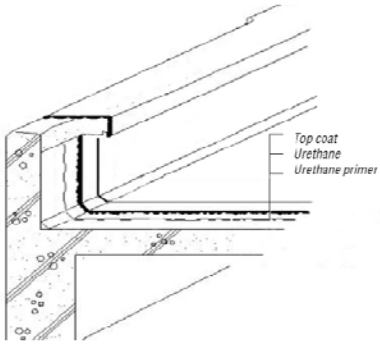
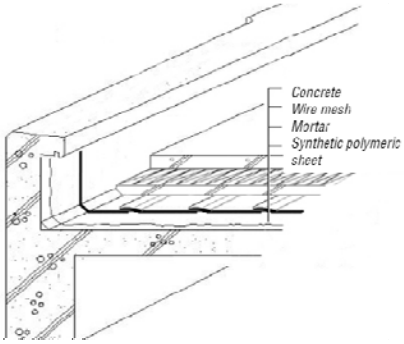
As the function and capability of a building vary, the importance of proper waterproofing for each building is emphasized. The waterproofing methods preferred for new buildings and for refurbishment are shown in Figure 2. Subsequently, the top three preferred waterproofing methods were chosen for comparison in our research: asphalt, sheet, and membrane waterproofing.

Figure 2. Waterproofing method preference [7].



In order to calculate $LCCO_2$ and LCC by each waterproofing method, the components of three waterproofing methods are identified in Table 1 according to the itemized unit cost and a standard of estimate.

Table 1. Components of roof waterproofing system.

Method		Components
Asphalt		• Asphalt • Asphalt primer • Asphalt felt • Asphalt roofing • Heavy oil • Cement, Gravel, Sand, Wire mesh
Membrane		• Urethane • Urethane primer • Top coat
Sheet		• Synthetic Polymeric Sheet • Cement, Gravel Sand, Wire mesh

4.2. LCC Assessment Method

In LCC analysis, cost factors identified using cost breakdown structure (CBS) are generated continuously over the lifecycle of a building. To maintain the equivalent value of the cost, which is created on a different timeline, it is necessary to convert all cost factors in CBS into the same value for accurate LCC calculations. In addition, the time reference point for converting different values should be decided in advance. This is because the LCC method can be divided into three sub-methods, based on the reference point: the present, annual value method, and future value method. Generally, the present and future value methods are useful for comparing alternatives with equal calculation periods, whereas the annual value method is useful when the periods are not identical. These three methods are correlated but the present and annual value methods are generally adopted for LCC calculations.

4.3. Repair Period and Repair Rate

In this study, the waterproofing time and repair rate suggested in the 'Housing Act Enforcement Regulations in Korea' are the basis for calculating the LCC, and the detailed numbers are listed in Table 2.

Table 2. Repair period and ration.

	Area	Period	Ratio (%)
Asphalt waterproofing	Partial	8	10
	Full	25	100
Membrane waterproofing	Partial	5	10
	Full	15	100
Sheet waterproofing	Partial	8	20
	Full	20	100

4.4. Analysis Period

Analysis period is a crucial variable that can influence the LCC calculation; therefore, sufficient rigor must be exercised for determining this period [17,18]. The analysis period is not merely a comparison process for input costs over the entire life but the critical point that decides the break-even point of a project. Therefore, the period should be calculated by considering building attributes and purpose. There is a broad consensus that the concept of durable years is associated with a lifecycle accounting approach to building design, construction, and management. Each subsystem is assigned an optimum expected useful life and installed accordingly. For waterproofing, its lifetime is equal to the lifetime of a building as the waterproofing function is expected to be performed over the lifecycle of the building, as shown in Table 3 [19].

Table 3. A durable period of a build.

Period	Types of asset
5 years (4–6 years)	Vehicle and transport. Equipment, instrument and tool
12 years (9–15 years)	Ship and aircraft
20 years (15–25 years)	All structure building including a brick building, block building, concrete-ramen building, wooden building, wooden-mortar building
40 years (30–50 years)	Steel frame, Steel-concrete structure, masonry stone structure, all beam structure building

There is no certain durable period in LCC estimations, but it ranges between 30 and 50 years. In this research, 45 years is considered as the durable period for the analysis of a build-transfer-lease project.

4.5. Discount Rate

As mentioned previously, future cost has a different value than the current value, even for identical face values. To resolve this difference, a discount rate, which is the interest rate used in discounted cash flow analysis for determining the present value of a future cash flows, is applied. The rate can be classified as a nominal discount rate, which does not consider the inflation rate, and the real discount rate, which includes inflation. In the LCC analysis, the real discount rate is usually adopted as the discount rate [20]. Therefore, the real discount rate is applied according to Equation (1).

$$(1+i_n)=(1+i_r)\times(1+f) \quad \therefore i_r=\frac{(1+i_n)}{(1+i)}-1 \tag{1}$$

where, i_r: real discount rate, i_n: nominal discount rate, f: rate of inflation.

The interest rate of Korean banks and the CPI (Consumer Price Index) from national statistics are used for calculating the nominal discount rate and inflation rate, and the calculated real discount rate is shown in Table 4.

Table 4. Real discount rate.

Year	Interest rate (%)	Consumer Price Index (CPI, Y2010 = 100)	Inflation rate (%)	Real rate of interest (%)
1996	9.00	63.15	9.00	3.83
1997	10.59	65.96	4.44	5.89
1998	13.39	70.91	7.51	5.47
1999	7.05	71.49	0.81	6.19
2000	7.08	73.10	2.26	4.71
2001	5.46	76.08	4.07	1.34
2002	4.71	78.18	2.76	1.89
2003	4.15	80.92	3.51	0.61
2004	3.75	83.83	3.59	0.15
2005	3.57	86.14	2.75	0.79
2006	4.36	88.07	2.24	2.07
2007	5.01	90.30	2.53	2.41
2008	5.67	94.52	4.67	0.95
2009	3.23	97.13	2.76	0.46
2010	3.18	100.00	2.96	0.22
2011	3.69	104.00	4.00	−0.30

4.6. LCC Calculation

The fundamental cost information for calculating the LCC of roof waterproofing construction can be divided into three categories: initial construction cost, O&M cost, and disposal cost. To obtain relevant cost information, identified components of each construction method and a standard of estimation and itemized unit cost from 2009 are used for calculation. In general situations, the bill of

quantity includes site overhead costs and general overhead costs. For objective comparison, these costs were excluded from this study.

The initial construction cost for each method was calculated using a standard of estimation and the itemized unit cost by process analysis. As a result, the initial costs of three methods are in the order of asphalt, membrane, and sheet waterproofing. O&M cost or repair cost, in this case, is calculated based on the "Housing Act Enforcement Regulations". In the case of asphalt and membrane waterproofing, repair work is needed at the rate of 10%, eight years after the initial work. Based on the repair rate, the rate of 10% for the total area is calculated considering the disposal of previous work and repair work for eight-layered asphalt waterproofing. The repair rate for sheet waterproofing work is assumed as 20% and is calculated in a manner that is identical for the former work. The "2008 Unit Price for Construction Waste by a Location in Korea" is applied for demolition and disposal work for a waterproofing layer and the repair cost for each method are presented in table. The outcomes of the cost calculations are given in Table 5. The result shows that sheet waterproofing accounts for the highest cost for single partial waterproofing repair, followed by asphalt and membrane waterproofing. Disposal cost is generated owing to the removal of the existing waterproofing layer. In order to calculate the disposal cost, the "2008 Unit Price for Construction Waste by a Location in Korea" standard is applied to all three study methods.

Table 5. Repair cost for a roof waterproofing system.

System	Specification	Unit (m^2)	Material cost	Labor cost	Total
Asphalt (Repair period: 8 years, 10%)	Major repair	0.1	1338	3094	4432
	Waterproof layer demolition and disposal	0.1			2439
	Sum				6871
Membrane (Repair period: 5 years, 10%)	Major repair	0.1	2624	1530	4154
	Waterproof layer demolition and disposal	0.1			2439
	Sum				6592
Sheet (Repair period: 8 years, 20%)	Major repair	0.2	2322	4001	6323
	Waterproof layer demolition and disposal	0.2			4877
	Sum				11,200.4

5. $LCCO_2$ Estimation

Prior to the calculation of CO_2 emission cost by roof waterproofing in the initial stage, the construction materials corresponding to the input-output tables, which categorize 404 items of industrial materials, should be classified. The waterproofing methods selected for this study are classified in Table 6 and the components of each method are listed. Based on this classification, material quantity per unit is calculated by referring to the itemized unit price and a standard of estimation. The estimated quantity of a material is multiplied with the CO_2 emission basic unit (kg-CO_2/won) for arriving at the CO_2 emission and emission cost.

Table 6. Component classification of roof waterproofing system.

System	Material	Unit	Quantity
Asphalt	Asphalt	kg	7.1
	Asphalt primer	L	0.4
	Asphalt felt	m^2	1.1
	Asphalt roofing	m^2	2.2
	Heavy oil	L	0.8
	Cement	kg	6.8
	Gravel	kg	0.1913
	Sand	m^3	0.0098
	Wire mesh	kg	3.486
Membrane	Urethane	kg	3.9
	Urethane primer	kg	0.3
	Coating material	kg	0.3
	Cement	kg	6.8
	Gravel	kg	0.1913
	Sand	m^3	0.0098
	Wire mesh	kg	3.486
Sheet	Synthetic polymeric sheet	m^2	1.2
	Cement	kg	6.8
	Gravel	kg	0.1913
	Sand	m^3	0.0098
	Wire mesh	kg	3.486

5.1. Selection of Environmental Load Database

Construction materials in basic units are a prerequisite for constructing the database of the amount of energy consumed and CO_2 emission, which is required for estimating the energy consumption and CO_2 emission of the components and activities of roof waterproofing. To this end, the environment load basic unit database suggested by a previous Korea Institute of Construction Technology (2004) is adopted. In the previous study, detailed data on the energy consumption of construction materials and resources with basic units of CO_2 emission using input-output tables was calculated. Based on the previous study, the materials and resources pertinent to each method are analyzed for calculating CO_2 emissions involved in individual roof waterproofing according to the industrial categories in response to the input-output tables as suggested in Table 7.

Table 7. CO_2 emission basic unit and energy consumption of materials and products.

Code	Part name	Material	CO_2 emission amount (t-CO_2/Mwon)
00390100	Sand	Sand	0.3538
00390200	Gravel	Gravel	0.3538
01440100	Heavy oil	Heavy oil	3.7367
01920200	Asphalt product	Asphalt	1.7535
01710100	Wax and coating product	Coating material	1.815

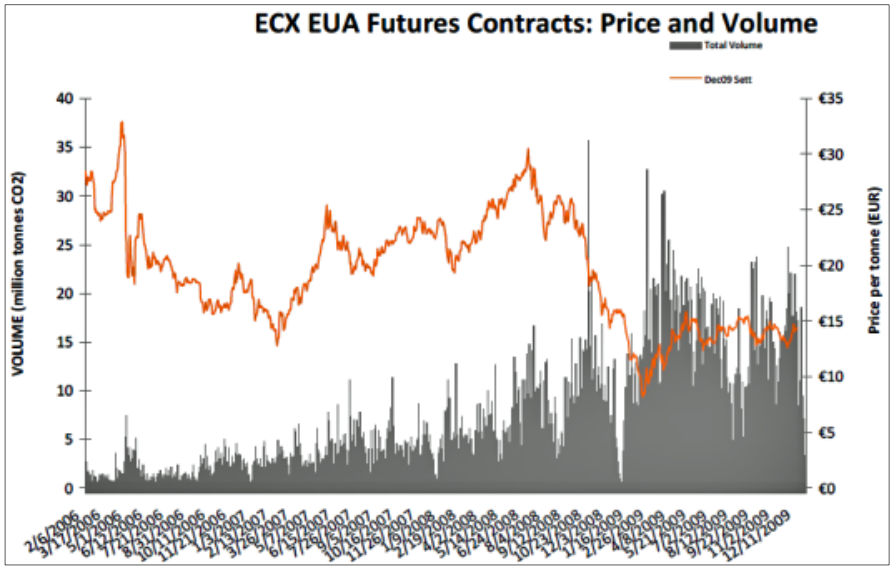
Table 7. *Cont.*

Code	Part name	Material	CO_2 emission amount (t-CO_2/Mwon)
01650301	Thinner	Thinner	1.602
01850101	Normal cement	Cement	6.616
01550100	Synthetic rubber	Synthetic polymer sheet	1.7407
01670100	Adhesive(industrial)	Primer	1.382
01650201	Urethane product	Urethane	1.602
01920200	Asphalt product	Asphalt primer	1.7535
01920200	Asphalt product	Asphalt felt	1.7535
01920200	Asphalt product	Asphalt roofing	1.7535
02210103	Steel net	Wire mesh	3.738

5.2. Application of CO_2 Market Price

The cost of $LCCO_2$ emission can be estimated by multiplying the required material cost of a component with the CO_2 emission basic units of identified major construction materials. The multiplied cost should be converted into the current market-traded CO_2 emission price. As mentioned earlier, there are various markets for trading emission rights with the intention of controlling air pollution in developed countries. Among various markets, the price of the EU Allowance (EUA), which is traded in the EU Emission Trading Scheme (EU ETS), is adopted to calculate the $LCCO_2$ and the average price of CO_2 emission (from 2005 to 2009), as suggested by ECX, is applied. The average price is 19.73 EUR/ton. In addition, the average Euro:Won exchange rate in 2009 is applied, which is the standard currency in the European Climate Exchange (ECX) as shown in Figure 3.

Figure 3. EU Allowance (EUA) price (2006–2009).



5.3. $LCCO_2$ Cost Calculation

The CO_2 emission volume can be calculated from the product of three variables: required material quantity, material unit cost, and CO_2 emission basic unit. The calculated results are presented in Table 8.

Table 8. CO_2 emission volume (m^2).

Systems	Material	Unit cost	Quantity	CO_2 basic unit	CO_2 emission volume	Sum
Asphalt	Asphalt primer	1277	0.0005108	1.7535	0.0008957	0.0297637
	Blown asphalt	730	0.0051830	0.861	0.0090884	
	Asphalt felt	1666	0.0018326	1.7535	0.0032135	
	Asphalt roofing	500	0.0011000	1.7535	0.0019289	
	Heavy oil	654	0.0005326	3.7367	0.0019902	
	Cement	79	0.0005372	6.616	0.0035541	
	Gravel	12,500	0.0002391	0.3538	0.0000846	
	Sand	12,500	0.0001225	0.3538	0.0000433	
	Wire mesh	688	0.0023984	3.738	0.0089651	
Membrane	Urethane	4900	0.0005134	1.382	0.0306142	0.0487873
	Urethane primer	4900	0.0191100	1.602	0.0026681	
	Coating material	1277	0.0014700	1.815	0.0007095	
	Thinner	3271	0.0013411	1.602	0.0021485	
	Cement	79	0.0005372	6.616	0.0035541	
	Gravel	12,500	0.0002391	0.3538	0.0000846	
	Sand	12,500	0.0001225	0.3538	0.0000433	
	Wire mesh	688	0.0023984	3.738	0.0089651	
Sheet	Synthetic polymer sheet	6000	0.0072000	1.7407	0.0125330	0.0258896
	Cement	79	0.0005372	6.616	0.0035541	
	Gravel	12,500	0.0002391	0.3538	0.0000846	
	Sand	12,500	0.0001225	0.3538	0.0000433	
	Primer	688	0.0005134	1.382	0.0089651	
	Wire mesh	1277	0.0023984	3.738	0.0007095	

Based on the calculated CO_2 emission volume, CO_2 emission cost is obtained by multiplying it with the average EUA price and the average currency price, as listed in Table 9. The CO_2 emission cost of roof waterproofing in terms of required materials is in the following order: membrane waterproofing, asphalt waterproofing, and sheet waterproofing.

Table 9. Cost for CO_2 emission at construction stage.

	CO_2 emission volume	Average price of EUAs (EUR/ton)	Average exchange currency	CO_2 emission cost
Asphalt waterproofing	0.0297637	19.73	1809.65	1062.70
Membrane waterproofing	0.0487873			1741.92
Sheet waterproofing	0.0258896			924.37

Roof waterproofing maintenance work involves partial or complete demolition. Therefore, the equipment used for demolition and rework is input for roof waterproofing maintenance work. This input can be a factor in calculating the cost of roof waterproofing maintenance work. In the case of equipment, a breaker CO_2 emission basic unit proposed by the Table 10 can be used for calculating the cost of demolition work as part of maintenance work.

Table 10. CO_2 emission cost for a waterproofing layer demolition.

Equipment	Unit (m^2)	CO_2 basic unit (kg-CCO_2/m^2)	Average price of EUAs (EUR/ton)	Average exchange currency (year)	Costs (Won/m^2)
Breaker	0.12	0.687	19.73	1809.65	2452.89

The initial CO_2 emission cost calculation method is used for materials, and the cost of a sample repair and replacement work is presented in Tables 11 and 12. The calculated results show that the membrane-waterproofing method requires the highest expense in maintenance stage, followed by asphalt and sheet waterproofing, as can be seen in Table 12.

Table 11. CO_2 emission cost for repair.

System	Specification	Unit (m^2)	Material cost	Labor cost	Total
Asphalt (Replacement period: 25 years, 10%)	Partial repair	0.1	106.27	0	106.27
	Waterproof layer demolition(breaker)	0.1			245.29
	Sum				351.56
Membrane (Replacement period: 15 years, 10%)	Partial repair	0.1	174.19	0	174.19
	Waterproof layer demolition(breaker)	0.1			245.29
	Sum				419.48
Sheet (Replacement period: 20 years, 20%)	Partial repair	0.2	184.87	0	184.87
	Waterproof layer demolition(breaker)	0.2			409.58
	Sum				675.45

Table 12. CO_2 emission cost for replacement.

System	Specification	Unit (m^2)	Material cost	Labor cost	Total
Asphalt (Replacement period: 25 years, 10%)	Partial replacement	0.1	1062.70	0	1062.70
	Waterproof layer demolition(breaker)	0.1			2452.89
	Sum				3515.59
Membrane (Replacement period: 15 years, 10%)	Partial replacement	0.1	1741.92	0	1741.92
	Waterproof layer demolition(breaker)	0.1			2452.89
	Sum				4194.81
Sheet (Replacement period: 20 years, 20%)	Partial replacement	0.2	924.37	0	924.37
	Waterproof layer demolition(breaker)	0.2			2452.89
	Sum				3377.27

In addition, the cost of transporting debris to a landfill or temporary disposal site should be considered while calculating the CO_2 emission cost of the demolition and disposal stage. However, owing to the very limited amount of construction waste from roof waterproofing, this cost can be expected to be a very small percentage of the total cost. In addition, because there is uncertainty in

setting a standard for distance and vehicles for handling the waste, the cost of CO_2 emission from transport in the demolition and disposal stage is not considered.

6. LCC Comparison Including $LCCO_2$

6.1. Initial Cost

As suggested in Table 13, the initial construction cost excluding CO_2 emission cost is in order of asphalt, membrane, and sheet waterproofing, whereas the cost for CO_2 emission of each method is in a different order: membrane, asphalt, and sheet waterproofing. Despite the different CO_2 emission costs, the order of total cost for each method does not change, as the CO_2 emission cost required in the initial stage accounts for a relatively small portion of the total cost. Therefore, the total cost considering the CO_2 emission cost is almost the same as that without considering it.

Table 13. Cost for construction and CO_2 emission at initial stage.

System	Initial construction cost	Initial CO_2 emission cost	Sum
Asphalt waterproofing	44,319	1062.7	45,382
Membrane waterproofing	41,538	1741.9	43,280
Sheet waterproofing	31,616	924.4	32,541

6.2. Maintenance and Repair Cost

In LCC analysis, cost factors identified by CBS are continuously generated over the lifecycle of a building. All cost factors in CBS are discounted to their equivalent present values based on the relevant discount factors as part of LCC procedure. In addition, the time-based milestones should be obvious. Tables 14 and 15 represent the cost of maintenance and repair in current prices and the net present value by the number of years.

Table 14. Accumulated operation and maintenance cost ($LCCO_2$ cost excluded).

Year	Asphalt waterproofing		Membrane waterproofing		Sheet waterproofing	
	Current price	Present value	Current price	Present value	Current price	Present value
5			6592	5714		
8	6871	5466			11,200	8911
10			13,185	10,668		
15			79,109	53,603		
16	13,741	9815			22,401	16,000
20			85,701	57,325		
24	82,447	44,410			78,403	47,615
25			92,294	60,550		
28					89,603	52,645
30			158,218	88,513		
32	89,317	47,163				
35			164,810	90,937		

Table 14. *Cont*.

Year	Asphalt waterproofing		Membrane waterproofing		Sheet waterproofing	
	Current price	Present value	Current price	Present value	Current price	Present value
36					100,804	56,647
40	96,188	49,352	171,403	93,038	156,806	75,495
44					168,006	77,679
45	103,058	51,250	237,327	111,250		
Repair	34,593	16,655	39,554	22,140	56,002	28,216
Replacement	68,705	34,596	197,772	89,110	112,004	49,463

Table 15. Accumulated operation and maintenance cost ($LCCO_2$ cost included).

Year	Asphalt waterproofing		Sheet waterproofing		Membrane waterproofing	
	Current price	Present value	Current price	Present value	Current price	Present value
5					6838	5927
8	7222	5746	11,876	9448		
10					13,675	11,065
15					83,794	56,732
16	1444	10,317	23,752	16,965		
20					90,632	60,592
24	8666	46,683	83,131	46,864		
25					97,470	63,938
28			96,007	52,198		
30					167,589	93,689
32	93,887	49,576				
35					174,426	96,194
36			106,883	56,441		
40	101,109	51,878	166,262	75,366	181,264	98,272
44			178,138	78,742		
45	108,332	53,873			251,383	117,744
Repair	36,111	17,507	59,379	29,918	41,026	22,964
Replacement	72,221	36,366	118,759	48,824	210,357	94,780

In Table 16, four factors of maintenance and repair are compared with; the initial investment cost and; repair cost; replacement cost. The results show that the initial cost for asphalt is demanded, whereas the repair and replacement cost of membrane waterproofing are higher than those in other methods.

Table 16. Analysis of maintenance cost.

System	Initial construction costs	Repair cost	Replacement cost	Cost for O&M	Total
Asphalt waterproofing	45,382	17,507	36,366	53,873	99,255
Membrane waterproofing	43,280	22,964	94,780	117,744	161,024
Sheet waterproofing	32,541	29,824	48,824	78,648	111,189

6.3. LCC Comparison Including $LCCO_2$

Regardless of its high initial capital cost, the asphalt waterproofing method is the most economic method for a lifetime of 45 years. In contrast, the total cost of sheet waterproofing is highest despite having the lowest initial investment. This implies that $LCCO_2$ can influence the total construction cost and should be considered for economic construction. In addition, $LCCO_2$ can greatly influence the total cost, depending on structure lifetime, despite the fact that $LCCO_2$ accounts for only a small part of LCC. This can be evidenced by the changed ratio of $LCCO_2$ as shown in Table 17. The asphalt waterproofing LCC ratio compared with the LCC of membrane system is increased by 1% when the CO_2 emission cost is considered while the LCC cost ratio of sheet system shows the three times increase.

Table 17. LCC ratio comparison.

	Asphalt	Membrane	Sheet
LCC	31,901.95	52,306.02	46,851.83
Ratio (%)	61	100	90
LCC + LCCO2	33,222.68	53,514.41	49,511.74
Ratio (%)	62	100	93

7. Conclusions

This study proposes LCC analysis for integrating the economic aspect with the environmental aspect by integrating the $LCCO_2$ of each waterproofing method into the LCC. The waterproofing methods selected for this research are sheet, asphalt, and membrane waterproofing. The costs for these three methods over their lifetimes are analyzed and LCC and $LCCO_2$ are calculated. The following conclusions are drawn about the major drivers of this research:

(1) In terms of initial capital cost, asphalt waterproofing has the highest CO_2 emission cost, followed by membrane and sheet waterproofing. However, LCC including $LCCO_2$ suggests that membrane waterproofing requires the highest cost, followed by sheet and asphalt waterproofing. In terms of initial capital cost, sheet waterproofing can be competitive, but it is expensive in the maintenance and repair stage. Asphalt waterproofing, however, has a high initial cost and low maintenance cost. Therefore, asphalt waterproofing can be the most economic method given that the $LCCO_2$ is considered in LCC.

(2) The LCC for each method including $LCCO_2$ has resulted in a valid economic perspective, i.e., although the initial cost for sheet waterproofing is the lowest, asphalt waterproofing is more economical based on LCC analysis.

(3) $LCCO_2$ is a relatively small portion of LCC, and at a glance, may have little influence on the construction and maintenance costs. However, the length of LCC or durability of a building increases the $LCCO_2$, and can accumulate into an amount that could have an economic impact on decision-making. Therefore, it can be concluded that $LCCO_2$ can be a vital factors in the process.

In this research, LCC analysis of roof waterproofing methods is proposed for a new building or refurbishment of existing buildings. The analysis framework can be adopted for different construction methods and structures. In addition, it can be considered for various industries and other construction

projects for decision-making in the initial planning and design stage. The research process implies that cost calculation in the initial and maintenance stages is reasonably reliable owing to the detailed CO_2 emission basic unit data in input-output tables. However, the data in the tables has limited use in the demolition stage. As a basic unit database for that stage is not available, historical data is used in this study. Therefore, further studies may have higher reliability and objectivity provided that the data relevant to the disposal and demolition stage can be used as basic unit data.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Project Management Institute (PMI). *Guide to the Project Management Body of Knowledge*; PMI: Newtown Square, PA, USA, 2004.
2. Khasreen, M.M.; Banfill, P.F.G.; Menzies, G.F. Life-cycle assessment and the environmental impact of buildings: A review. *Sustainability* **2009**, *1*, 674–701.
3. Lawrence, T.M.; Braun, J.E. Evaluation of simplified models for predicting CO_2 concentrations in small commercial buildings. *Build. Environ.* **2006**, *41*, 184–194.
4. Radhi, H. Evaluating the potential impact of global warming on the UAE residential buildings—a contribution to reduce the CO_2 emissions. *Build. Environ.* **2009**, *44*, 2451–2462.
5. Oh, S.K.; Bae, K.S.; Kim, Y.S. A study on the evaluation of composite coatings of cement and powder used as waste tire and glass. *Archit. Inst. Korea* **2004**, *20*, 47–52.
6. Kang, C.H.; Kim, Y.S. The current status and case studies on the waterproofing defects in the underground parking lot of apartment buildings. *Proc. Archit. Inst. Korea* **2001**, *21*, 503–506.
7. An, G.U.; Lee, J.Y. Defection analysis of the waterproof work for the quality control of construction site. *Archit. Inst. Korea* **2005**, *21*, 123–130.
8. Oh, S.K.; Kwak, K.S.; Choi, S.M.; Kwan, S.W. Improvement of selection system of waterproofing methods for concrete structure. *Korea Inst. Build. Constr.* **2007**, *7*, 99–106.
9. Dale, A.T.; Lucena, A.F.P.; Marriott, J.; Borba, B.S.M.C.; Schaeffer, R.; Bilec, M.M. Modeling future life-cycle greenhouse gas emissions and environmental impacts of electricity supplies in Brazil. *Energies* **2013**, *6*, 3182–3208.
10. Choi, O.Y.; Kim, T.; Kim, G. A study on selection of roof waterproofing method by analyzing life cycle costing. *Korea Inst. Build. Constr.* **2008**, *1*, 127–134.
11. Choi, S.M.; Oh, S.K.; Seo, C.H. A study on the selection of the waterproofing methods which VE/RWLCC analysis methodology in roof of structure. *Archit. Inst. Korea* **2009**, *25*, 161–168.
12. Wang, C.; Zhang, L.; Yang, S.; Pang, M. A hybrid life-cycle assessment of non-renewable energy and greenhouse-gas emissions of a village-level biomass gasification project in China. *Energies* **2012**, *5*, 2708–2723.
13. Promjiraprawat, K.; Limmeechokchai, B. Assessment of Thailand's energy policies and CO_2 emissions: Analyses of energy efficiency measures and renewable power generation. *Energies* **2012**, *5*, 925–937.

14. Kim, J.Y.; Lee, S.E.; Sohn, J.Y. An assessment of the energy consumption & CO_2 emission during the construction stage of apartments. *Archit*. *Inst*. *Korea* **2005**, *21*, 199–206.
15. Gao, L.; Winfield, Z.C. Life cycle assessment of environmental and economic impacts of advanced vehicles. *Energies* **2012**, *5*, 605–620.
16. Lee, B.Y.; Kim, B.R.; Kim, G.H. Comparison of construction costs of masonry wall types, including CO_2 emission costs. *Korea Inst*. *Build*. *Constr*. **2010**, *10*, 83–90.
17. KICT. Life cycle analysis annual report. Available online: http://www.kict.re.kr/ (accessed on 27 September 2013).
18. Jung, S.S.; Kim, D.W. A study on the development of cost breakdown structure in present worth method and annul worth method by HAVC system for systematic LCC calculation. *Archit*. *Inst*. *Korea* **2002**, *18*, 167–174.
19. Son, B.S.; Jang, M.H.; Lee, H.Y. A method of economic analysis for remodelling of apartments using the life cycle costing. *Archit*. *Inst*. *Korea* **2005**, *21*, 73–81.
20. Choi, M.S.; Kim, M.H. The variation characteristics of life cycle cost in a office building according to the discount rates and inflation rates. *Archit*. *Inst*. *Korea* **2006**, *22*, 131–137.