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A Study on the Analysis of CO_2 Emissions of Apartment Housing in the Construction Process

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Abstract: Recent research in the construction industry has focused on the reduction of CO_2 emission using quantitative assessment of building life. However, most of this research has focused on the operational stage of a building's life cycle. Few comprehensive studies of CO_2 emissions during building construction have been performed. The purpose of this study is to analyze the CO_2 emissions of an apartment housing during the construction process. The quantity of CO_2 emissions associated with the utilization of selected building materials and construction equipment were used to estimate the CO_2 emissions related to the apartment housing life cycle. In order to set the system boundary for the construction materials, equipment, and transportation used, 13 types of construction work were identified; then the CO_2 emissions produced by the identified materials were calculated for each type of construction work. The comprehensive results showed that construction work involving reinforced concrete accounted for more than 73% of the total CO_2 emissions. The CO_2 emissions related to reinforced concrete work was mainly due to transportation from the supplier to the construction site. Therefore, at the time that reinforced concrete is being supplied, shipping distance and fuel economy management of concrete transportation vehicles should be considered thoroughly for significant reduction of CO_2 emissions.

Keywords: apartment housing; construction process; CO_2 emissions

1. Introduction

Much effort has been made to improve environmental regulations in order to properly respond to climate change associated with global warming, both overseas and domestically throughout all industries. In order to prepare for climate change, the government has announced a voluntary reduction goal, called the Intended Nationally Determined Contributions (INDC) to reduce domestic greenhouse gases by 37%, compared to Business as Usual (BAU) [1]. Amid this, the construction industry, as a core industry, has caught the attention of many for its potential contribution to the achievement of this domestic greenhouse gas reduction goal. The construction industry is a large-scale consumption industry that is responsible for about 30–40% of the CO_2 emissions in all industries [2–4]. We are in a state where technology that can reduce CO_2 emissions is becoming a necessity. Technology that could achieve the CO_2 emissions reduction goal through a realistic CO_2 emissions reduction plan, over the entire life cycle of buildings, is needed. In order to reduce the amount of CO_2 emissions that are inevitable over the entire life cycle of buildings, the construction industry is evaluating this via quantitative investigation, and research on methods that could reduce or improve carbon emissions are actively underway [5]. In order to reduce the CO_2 emissions that are released over the life cycle of a building, the CO_2 emissions data must first be analyzed for each stage, and then a building's greenhouse gas evaluation must be performed considering its entire life cycle. However, more research is currently being performed on CO_2 emissions assessment at the operational stage, where more energy is used. In particular, there is very little research on CO_2 emission assessment of construction processes because data analysis is difficult due to the short construction period, and because data is difficult to secure [6,7].

This study focused on the construction stage for the reduction and management of CO_2 emissions of the apartment housing. The main purpose of this study is to suggest a CO_2 emission assessment method for the apartment housing construction process. Another purpose is to analyze the CO_2 emissions characteristics for each of the 13 main work types used during construction of the apartment buildings, using CO_2 emissions evaluation proposals of apartment housing construction projects, and construction records for actual construction sites.

In this study, apartment buildings construction sites were the subjects and the CO_2 emissions characteristics for construction materials and construction equipment were analyzed by the work types that occur in each stage. The following process was used to quantitatively assess the amount of CO_2 emissions from apartment housing construction, and reflects actual data [8,9].

First, the life cycle assessment was divided into three stages: transportation, construction, and disposal, to assess the CO_2 emissions from the construction site. The assessment subjects, which were construction materials and equipment, were the construction materials and equipment invested into each process.

Second, the amount of CO_2 emissions from the transportation stage was limited to the fuel consumption of the transportation vehicles required to transport necessary materials to the construction site. An estimation method was proposed for CO_2 emissions that considered the transportation distance, transportation vehicle type and average fuel efficiency, number of transportation vehicles, and load for each construction material.

Third, the amount of CO_2 emissions during the construction stage was the total fuel and electricity used by construction machines, transportation equipment, the field office, and other facilities that were used on site during construction. The amount of fuel and electricity used during the construction stage for machine equipment and electricity usage was calculated by analyzing data from standard construction estimates and data from the field office.

Fourth, the amount of CO_2 emissions during the disposal stage was estimated by first calculating the amount of construction waste that occurs by work type. This was done by reviewing the construction materials excess, then quantitatively calculating the amount of CO_2 emissions according to the method of handling construction waste, based on the statistical research report on the recycling of construction waste. With regard to the carbon emission coefficient in relation to the amount of construction materials used, and the amount of energy consumed in each stage, the emission factor of the Korea National life cycle inventory database (LCI DB) and the Korea National DB construction material environment information were applied. The flow of this study is shown in Figure 1.

An assessment method was created regarding the amount of energy used and the CO_2 emissions from construction materials and equipment in relation to 13 main types of construction work. This was done by dividing the construction process into three stages: transportation, construction, and disposal. A database was built for each stage, and the amount of CO_2 emissions was estimated using it. The 13 main work types during the apartment construction process were deduced, and an analysis of the CO_2 emissions characteristics of each stage was performed.

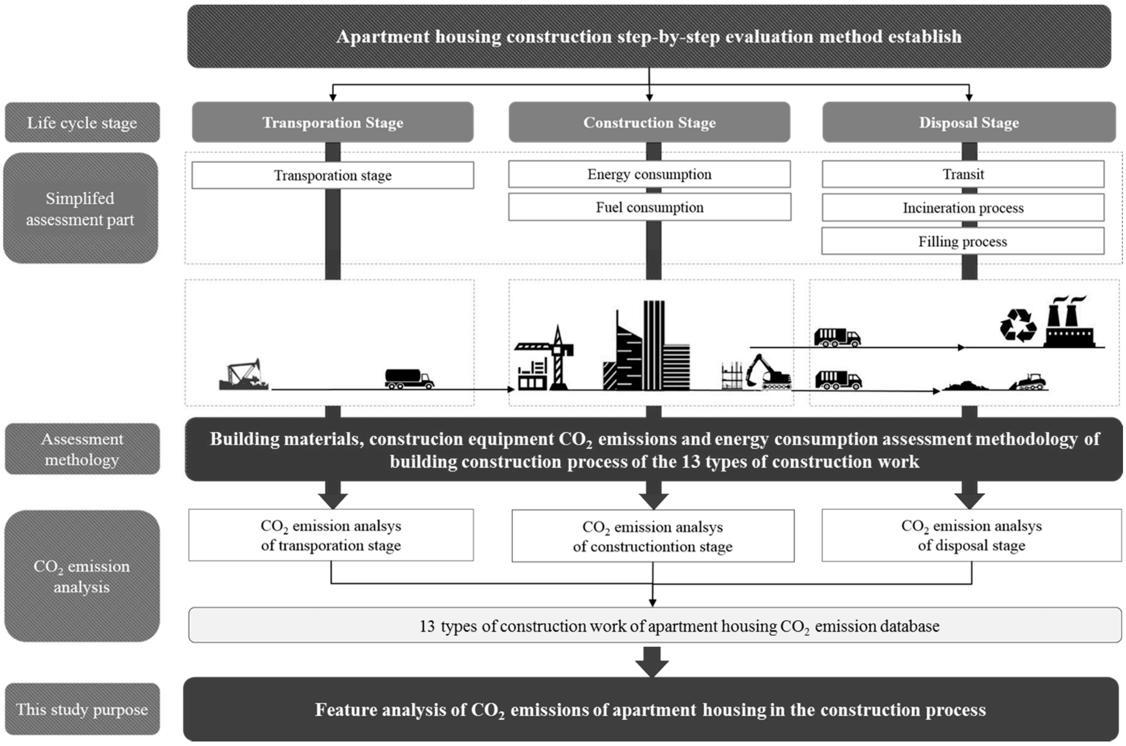

Figure 1. The conceptual flow chart of this study.

2. Literature Review

2.1. Theory of the Building LCA Assessment Method

Life cycle assessment (LCA) is a method that includes record of a list of invested materials and products related to the system life cycle of a product, and which allows examination of the potential environmental impacts related to these. For this study, when the list-analysis results and impact-assessment results were interpreted, research was actively performed according to the main methodology. This methodology has been used for environmental performance assessments of buildings from the 1990s to present day. Overseas LCA studies have proceeded as government-directed projects since 1970, and the majority of the research results on creating a LCI DB basic unit depending on the life cycle stage are already complete [10]. Research is also actively underway in Korea both nationally and publically, on a regular basis. Life cycle assessment is a tool that quantitatively lists the resources and energy that are used and the pollutants that are released during the product system's life cycle. It also systematically assesses their potential adverse effects on the environment. LCA is also used to derive measures to minimize and improve these adverse effects under the supervision of the Korea Ministry of Environment. It is applied to a product's eco-friendly design and other environmental claims, process improvements, and public policy establishment through the ISO 14040 series. LCA is divided into the four stages shown in Figure 2.

The definition of purpose and scope is the basic stage that sets the study's purpose and the system's boundary, which must be defined first in the life cycle assessment. Record analysis is the stage that quantifies the materials that are used and the products related to the product system. During this stage, data that describes all energy and by-product raw materials that are used and calculated, are collected and used in the calculations. Data are collected through a repetitive process, and new data demands and restrictions can be expected in order to achieve the purpose of the study by acquiring more information for each system boundary. Impact assessment uses the list-analysis results, and its purpose is to assess the importance of potential environmental impacts [11,12]. During impact assessment, listed data are generally linked to a specific environmental impact category, and category score, in order to understand their impacts and to provide information in the interpretation stage. An assessment range is set according to the LCA methodology of this type of series, and is generally created according to ISO 21930 as shown in Figure 3.

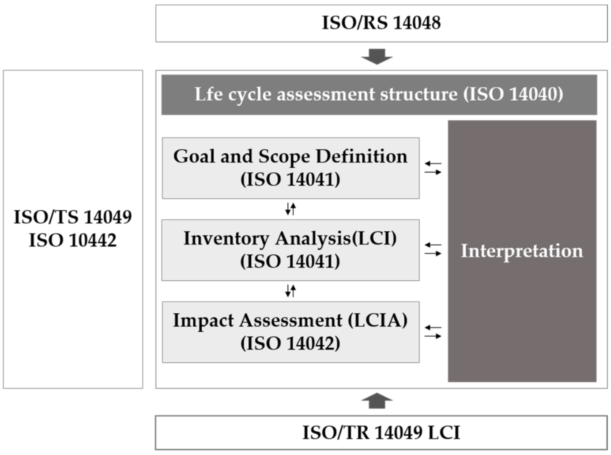

Figure 2. LCA's stages according to ISO 14040.

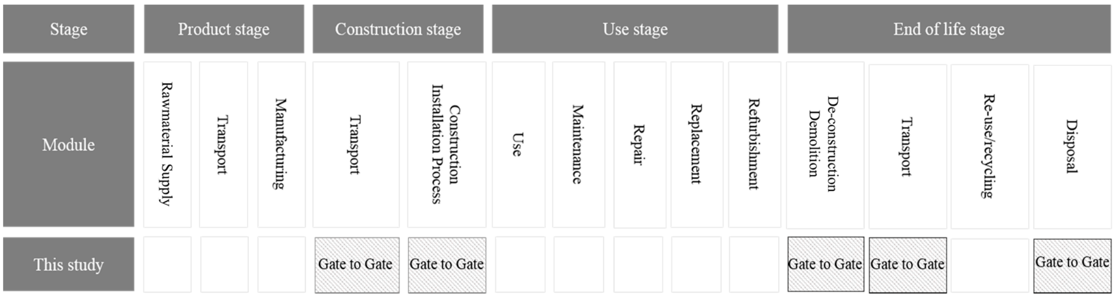

Figure 3. Life cycle stages for the building assessment in ISO 21930.

This study was set on gate-to-gate life cycle assessment, and an analysis was performed on CO_2 emission characteristics by dividing the construction process, from a building's life cycle assessment range, into transportation, construction, and demolition stages [13,14].

2.2. Research on the Construction Process

Preceding literature was reviewed regarding methods to estimate the amount of CO_2 emissions from construction equipment and materials used during the apartment construction process in Table 1. Kim et al. presented an estimation study on the amount of energy consumed and CO_2 released, for each work type during the apartment design stage. Chung et al. calculated the amount of energy consumed and CO_2 released in the building establishment stage and construction stage. After considering the results in preceding literature on the calculation methods for CO_2 emissions, it was found that most existing studies applied the LCA model based on input-output analysis [15,16]. The input-output analysis method enables easy abundant data calculation. It is an analysis method that describes the inter-industry relation table's connections in units of monetary value, and considers energy or resources according to the flow of monetary amounts and goods. However, because the LCA model based on input-output analysis calculates the amount of CO_2 emissions only by using information on the cost of products or services, its disadvantage is that it can only be used as an assessment outline. It is also limited as it does not consider system boundaries, fuel extraction, processing, production process, waste disposal, and other various factors regarding used materials that should be considered in the construction process. The key preceding research and literature on important factors that should be considered in the construction process, including environment, materials, equipment, transportation, and management were examined. However, there is very little research on CO_2 emission assessment of construction processes because data analysis is difficult due to the short construction period, and data is difficult to secure. Hadjimitsis et al. analyzed the amount of energy used with regard to concrete in the transportation stage, Jo et al. analyzed the weight of the construction work and managing work type component category conclusion [17,18], and Murat et al. suggested that recycling of ferrous and non-ferrous metals, cardboard, plastic and glass maximize the environmental and economic savings. Also, Roh et al. analyzed the CO_2 emission characteristics regarding concrete construction. After analyzing the previous research performed in Korea regarding construction processes, it was found that the research was focused only on analyzing some work types and on the amount of energy used in the construction process [19,20]. Moreover, limitations were seen in the amount of CO_2 emissions that occurred in the transportation of construction materials, construction process, and process of disposing of construction waste, all of which are involved in the construction process, and which were generally not being considered. Although the use of construction equipment and materials, transportation, energy use on site, and other matters were defined in detail, there were still parts that were excluded from consideration. Research on the basis of calculation used in actual CO_2 assessment was not being performed. Most research evaluated only a portion of construction work types, or was based on specific materials or equipment used at the construction site. As a result, research that includes construction materials, construction equipment, construction work types, transportation, construction process, construction waste disposal, and other factors should be conducted. This study looked into the construction process that was divided into transportation, construction, and demolition stages for a detailed assessment. Moreover, this work was focused on analyzing construction equipment, transportation equipment, and construction materials. In addition, an individual method using the Korea National LCI DB was used instead of using existing analyses of CO_2 emissions based on monetary values, to perform an analysis on CO_2 emissions characteristics for each work type during apartment construction. In prior studies regarding the assessment of CO_2 emissions during the construction process, CO_2 emission-impact factors were merely listed, or only extremely limited factors were applied to the building environmental impact assessment and analysis process [21,22].

Table 1. Review of existing literature.

Division	Summary	Analysis Target				Analysis Method
		Transit Equipment	Construction Equipment	Construct Work	Input Material	
Hadjimitsis, D.Gand et al.	Environmental Impact and Energy Consumption of Transport Pavements in Cyprus	■				Budget statement by district Industry-related analysis
Murat K et al.	Life Cycle Assessment and Optimization-Based Decision Analysis of Construction Waste Recycling for a LEED-Certified University Building sustainable				■	Quantity calculation sheet Industry-related analysis
Choi MS et al.	Calculate unit cost for building materials input by type of apartment building construction				■	Quantity calculation sheet Industry-related analysis
Kim JY et al.	Analysis of energy consumption for construction materials and calculation of CO_2 emissions				■	Quantity calculation sheet Industry-related analysis
Jeong YC et al.	A Study on the Appropriateness of the Application of the Input-Output Table according to the Calculation of CO_2 Emission Unit Value by Major Materials				■	Quantity calculation sheet Industry-related analysis
Kim DH et al.	A Study on the Estimation of Energy Consumption and Carbon Dioxide Emission of Building Materials Entered by Construction Type			■	■	Quantity calculation sheet Industry-related analysis
Kim KW et al.	Investigation and analysis of the influence factors of oil consumption on building equipment and materials during construction phase of apartment house		■		■	Industry-related analysis
Kim JW et al.	A Study on the Development of CO_2 Evaluation Method for Concrete Liquefied Transportation in the Construction Phase of Apartment Buildings	■				Industry-related analysis

■: Analysis target in the construction process.

3. Methodology

3.1. Overview

In this study, the construction process of the apartment housing was divided into transportation, construction, and disposal stage for the purpose of analyzing CO_2 emission characteristics of the apartment housing construction process in Figure 4.

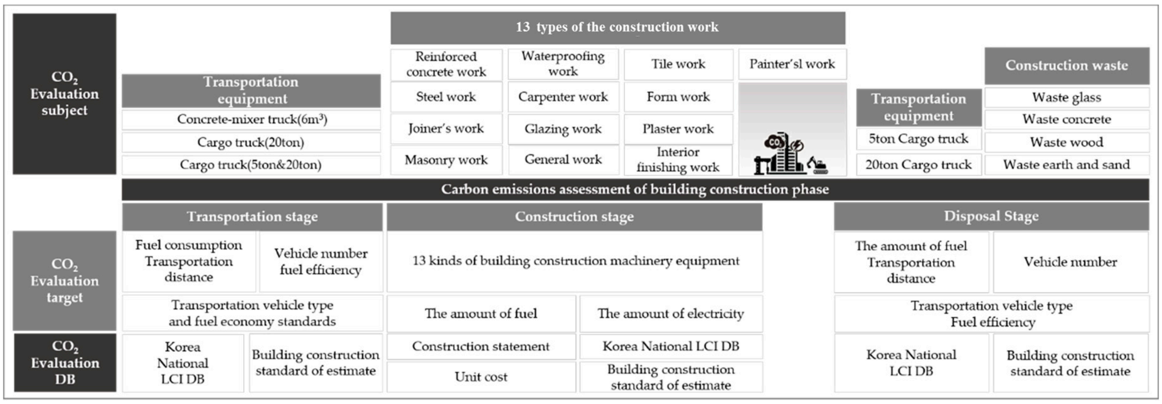

Figure 4. CO_2 emission assessment method proposed in construction process.

In order to estimate the amount of energy used in vehicles transporting materials to the apartment housing construction site, the amount of CO_2 emissions in the transportation stage was limited to the amount of fuel used by transportation vehicles when transporting materials from the supply location to the construction site. The distance for fuel consumption calculation was estimated based on scenario. Based on previous research, a CO_2 emissions-assessment method considering the distance, average fuel efficiency, number of transportation vehicles, and load (depending on the amount of construction materials used) was presented. The amount of CO_2 emissions during the construction stage was the total fuel and electricity used by construction machines and equipment, transportation equipment, the field office, and other facilities used for and during construction on site. The amount of fuel and electricity used during the construction stage for machine equipment and electricity usage was calculated by analyzing data from Korean standard construction estimates and from Korea breakdown cost tables. The amount of CO_2 emissions during the disposal stage was estimated by first calculating the amount of construction waste that occurred (by work type) based on surcharges on the construction materials, then quantitatively calculating the amount of CO_2 emissions according to the method of handling construction waste, based on a statistical research report on the recycling of construction waste. With regard to the CO_2 emission factor regarding the amount of construction materials used and the amount of energy consumed in each stage, the Korean National LCI DB and the Korean National DB of the construction-material environmental information was applied [23,24]. In the transportation stage, distance and fuel for transportation equipment for CO_2 evaluation were analyzed, and Korean standard product and national LCI DB were applied. In the construction phase, the construction specification, the national LCI DB, and the Korean Standard Specification were applied to analyze the amount of fuel and the amount of power applied to evaluate 13 construction types. In the disposal stage, the national LCI DB and the Korean Standard Package were applied to analyze the distance fuel for the waste transportation equipment.

3.2. Estimation Method in the Transportation Stage

The main factors that must be considered in order to estimate the amount of CO_2 emissions in the transportation stage are mainly the amount of construction materials used, and the equipment used for transportation [25]. Also, it considered the transportation distance and the vehicles used to load at the supply and construction sites. This data was used to estimate the amount of energy used, which was then converted to an estimate of the amount of CO_2 emissions. This calculation method includes use of the amount of materials at the construction site to deduce the number of transportation vehicles used, and fuel consumption was calculated by using the transportation distance and vehicle fuel efficiency. To do this, the distance to the construction site (from the supply sites), type of vehicle and standard fuel efficiency, and the number of vehicles used must be considered. Because the length of time that transportation vehicles used at a site is flexible, it is impossible to quantify work capacity that depends on the type of vehicle [26,27].

In this study, the loads of vehicles listed in standard construction estimates were investigated, along with the main transportation vehicles observed at the actual site, in order to calculate the number of transportation vehicles according to the supply output value of each construction material. The amount of fuel that was consumed during the transportation stage was calculated by multiplying the distance to the site by the average fuel efficiency of each vehicle. The assessment range of the transportation stage was limited to the fuel consumption for one-way transportation of construction materials by the types of vehicles used for each work type.

In this study, the transportation vehicles and transportation distance regarding the materials used were set as shown in Table 2, and the number of transportation vehicles was calculated according to the supply output value for each construction material. Equations (1) and (2) show the calculation formulas for fuel consumption and CO_2 emissions, respectively, during the transportation stage [28,29]. The transportation distance was set to 40 km as referenced from the guideline of Korea Ministry of Land, Infrastructure and Transport standard specification for construction [29].

$$DO_t = \sum\left(U_t \times \frac{k}{M_t}\right) \tag{1}$$

DO_t: Amount of Fuel Consumed in the Transportation Stage (ℓ)
U_t: Number of Vehicles Used (n)
k: Distance (km)
M_t: Transportation Vehicle Fuel Efficiency (km/L)

$$C_t = \sum(DO_t \times EF_t) \tag{2}$$

C_t: Amount of CO_2 Emissions in the Transportation Stage (kg-CO_2)
DO_t: Amount of Fuel Consumed in the Transportation Stage (L)
EF_t: Fuel Emission Factor (kg-CO_2/L)

Table 2. Construction equipment calculated in accordance with the input material.

Input Materials	Transportation Vehicle	Transportation Distance
Concrete	Concrete-mixer truck (6 m^3)	40 km
Steel	Cargo truck (20 ton)	40 km
Subsidiary material	Cargo truck (5 ton and 20 ton)	40 km

3.3. Estimation Method in the Construction Stage

In order to estimate the amount of CO_2 emission in the construction stage, this study created categories of fuel consumption and electricity consumption amounts, and calculated the total amount of fuel and electricity used for construction machines and equipment, transportation equipment, field office, and other facilities at the construction site, used for constructing buildings. For the amount of fuel consumed, the number of days and time that equipment was used, according to each work type, was calculated by analyzing the equipment usage conditions from the construction report. The fuel efficiency for each kind of equipment was based on the operating expenses estimated in the standard construction estimate. Electricity consumption was calculated by obtaining the monthly electricity usage statement for the entire construction period, and calculating the electricity consumption according to the duration of each work type based on the progress schedule. If multiple work types proceeded simultaneously, according to the characteristics of the construction process, the relevant electricity consumption was divided up between the number of construction days for the overlapping work types. In this study, for construction processes in which the construction method (including construction conditions by site) and equipment usage differed, data regarding construction machines and equipment, and transportation equipment used at the actual construction site were obtained from the supply output lists from the actual construction site, and from construction reports. Data regarding the amount of fuel used were analyzed. Data were also analyzed regarding electricity consumption from the actual field office. The calculation formula for the amount of CO_2 emissions according to fuel and electricity consumption during the construction stage is shown in Equations (3) and (4), respectively [30].

$$C_{co} = \sum(M_c \times T_c \times EF_c \times U_c) \tag{3}$$

C_{co}: Amount of Fuel CO_2 Emissions in the Construction Stage
M_c: Fuel Efficiency (L/h)
T_c: Time (h)
EF_c: Fuel Emissions Factor (kg-CO_2/L)
U_c: Work Equipment Qty. (n)

$$C_{ce} = \sum(I_c \times EF_c) \tag{4}$$

C_{ce}: Amount of Electricity CO_2 Emissions in the Construction Stage
I_c: Electricity Usage Amount (kwh)
EF_c: Electricity Emissions Factor (kg-CO_2/kwh)

3.4. Estimation Method in the Disposal Stage

In order to estimate the amount of CO_2 emissions in the disposal stage, the amount of construction waste that occurs for each work type was estimated, and the amount of CO_2 emissions, according to the processing method of each construction waste, was calculated. In order to estimate the amount of construction waste that occurs by work type, the waste generation estimation method based on surcharge was used. In this study, the premium rate was applied as a means to predict waste at the construction site, and the surcharge value that was presented in the standard construction estimate issued in 2012 (by the Korea Institution of Construction Technology and the Ministry of Land). Construction waste was divided into construction demolition waste, combustible waste, and nonflammable waste according to the method of handling construction waste, which are handled through intermediate processing agencies, incinerators, and landfills, respectively. When calculating data regarding intermediate processing agencies, because data differs from different companies, the incineration and landfill rate referred to the present processing conditions of waste for each construction material according to the Korea Waste Statistical Yearbook in 2012. The surcharges, weight conversion factor, landfill, and incineration emissions factor were considered for each construction material according to the amount used, in order to estimate the amount of CO_2 emissions that occur in the incineration and landfill process Equation (5). The amount of energy consumed during the construction waste transportation process was calculated using Equations (6) and (7), based on the amount of fuel consumed in the vehicles that transport the waste to landfills and incinerators.

The estimation method for the amount of CO_2 emissions in the construction waste transportation stage was identical to that of the construction process above, and it was set as the amount of energy consumed by transportation equipment according to waste volume. In order to do this, the amount of construction equipment, standard fuel efficiency, and the distance to landfills and incinerators were applied to calculate the amount of fuel used during transportation. The assessment scope of the waste transportation process was limited to the amount of fuel consumed by vehicles providing one-way transportation of construction waste [31,32].

$$C_{dl} = \sum(DM_d \times EF_{dl} \times L_d) \tag{5}$$

C_{dl}: Amount of CO_2 Emissions in Landfill Process of the Demolition Stage (kg-CO_2)
DM_d: Construction Waste Volume (kg)
L_d: Landfill Rate (%)
EF_{dl}: Landfill Emissions Factor (kg-CO_2/kg)

$$C_{di} = \sum(DM_d \times EF_{di} \times I_d) \tag{6}$$

C_{di}: Amount of CO_2 Emissions in Incineration Process of the Demolition Stage (kg-CO_2)
DM_d: Construction Waste Volume (kg)
I_d: Incineration Rate (%)
EF_{di}: Incineration Emissions Factor (kg-CO_2/kg)

$$DO_d = \sum\left(U_d \times \frac{k}{M_d}\right) \tag{7}$$

DO_d: Amount of Fuel Consumed in the Construction Waste Transportation Stage (L)
U_d: Number of Vehicles Used (n)
k: Distance (km)
M_d: Transportation Vehicle Fuel Efficiency (km/L)

$$C_d = \sum(TO_d \times EF_d) \tag{8}$$

C_d: Amount of CO_2 Emissions in the Construction Waste Transportation Stage (kg-CO_2)
TO_d: Amount of Fuel Consumed by Transportation Equipment (L)
EF_d: Fuel Emissions Factor (kg-CO_2/L)

4. Results

4.1. Overview

The architectural overview of the evaluation subject is summarized in Table 3. In order to analyze the CO_2 emission characteristics during the apartment housing construction process, 1004 household, reinforced concrete apartment houses (combined area of 208,393 m^2) were selected in Seoul, Korea.

Table 3. Architectural Overview.

Description	Contents	Description	Contents
Business name	Seoul M Urban Development Project	Structural system	Reinforced concrete, bearing wall structure
Local district	Semi-residential area	Building type	Flat-type and tower-type Apartment
Architectural drawing	Apartment house	Household number	1004 Household
Building scale	16 stories above ground/2 stories below ground	Land area	5,633,600 m^2
Number of buildings	13 buildings	Total floor area	20,839,380 m^2

This study targeted the 13 types of construction work such as, Reinforced concrete works, Steel works, Carpenters works, Waterproofing works, Tile works, Glass works Painter's works, Form works, Plaster works, Interior finishing works, General works, Joiner's works and Masonry works. Then, the CO_2 emissions characteristics for each work type and the main material-types were deduced. In order to compare analysis results, the emission amount was calculated by dividing it by the total area.

4.2. Analysis of CO_2 Emission Characteristics by Work Type

4.2.1. Transportation Stage

In order to deduce the amount of fuel consumed by each work type in the transportation stage, the amount of CO_2 emissions in the transportation stage was estimated by considering fuel efficiency regarding the number of vehicles used, transportation distance, and each kind of equipment. The transportation equipment count, according to the load sizes of equipment that transported materials to the construction site, was analyzed as shown in Table 4. The results showed that most of the material was reinforced concrete in the case of 20-ton trucks and 6 m^3 concrete-mixer trucks. For 5-ton trucks, most of the material was for tile work. The total amount of CO_2 emissions from the transportation stage analysis results was 5.46 kg-CO_2/m^2 in as shown Figure 5. The amount of CO_2 emissions from reinforced concreted work accounted for 89% of all work types, which was analyzed to display most of the CO_2 emission characteristics. The analysis results for the CO_2 emission characteristics of other kinds of construction, were analyzed in the order waterproof construction, tile work, and plastering; and the amount of CO_2 emissions for each construction type was 0.08 kg-CO_2/m^2, 0.07 kg-CO_2/m^2, and 0.06 kg-CO_2/m^2, respectively. After analyzing 34,500 transportation vehicles used at the construction site for each work type, the amount of CO_2 emissions from the 30,422 concrete transportation vehicles used for the reinforced concrete work accounted for around 75% of the amount of CO_2 emissions for the entire transportation stage. Therefore, it was found that the load distance between the construction site and the concrete manufacturer (when concrete is collected for reinforced concrete work), and the fuel efficiency of concrete transportation vehicles must be managed in order to reduce the amount of CO_2 emissions in the construction process.

4.2.2. Construction Stage

In the construction stage, the amount of CO_2 emissions can be analyzed using the amount of fuel and electricity consumed for each work type. In order to do this, equipment that was used at the actual construction site was categorized as shown in the construction stage data in Table 4, and the number of construction equipment work types that were used was analyzed in detail. Results showed that most of the equipment was used on reinforced concrete work, and that the 50-ton mobile crane was used in more work types than was other equipment. Electricity consumption was estimated by multiplying the emissions factor by the amount of electricity used in the field office, and the resulting value was estimated by considering the total area and the total value of the calculated fuel consumption and electricity consumption. After analyzing the construction process, the amount of fuel consumed was found to be 0.32 kg-CO_2/m^2, the amount of electricity consumed was 2.97 kg-CO_2/m^2, and the total amount of carbon emissions in the construction stage was 3.29 kg-CO_2/m^2 as shown in Figure 6. After analyzing the reinforced concrete work from the construction stage; fuel and electricity consumption accounted for around 31% of all work types. Among other work types, waterproof construction took up 9%, and plastering took up 8%. With regard to the amount of CO_2 emissions in the construction stage, high CO_2 emission characteristics were expected according to the construction method and equipment that was used at the actual site, but the amount of emissions was relatively low compared to the preceding transportation stage.

Table 4. Input breakdown by work type in the apartment housing construction.

Stage	Emission Factor	Category			Input Breakdown by Work Type												
		Machine Equipment	**Equipment Specification**	**Unit**	**Form Work**	**Rein-Forced Concrete Work**	**Steel Work**	**Masonry Work**	**Water Proofing Work**	**Painter's Work**	**Tile Work**	**Masonry Mason's Work**	**Joiner's Work**	**Glazing Work**	**Carpenter Work**	**Interior Finishing Work**	**Finishing's Work**
Transportation stage	Oil	Cargo truck	5 ton	N	-	8	4	2	-	-	296	-	14	21	-	126	59
			20 ton	N	41	1618	-	578	474	368	237	96	-	-	219	-	-
		Mixer truck	6 m^3	N	-	30,422	-	-	-	14	-	-	-	-	-	-	-
Construction stage	Oil	Backhoe	0.6 m	N	15	2	-	-	-	-	-	-	-	-	-	-	-
			0.8 m	N	12	-	-	-	-	-	-	-	-	-	-	-	-
			1.8 m	N	3	-	-	-	-	-	-	-	-	-	-	-	-
		Pump car	36 m	N	-	221	-	-	-	-	-	-	-	-	-	-	-
			52 m	N	-	9	-	-	-	-	-	-	-	-	-	-	-
		Mobile crane	100 ton	N	-	18	-	-	-	-	-	-	-	-	-	-	-
			50 ton	N	-	62	-	2	-	1	1	3	2	1	-	1	-
		Dozer	6 P	N	2	-	-	-	-	-	-	-	-	-	-	-	-
	Electricity	Site electric power consumption		kwh	46,725	190,965	11,642	26,410	40,630	54,851	52,820	32,504	32,504	24,378	28,441	46,725	42,662
Disposal stage	Oil	Cargo truck	20 ton	N	-	286	1	29	24	20	13	5	-	-	11	-	-
	Landfill waste	Construction wastes		kg	-	1228	-	2370	-	180	-	-	-	-	-	-	-
		Combustible wastes		kg	-	4123	-	876	-	7071	-	-	-	-	-	-	5982
		Incombustible wastes		kg	-	-	-	-	-	-	13,334	-	-	208	-	14,439	-
	Incineration waste	Construction wastes		kg	-	-	-	-	-	-	-	-	-	-	-	-	-
		Combustible wastes		kg	-	-	1176	-	-	-	-	-	-	-	-	2815	-
		Incombustible wastes		kg	-	-	-	-	-	-	-	-	-	-	-	199	-

4.2.3. Disposal Stage

For transporting construction waste, the vehicle loads for the amount of construction waste involved in each work type was considered in Table 4 and the vehicle loads were analyzed. After analyzing the input breakdown by work type, it was found that reinforced concrete work accounted for a large proportion. For the landfill and incineration processes, the detailed amounts involved in construction waste for each work type were analyzed in Table 4. The landfill-incineration emissions factor regarding construction waste, and data regarding the landfill-incineration rate, were analyzed by referencing a statistical survey report on construction waste recycling, and the Korea statistical yearbook for waste from the Korea Ministry of Environment. After analyzing the demolition stage of this study, the total amount of CO_2 emissions was found to be 0.076 kg-CO_2/m^2 as shown in Figure 7, which was the lowest figure among the three stages. Moreover, because waste from rebar, concrete, and related products are abundant during work with reinforced concrete, it was found that higher amounts of CO_2 emissions resulted from work with reinforced concrete than from other work types. Because the amount of CO_2 emissions from the landfill process was 98%, it accounted for the majority of the demolition stage emissions, and analysis showed that the amount of CO_2 emissions from waste produced from plaster boards took up a high proportion among the other construction wastes in the landfill process.

4.3. Comprehensive Analysis

An analysis of the CO_2 emission characteristics for each stage of the apartment construction process by work type is shown in Table 5. The total CO_2 emission characteristics by each stage in the construction process are shown in Figures 5–8.

Table 5. CO_2 emission by work type analysis in the apartment housing construction.

(Unit: kg-CO_2/m^2)				
Stage Classification	**Transportation Stage**	**Construction Stage**	**Disposal Stage**	**Total**
Form work	0.001	0.258	0.000	0.259
Reinforced concrete work	5.053	1.198	0.043	6.294
Steel work	0.003	0.001	0.001	0.005
Masonry work	0.125	0.127	0.006	0.258
Water proofing work	0.077	0.195	0.005	0.277
Plaster work	0.061	0.264	0.004	0.329
Tile work	0.070	0.253	0.006	0.329
Masonry mason's work	0.016	0.157	0.001	0.174
Joiner's work	0.001	0.156	0.000	0.157
Glazing work	0.002	0.119	0.001	0.122
Carpenter work	0.036	0.138	0.007	0.181
Interior finishing work	0.013	0.225	0.001	0.239
Painter's work	0.006	0.205	0.003	0.214
Total	5.463	3.295	0.078	8.838

An assessment of each stage of the construction process showed that reinforced concrete work was the work type with the highest proportion of CO_2 emissions, and after analyzing the total CO_2 emissions characteristics of the entire construction process, most of the CO_2 emissions of reinforced concrete work stemmed from the transportation stage. An assessment of the amount of CO_2 emissions in the construction process by each stage showed that the total emissions from reinforced concrete work was 8.83 kg-CO_2/m^2, which was around 73% of the entire amount of CO_2 emissions. Of this, 89% was from the transportation stage, and the total proportion of CO_2 emissions during the construction stage was about 36%. Also, the construction waste transportation proportion was around 57% in reinforced concrete work at the disposal stage, and although the amount of CO_2 emissions from all work types was small, an analysis showed that CO_2 emissions were abundant during the process of incinerating wallpaper and other materials used in wood work and other interior finishing work. The amount of CO_2 emissions released from plaster boards and insulation materials in the landfill process was abundant in the order reinforced concrete work, wood work, masonry work, and tile work. By analyzing CO_2 characteristics from the apartment housing construction process, we believe that activities to reduce CO_2 emissions must begin by managing the load distance between the construction site and concrete manufacturer when collecting concrete for reinforced concrete work, and by managing the fuel efficiency of concrete transportation vehicles. It is expected that the assessment process of CO_2 emission during the construction phase based on the apartment housing evaluation done in this research would be applicable in other studies in South Korea as well as other countries. However, the regional applicability range could be comparatively limited as the established data base of the research is based on the actual data of multi-unit dwellings that are built in South Korea.

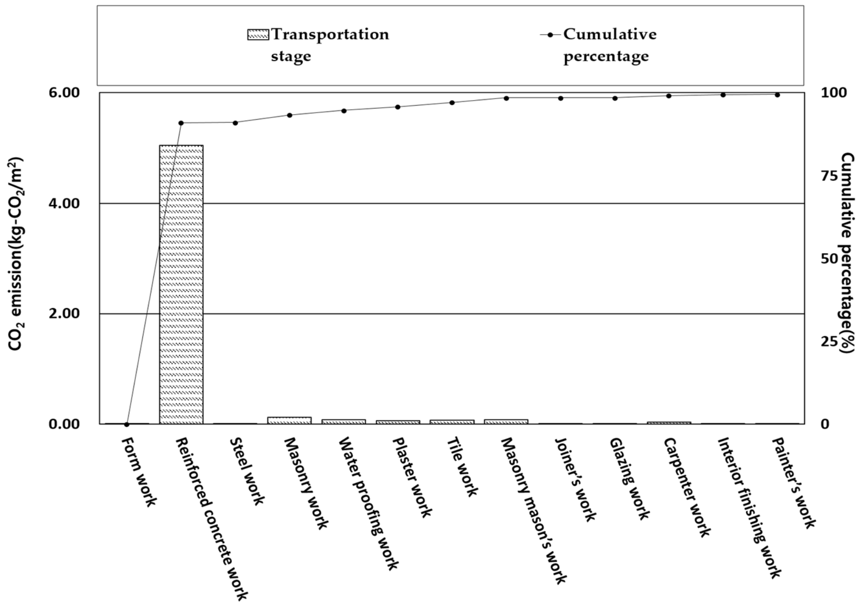

Figure 5. Work type CO_2 emission in transportation stage.

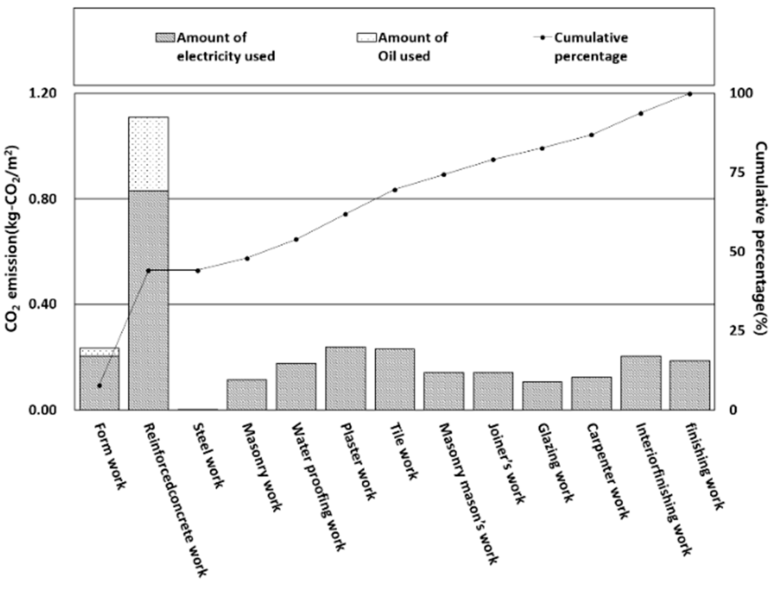

Figure 6. Work type CO_2 emission in construction stage.

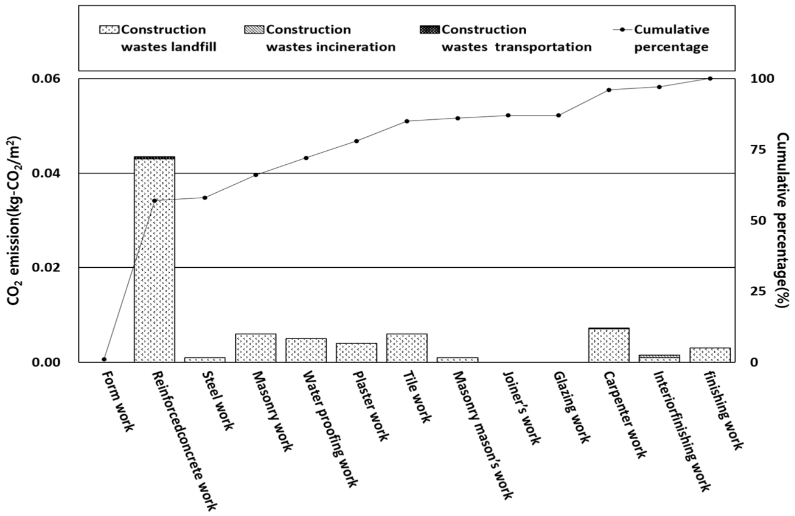

Figure 7. Work type CO_2 emission in disposal stage.

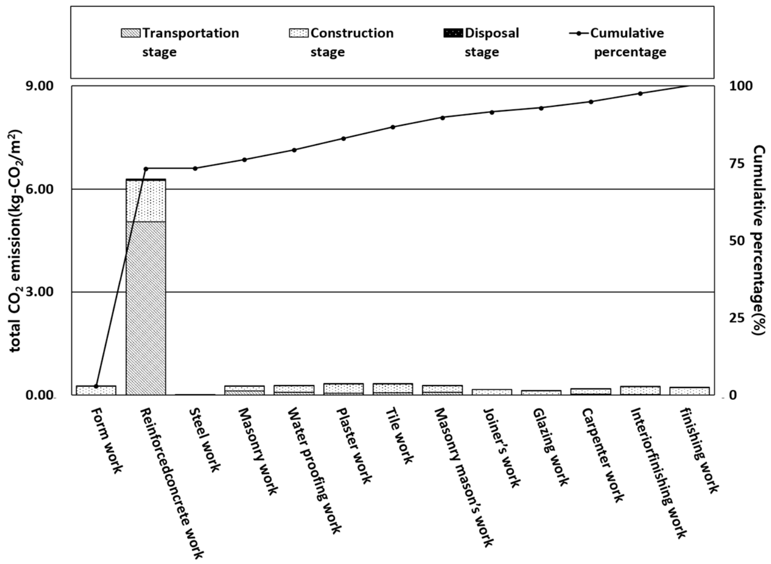

Figure 8. Work type CO_2 emission in construction process.

5. Conclusions

This is part of a study for the reduction and management of CO_2 emissions from construction processes during the entire life cycle of buildings. The purposes of this study was to suggest a CO_2 emissions assessment method for each stage of the apartment housing construction process, and to analyze CO_2 emissions characteristics by stage for each of the 13 types of the construction work using construction records from actual work sites. From these, the following conclusions were obtained.

1. In order to analyze the total amount of CO_2 emissions for each work type of the apartment housing construction process, this study obtained the establishment breakdown and construction records of actual apartment houses, construction records, and other construction books from which to analyze CO_2 emission characteristics.
2. System boundaries were established in order to analyze the CO_2 emission characteristics of the apartment construction process. In order to do this, the construction process was divided into transportation, construction, and disposal stages, and the amount of CO_2 emissions was assessed using the assessment method presented in this study.

3. After analyzing construction CO_2 emissions by stage for apartment construction, the total amount of CO_2 emissions was estimated to be 8.83 kg-CO_2/m^2. The amount of CO_2 emissions from the transportation stage, construction stage, and disposal stage, was 5.46 kg-CO_2/m^2, 3.29 kg-CO_2/m^2, and 0.07 kg-CO_2/m^2 respectively.
4. The proportion of total CO_2 emissions of reinforced concrete work was about 73% of the total amount of CO_2 emissions from the apartment construction process, which is an overwhelming proportion. The amount of CO_2 emissions from reinforced concrete work was found to be mainly from the transportation stage.
5. From this, we deduced that the load distance between the construction site and the concrete manufacturer (when collecting concrete for reinforced concrete work), and the fuel efficiency of concrete transportation vehicles, must be managed to significantly reduce the amount of CO_2 emissions resulting from construction.
6. We believe that in order to reduce the amount of carbon emissions in the construction stage in the future, priority should be given to reducing the concrete load distance in reinforced concrete work, which produces the most CO_2 emissions, and to considering the use of high-efficiency heavy transportation equipment.

As a result of analyzing CO_2 emission characterized by construction type, it was found that in the case of reinforced concrete construction, which has the highest CO_2 ratio, the amount of emission was higher in the transportation phase than in the construction phase. This proved that the assumption that transportation distance greatly contributes in CO_2 emission during the construction work. Therefore, when the work of reinforced concrete construction is supplied and received, it is analyzed that management of fuel mileage is necessary for CO_2 emission reduction due to construction work.

In order to reduce carbon emissions during the construction process, it is considered that priority should be given to the reduction of the shipment distance of concrete and the use of high-efficiency transportation equipment in the reinforced concrete construction with the greatest CO_2 emission.

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