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CO_2 Emissions and Cost by Floor Types of Public Apartment Houses in South Korea

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Abstract: In each country in the world, there is a strong need for all industries to reduce CO_2 emissions for sustainable development as a preparation for climatic change. The biggest issue in many developed countries, including the United States, is to reduce CO_2 emissions for the upcoming implementation of Carbon Emissions Trading. The construction industry, in particular, which accounts for up about 30% of CO_2 emissions, will need studies on the amount of CO_2 emissions. The purpose of this study is to present the most environmentally friendly and economical apartment house plan types according to the increasing number of layers by evaluating the amount of CO_2 emissions and economic efficiency. The results indicated that flat and Y-shaped types are more eco-friendly and economical in lower levels of less than 20 stories. However, the L-shaped type is more highly eco-friendly and economically efficient in higher levels of more than 20 stories. The results of this paper would help to make a decision on the building types and the number of stories in the early stages of construction.

Keywords: apartment house; type of housing; CO_2 emission; cost

1. Introduction

Internationally, greenhouse gases (GHGs) are arguably the most prevalent environmental problem. According to the International Energy Agency (IEA), buildings account for almost 30% of GHG emissions. Accordingly, extensive effort has been focused on reducing GHG emissions in the building industry over the last few decades. In addition, the reduction of GHGs and the execution of carbon emissions trading schemes have become some of the most important issues in the world. As a result, many nations have announced their goals for the long-term reduction of CO_2 emissions generated in a variety of industries. To comply with this international trend and to achieve sustainable development, Korea has also established a business-as-usual (BAU) GHG emission reduction target of 37% (851 million tons) by 2030 [1]. The construction industry consumes extensive energy, accounting for 30% to 40% of the CO_2 emissions generated by all industries. Accordingly, it plays a critical role in the reduction of CO_2 emissions in all countries, thus requiring practical reduction measures. As of 2010, 13,883,571 units of public apartment houses have been constructed in Korea, which accounts for 59% of the total number of houses in Korea. The amount of GHG emissions by energy use is 570.70 million metric tons of CO_2 equivalent, which accounts for 85.3% of the total GHG emissions in Korea [2,3]. To proactively cope with the Convention on Climate Change and to achieve sustainable development, CO_2 emissions of public apartment houses have been evaluated extensively. In Korea, flat-type public apartment houses, which provide suitable ventilation and air flow, were frequently constructed prior to the 2000s; recently, tower-type public apartment houses have primarily been constructed to maximize views and land use efficiency [4]. As such, different types of public apartment houses with various numbers of floors have been constructed. However, despite their construction, the CO_2 emissions and costs have not been evaluated based on variations in the amount of material according to the number of floors and type of apartment [5,6]. Studies evaluating the energy performance and CO_2 emissions of public apartment houses have been steadily conducted. Lee *et al.* [7] analyzed the energy performance of tower Y-type apartment houses. In addition, Noh [8] analyzed cooling and heating energy according to types of apartment houses. However, existing studies are limited because they performed analyses using only the reference floor, without applying real data from construction structures or considering variations in the amount of material according to the number of floors. Therefore, this study analyzed the type and number of floors of apartment houses that have been constructed in Korea and calculated the amounts of primary materials.

More specifically, architectural floor plans and structural plans of 100 public apartment houses built in Korea in the last five years were analyzed. Based on the results, public apartments were categorized as flat, tower Y, and tower L types as shown Figure 1, and two buildings of each type for 15, 20, 25, and 30 floors were selected as representative models. In addition, the amounts of expensive construction materials that can influence CO_2 emissions, such as concretes, reinforcement bars, and forms, were calculated according to the number of floors in public apartment houses. Thus, this study aims to recommend the most eco-friendly and economical types of apartment houses, considering the number of floors, by analyzing CO_2 emissions and costs for the calculated material amounts [9,10].

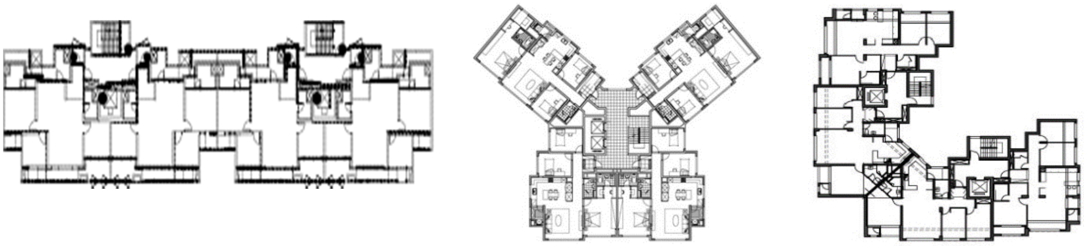


Figure 1. Floor types of apartment houses.

2. Literature Review

Oha *et al.* [11] proposed an optimum design model to analyze the relationship. A concrete-filled steel tube (CFT) column is one of the composite columns frequently used in building construction because of its structural performance, economic feasibility, and good space utilization; it has a high potential to reduce CO_2 emissions because, due to the combining of two heterogeneous materials, the relationship among CO_2 emissions, cost, and structural parameters in the green construction of buildings with CFT columns was not yet carried out. Boqiang *et al.* [12] provided an assessment of the potential of CO_2 mitigation in buildings by conducting empirical research on the determinants of building energy-related CO_2 emissions.

To build a calculation model for CO_2 emissions in the materialization stage of office buildings, Zhixing *et al.* [13] considered the CO_2 emissions generated from the production and transportation of construction materials and equipment, as well as the CO_2 emissions generated from the construction process. Guomin *et al.* [14] developed a model to estimate and compare emissions at foundation construction and demonstrate its application using two case studies. Foundation construction involves heavy machine usage which contributes to greenhouse gas (GHG) and non-GHG emissions. Chau *et al.* [15] applied the Monte Carlo method to generate probabilistic distributions for describing the CO_2 footprint of the superstructure of a high-rise concrete office building. The distribution profile was constructed with the material use data collected from 13 high-rise office concrete buildings in Hong Kong. Jingke *et al.* [16] analyzed GHG emissions during the construction phase of a case study building on the basis of an extended system boundary in the context of China by utilizing detailed onsite process data.

3. Evaluation Scope and Building Setup

One hundred architectural drawings and floor plans used in actual developments by companies in Korea were analyzed and categorized into flat, tower Y, and tower L types, as listed in Figure 1. For each type, two buildings were selected for 15, 20, 25, and 30 floors. As listed in Table 1, buildings with the same construction conditions were selected: an internal area of 84 m^2, four households on a floor, three bays, and a floor height of 2.8 m.

The evaluation buildings were chosen from three locations, namely Seoul, Chungcheongnam-do, and Ulsan, to reduce the variations in building material amount due to land conditions [17,18].

Table 1. Overview of evaluation building.

No.	Type	No. of Floors	Internal Area (m^2)	No. of Households on a Floor	Bay	Floor Height (m)	Location
1	Flat	15	84	4	3	2.8	Chung-nam
2		15	84	4	3	2.8	Chung-nam
3		20	84	4	3	2.8	Chung-nam
4		20	84	4	3	2.8	Chung-nam
5		25	84	4	3	2.8	Ulsan
6		25	84	4	3	2.8	Ulsan
7		30	84	4	3	2.8	Ulsan
8		30	84	4	3	2.8	Ulsan
9	Tower Y	15	84	4	3	2.8	Chung-nam
10		20	84	4	3	2.8	Chung-nam
11		20	84	4	3	2.8	Chung-nam
12		25	84	4	3	2.8	Chung-nam
13		25	84	4	3	2.8	Chung-nam
14		30	84	4	3	2.8	Chung-nam
15		30	84	4	3	2.8	Chung-nam
16	Tower L	15	84	4	3	2.8	Seoul
17		15	84	4	3	2.8	Seoul
18		20	84	4	3	2.8	Chung-nam
19		20	84	4	3	2.8	Chung-nam
20		25	84	4	3	2.8	Chung-nam
21		25	84	4	3	2.8	Chung-nam

Note: No. = Number.

4. Calculation of Material Amounts in Evaluation Buildings

4.1. Basis for Calculating Material Amounts

This study calculated the amounts of concrete, reinforcement bars, and forms by using the following equations. In a 2D drawing-based manual quantity estimation method, calculation procedures can vary, causing differences in results. In this study, therefore, the following were referred to: Reinforced Concrete Structure Estimation Standards, Korea Building Code (KBC); Korea Structural Concrete Design Code; Korean Construction Standard Specification (2013); and Construction Work Quantity Estimation (2007) [19–22].

First, for the manual quantity estimation for walls, wall thickness is multiplied by wall area (area of openings not included) in the column-beam wall. In the column-less walls, wall thickness is multiplied by wall height (floor height minus baseplate height) and the same number of walls as shown in Figure 2a.

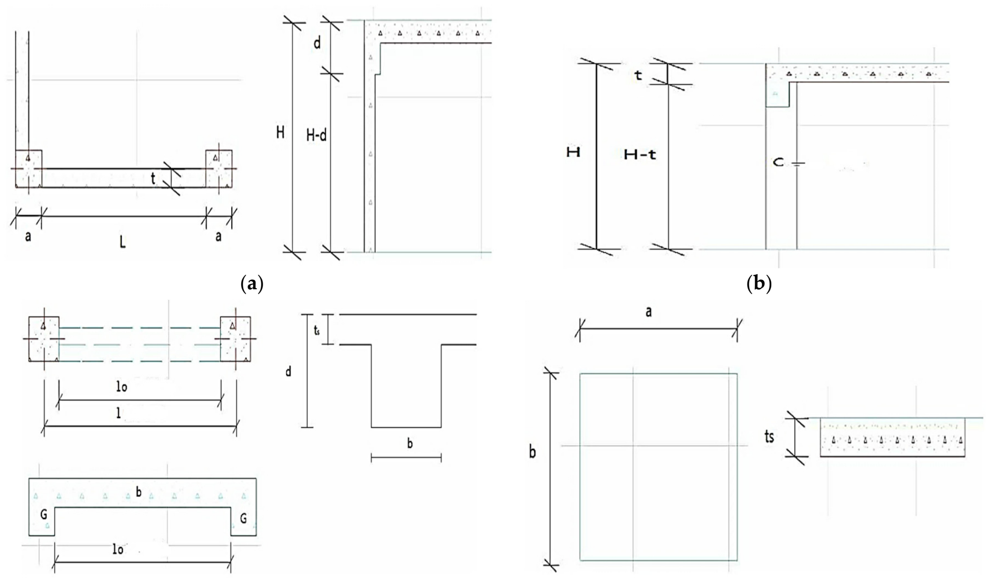


Figure 2. The standard of quantity estimation: (**a**) The standard of quantity estimation for the wall; (**b**) The standard of quantity estimation for the column; (**c**) The standard of quantity estimation for the beam; (**d**) The standard of quantity estimation for the slab.

At the form estimation, the column-wall combined parts are not subtracted. In addition, the openings (less than 1 m^2) in the wall are not subtracted from the form area, considering the materials that are present. They are subtracted from the form only when they are 1 m^2 or greater. The wall quantity estimation formulas are shown in Table 2.

Table 2. Calculation formula for the wall.

Division	Estimation Formula
concrete	$L \times t \times (H - d)$
form	$L \times 2 \times (H - d)$

Second, a column volume is calculated by multiplying a section area by column height and number of the columns with the same dimensions as shown in Figure 2b. In the column height, however, the thickness between the upper-floor baseplate and target-floor baseplate is subtracted.

For the estimation of the quantity of slab-less columns, the section area is multiplied by the column height. The column quantity estimation formulas are stated in Table 3.

Table 3. Calculation formula for the column.

Division	Estimation Formula
concrete	$a \times b \times (H - t)$
form	$2(a + b) \times (H - t)$

Third, beam height is subtracted from the baseplate thickness and multiplied by beam width. Then, the results are multiplied by beam length. After that, they are multiplied by the number of beams with the same dimensions as shown in Figure 2c. In this case, a large beam is set with inside distance among between the columns while a small beam is determined with inside length between the large beams. For the calculation of slab-less beams, the beam section area is multiplied by beam length without any subtraction. In addition, in the case of haunch parts, they are subtracted accordingly. The beam quantity estimation formulas are shown in Table 4.

Table 4. Calculation formula for the beam.

Division	Estimation Formula
concrete	$b \times (d - t_s) \times lo$
form	$(d - t_s) \times 2 \times lo$

Fourth, for the estimation of slab quantity, floor thickness is multiplied by floor area. At the estimation of floor form with the area under the slab, it should be subtracted from the wall thickness if the lower-floor wall is masonry as shown in Figure 2d. In the case of reinforced concrete walls, on the contrary, a total floor area is estimated without any subtraction. The slab quantity estimation formulas are shown in Table 5.

Table 5. Calculation formula for the slab.

Division	Estimation Formula
concrete	$a \times b \times t_s$
form	$(a \times b) + [2(a + b) \times t_s]$

The length of reinforcing bars is estimated by type and diameter. Then, the total length is multiplied by unit weight (kg/m) to get the total weight. Each floor is divided into wall, column, beam and slab to make sure that there is no redundancy in calculation. The total length of reinforcing bars is estimated after calculating the length of each piece and multiplying it by total quantity. In estimating the length of each piece of reinforcing bar, member length, joint length, dowel length and hook length should be considered as shown in Table 6.

Table 6. Calculation formula for length/piece of reinforcing bar.

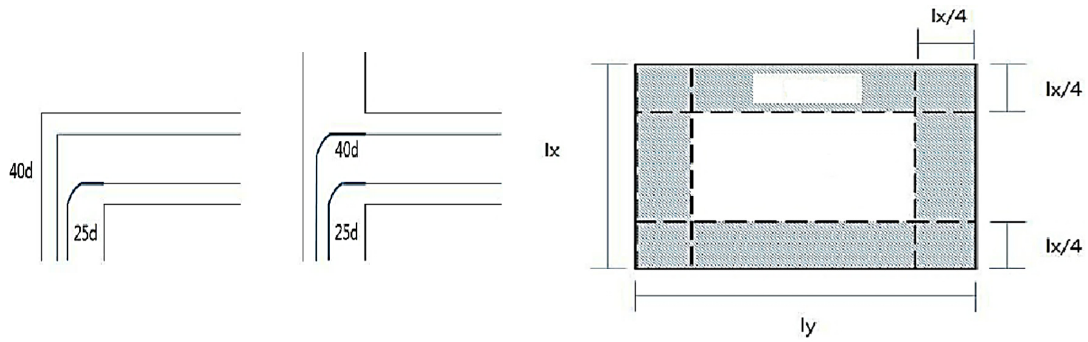
Category	Calculation Formulas
Member Length	Inside length = Dimension between member inside measurements (lo) Front length = Dimension of member front line (l) Outside length = Dimension between member outsides (l′)
Joint Length	Under tensile load = 40distance (unit: cm) Under compressive force = 25distance (unit: cm)
Dowel Length	Under tensile load = 40distance (unit: cm) Under compressive force = 25distance (unit: cm)
Hook Length	Column and beam = 10.3distance (unit: cm)

In principle, the quantity of reinforcing bars should be calculated after checking a drawing. If it is not possible to check the drawing, the quantity of reinforcing bars is estimated after dividing a scope of reinforcement placement by the placement interval. Then, a minor difference (one or two) can occur depending on the start point of reinforcement placement.

First, the quantity of wall reinforcing bars can be estimated by dividing them into line/point reinforcing bars or horizontal/vertical reinforcing bars. In vertical ones, dowel length is considered. In horizontal reinforcing bars, in contrast, joint length and number of joints are considered as shown in Figure 3a. In terms of the estimation of the number of joints, member length is divided by the length of each reinforcing bar as shown in Table 7.

Table 7. Calculation formula for the wall reinforcing bar.

Category	Calculation Formulas
Vertical reinforcing bars	(Member length + Dowel length) × quantity
Horizontal reinforcing bars	[Member length + (Joint length × Joint number)] × quantity



(**a**) (**b**)

Figure 3. The standard of quantity estimation for the reinforcing bar: (**a**) The standard of quantity estimation for the beam reinforcing bar; (**b**) The standard of quantity estimation for the slab reinforcing bar.

Second, for the estimation of the quantity of column reinforcing bars, they are divided into main bars, hoop bars and diagonal hoop bars. The length of the main bar member is set with column height, and the number of joints occurs at every floor as shown in Figure 3b. Furthermore, a hook is installed at column end only. The length of each main bar/diagonal hoop bar is set with the column circumference. Then, the number of main bars and diagonal hoop bars is estimated by dividing the column height by the reinforcement placement interval as shown in Table 8.

Table 8. Calculation formula for the column reinforcing bar.

Category	Calculation Formulas
Main Bar	(Member length + joint length + dowel length + hook) × quantity
Hoop Bar	Column circumference × quantity
Diagonal Hoop Bar	Column circumference × quantity

Third, for the estimation of the quantity of beam reinforcing bars, they are divided into upper main bars, bent-up bars, lower main bars and stirrup bars. In case of beams, estimation standards for the top-floor and middle-floor beams differ. In terms of the length of reinforcing bars in top-floor beams, the lengths of upper main bars and bent-up bars are estimated with the outside length, while the length of lower main bars is calculated with the inside length. For the length of reinforcing bars for middle-floor beams, however, the lengths of upper main bars, bent-up bars and lower main bars are all estimated with inside length as shown in Table 9.

Table 9. Calculation formula for the beam reinforcing bar.

Category		Calculation Formulas
Top-floor Beam	Upper Main Bar	[Outside length + (dowel length + hook) × 2 (both sides)] × quantity
	Bent-up Bar	[Outside length + (dowel length + hook) × 2 (both sides) + length of increase in bent-up bar] × quantity
	Lower Main Bar	[Outside length + (dowel length + hook) × 2 (both sides)] × quantity
	Stirrup Bar	End: Beam circumference × quantity Center: Beam circumference × quantity
Middle-floor Beam	Upper Main Bar	[Inside length + (dowel length + hook) × 2 (both sides)] × quantity
	Bent-up Bar	[Inside length + (dowel length + hook) × 2 (both sides) + length of increase in bent-up bar] × quantity
	Lower Main Bar	[Outside length + (dowel length + hook) × 2 (both sides)] × quantity
	Stirrup Bar	End: Beam circumference × quantity Center: Beam circumference × quantity

Fourth, for the estimation of the quantity of slab reinforcing bars, they were divided into end and center and classified by type of placement. Then, the length and quantity are estimated. In this case, slab dimensions are estimated with beams and their inside dimensions. Unless beams are available, total dimensions are used.

After figuring out the range of each reinforcing bar's placement after classifying the reinforcing bars by short and long sides up to one-fourth of inside length (l_x) in a short-side direction, the quantity is estimated. Furthermore, upper and lower reinforcing bars are classified in short- and long-side directions. In this case, the upper bars are divided into bent-up and top bars as shown in Table 10.

Table 10. Calculation formula for the slab reinforcing bar.

Category		Calculation Formulas
Short-sides direction	Upper Main Bar	l_x × quantity
	Lower Main Bar	l_x × quantity
	Bent-up	l_x × quantity
	Main Bar	(l_x/4 + dowel length) × quantity
Long-sides direction	Upper Main Bar	l_x × quantity
	Lower Main Bar	l_x × quantity
	Bent-up	l_x × quantity
	Main Bar	(l_x/4 + dowel length) × quantity

To evaluate the results of the quantity estimation performed by building type, they were modeled with a structural analysis programs in Korea called MIDAS [23]. For this, there was structural analysis on the load combination set by Korea Building Code-Structural (KBCS), using architectural and structural drawings by building type. Additionally, for the reinforcement placement, MIDAS-GEN's automatic reinforcement placement was used. Figure 4 reveals the results of each plane type's modeling.

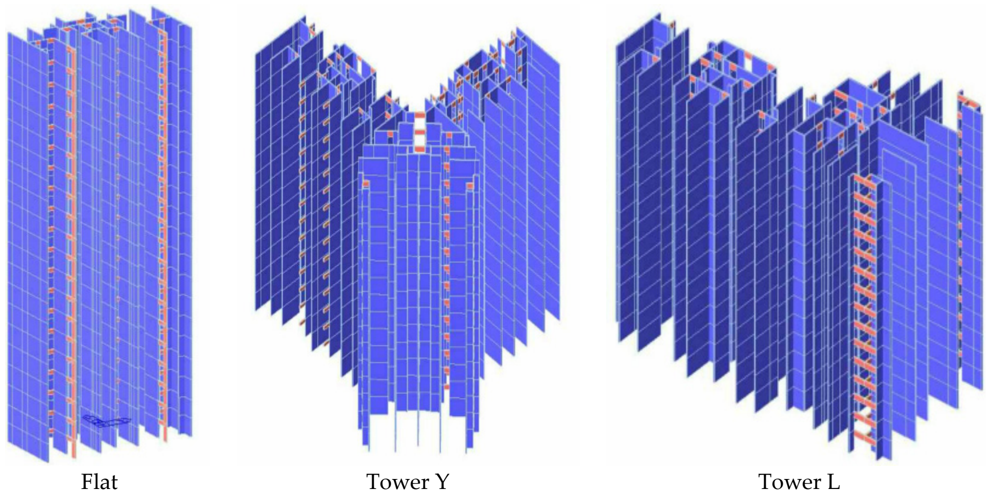


Figure 4. The results of plane type's modeling.

The concrete, form and reinforcing bar quantities obtained through a 2D drawing-based manual quantity estimation method and a program-based automatic quantity estimation method were almost same.

In the drawing-based quantity estimation, however, the parts that overlapped in the factor design dimensions are subtracted. In a program-based automatic quantity estimation method, in contrast, the quantity is estimated based on the factor information which has been modeled under design dimensions. Therefore, factor-overlapped parts are not subtracted. In this case, there is no subtraction of vertical length in the wall-beam, wall-slab and column-slab combinations. To minimize differences in the results, therefore, there should be modeling which considers the subtraction of the overlapped parts in a height direction equivalent to the manual quantity estimation standards at the time of building modeling.

In case of beams, columns and slabs, a difference was found in hoop bars, diagonal hoop bars, stirrup bars and main bent-up bars. Therefore, an error in the hoop bar and stirrup bar results can be minimized by adding the cover thickness of columns and beams during quantity estimation after building modeling.

4.2. Calculation and Variation Rates of Material Amounts in the Evaluation of Apartment Houses

In the use of concrete, vertical members such as core walls and columns were mostly divided in the vertical direction such as low, middle and high floors. Therefore, compressive strength is applied from high to low levels after zoning.

The classification of low floors is found in diverse forms depending on the building type. In general, however, it is about one-third of the total building floors. In this section, the compressive strength was revealed to be 24 MPa on average in walls and columns (vertical members). In general, concrete with a strength of 35 MPa is used for low floors.

In the case of high floors, the compressive strength of vertical members was 24 MPa on average. For middle floors, 35 MPa concrete is commonly used. In terms of horizontal members, 24 MPa concrete was mostly used for slabs. Recently, however, concrete with a strength of 30 MPa or stronger is used for slabs. Slab concrete appears to get stronger in connection with the vertical members [24]. In this study, therefore, a building was divided into two zones: Low zone (20th floor or lower) and high zone (above 20th floor). Concrete with a strength of 35 MPa was applied to the low zone, while 24 MPa concrete was used for the high zone, which was applied equally according to building type.

The amounts of concrete, reinforcement bars, and forms of a 15-floor flat-type apartment house were established at reference value of 1, and the change rate in the amount of materials was analyzed according to the number of floors and building types.

Table 11 lists the calculated amount and variation rate of concrete according to the number of floors for each type, and Figures 5 and 6 show the variation rate of the amount of concrete according to the number of floors and type of apartment house [25,26].

The rate of change in the calculated amount of concrete according to the number of floors was the most abrupt between the 20th and 25th floors at 0.48, which increased according to the number of floors.

For the tower Y type, the rate of increase was nearly constant at 0.3 for 20-floor or higher apartments.

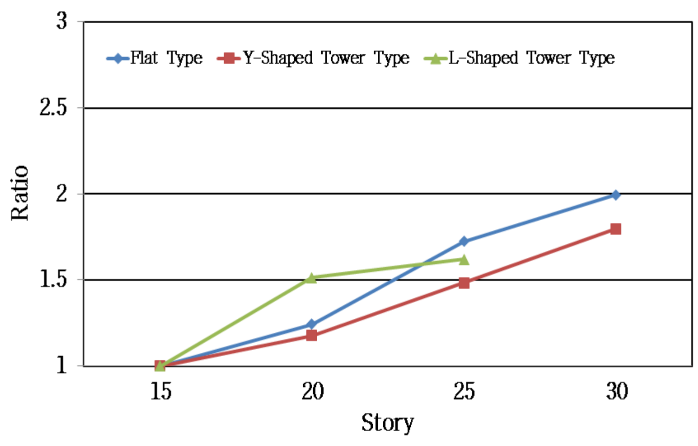


Figure 5. Change rate for amount of concrete based on the number of floor.

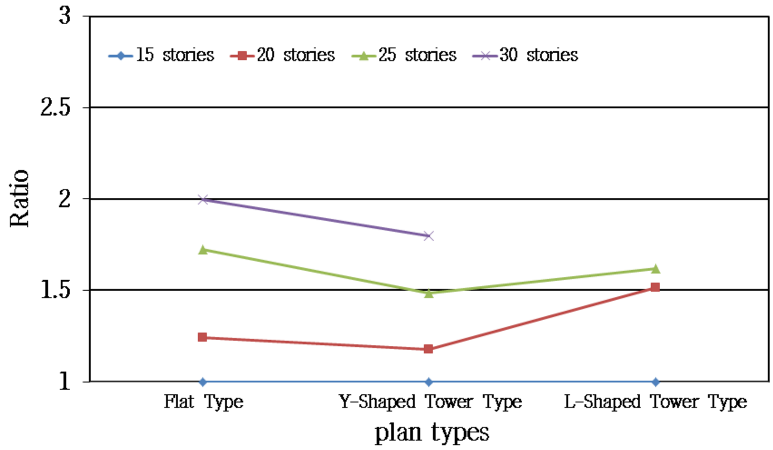


Figure 6. Change rate for amount of concrete based on each reference type.

Table 11. Calculated amount of concrete according to the number of floors and type.

Number of Floors	Type	Material Amount [m^3]	Average [m^3]	Change Rate
15 floors	Flat	3776 3795	3786	1.00
	Tower Y	3854	3854	1.00
	Tower L	3472 3519	3495	1.00
20 floors	Flat	4660 4751	4706	1.24
	Tower Y	4180 4298	4239	1.18
	Tower L	5183 5392	5287	1.51
25 floors	Flat	6400 6656	6528	1.72
	Tower Y	5675 5763	5719	1.48
	Tower L	5355 5965	5660	1.62
30 floors	Flat	7424 7680	7552	1.99
	Tower L	6514 6736	6625	1.80

For the tower L type, the most abrupt rate of change occurred in the lower floors between the 15th and 20th floors, at 0.51, but decreased to 0.11 in the higher floors at the 20th floor or above [27,28].

The comparison of the rate of change in the amount of concrete showed that the tower L type had the largest rate of change at the 20th floor, whereas the flat type had the largest rate of increase between the 25th and 30th floors.

Therefore, in terms of CO_2 emissions and cost, flat-type apartments are superior at floors lower than the 20th, whereas tower L-type apartments are superior at floors higher than the 20th.

Table 12 lists the results of the calculated amounts and their rates of change for reinforcement bars according to the number of floors and type; Figures 7 and 8 show rates of change for the amount of reinforcement bars according to the number of floors and type, respectively [29,30].

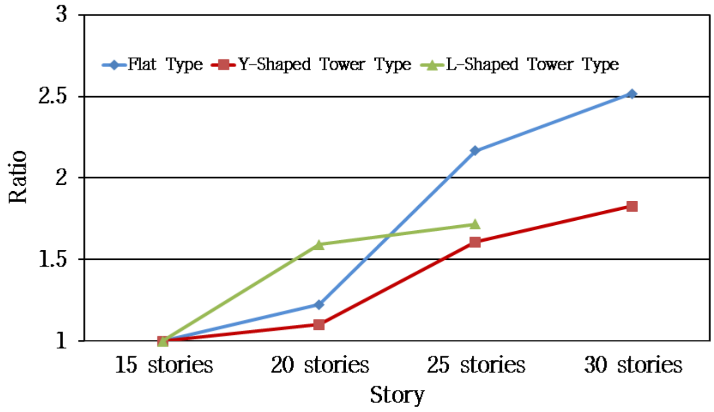


Figure 7. Change rate for amount of rebar based on the number of floor.

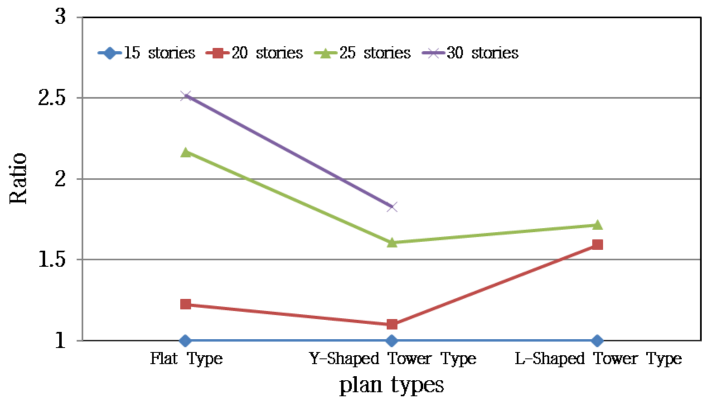


Figure 8. Change rate for amount of rebar based on each reference type.

Table 12. Result of calculated amounts of reinforcement bars according to number of floors and type.

Number of Floors	Type	Material Amount [ton]	Average [ton]	Change Rate
15 floors	Flat	180 181	181	1.00
	Tower Y	198	198	1.00
	Tower L	147 147	147	1.00
20 floors	Flat	212 231	222	1.23
	Tower Y	215 222	218	1.10
	Tower L	230 239	235	1.59
25 floors	Flat	385 399	392	2.17
	Tower L	287 292	289	1.61
	Tower L	248 258	253	1.72
30 floors	Flat	448 463	455	2.52
	Tower L	337 349	343	1.83

The rate of change in the calculated amount of reinforcement bars according to the number of floors was the highest between the 20th and 25th floors at 0.94; as for concrete, this value increased according to the number of floors. The tower Y type showed the largest increase in materials between the 20th and 25th floors, at 0.51.

For the tower L type, the most rapid rate of change occurred between the 15th and 20th floors, at 0.59, but this rate decreased to 0.13 at the 20th floor or above. Therefore, as for reinforced concrete, flat and tower Y types are superior at lower floors, whereas the tower L type is superior at higher floors in terms of CO_2 emission and cost [31,32].

The comparison of the rate of change in the amount of reinforcement bars by type showed that tower L type had the largest rate of change at the lower floors, whereas flat type showed the largest rate of increase between the 25th and 30th floors. In contrast, because tower Y type showed the largest increase between the 20th and 25th floors, it may be slightly disadvantageous to construct buildings of 20 floors or higher.

Table 13 lists the results of the calculated amounts of forms and their rates of change according to the number of floors and type; Figures 9 and 10 show rates of change according to the number of floors and type.

The calculation results for the amount of forms according to the number of floors revealed that flat type experienced a relatively low rate of increase but the lowest rate of change at the 25th floor or higher. The tower Y type showed the largest increase in materials between the 20th and 25th floors, at 0.43.

Therefore, the tower Y type is inferior at higher than the 25th floor. The tower L type showed a relatively high rate of increase for all floors.

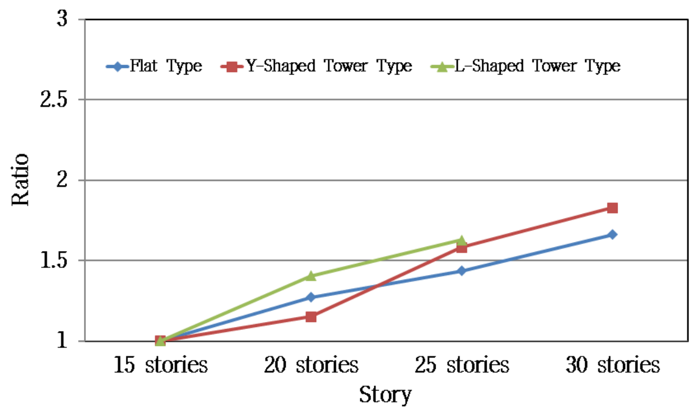


Figure 9. Change rate for amount of form based on the number of floor.

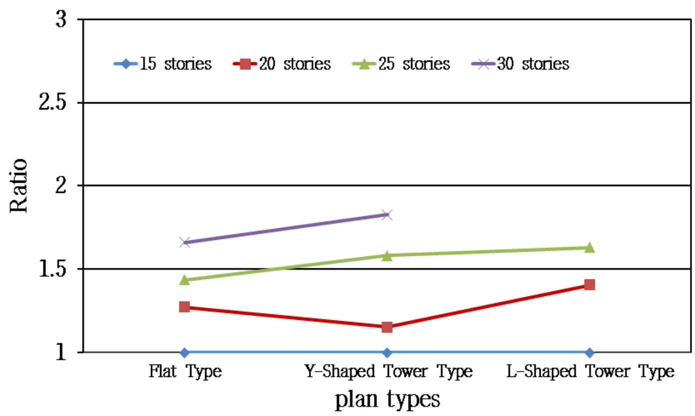


Figure 10. Change rate for amount of form based on each reference type.

Table 13. Result of calculated amounts of form according to the number of floors and types.

Number of Floors	Type	Material Amount (m^3)	Average (m^2)	Change Rate
15 floors	Flat	33,465 33,629	33,547	1.00
	Tower Y	32,031	32,031	1.00
	Tower L	30,939 31,383	31,161	1.00
20 floors	Flat	42,217 43,121	42,669	1.27
	Tower Y	35,962 37,928	36,945	1.15
	Tower L	43,013 44,676	43,845	1.41
25 floors	Flat	47,258 49,148	48,203	1.44
	Tower L	49,722 51,688	50,705	1.58
	Tower L	49,782 51,783	50,783	1.63
30 floors	Flat	54,819 56,710	55,764	1.66
	Tower L	57,585 59,551	58,568	1.83

The comparison of the rate of change in the amount of forms showed that the tower L type had the largest rate of change at the 20th and 25th floors, whereas the tower Y type had the largest rate of increase at the 30th floor.

5. Evaluation of CO_2 Emissions in Apartment Houses

5.1. Evaluation Method

The amount of CO_2 emissions was evaluated with respect to the concretes, reinforcement bars, and forms inputted per type of apartment houses; the evaluation scope was established as a production phase (cradle to gate). For the CO_2 emission factor of concrete, reinforcing bars and forms, the Korea Life Cycle Inventory DataBase (LCI DB) was applied [33–36].

5.2. Evaluation Results

Table 14 lists the evaluation results and the rate of change for CO_2 emissions in apartment houses.

Figure 11 shows the CO_2 emission rate of change; the values of 15-floor apartment houses per type were established as reference value 1. The difference in the rate of increase between the 15th and 20th floors of flat type was 0.25, but this difference rapidly increased to 0.51 between the 20th and 25th floors. The rate of increase decreased to 0.26 between the 20th and 30th floors. The difference in the rate of increase between the 15th and 20th floors of the tower Y type was low, at 0.06, but this increased rapidly to 0.49 between the 20th and 25th floors. The rate of increase decreased to 0.14 between the 20th and 30th floors. Finally, the difference in the rate of increase between the 15th and 20th floors of the tower L type increased rapidly to 0.51, but decreased as the number of floors increased. Therefore, flat and tower Y types are advantageous for lower floors, while the tower L type is advantageous for floors above the 25th floor.

Table 14. Results of evaluation and rate of change for CO_2 emissions per evaluation building.

Number of Floors	Type	CO_2 Emission ($kg\text{-}CO_2$)	Average ($kg\text{-}CO_2$)	Based on Each Reference Type	Based on 15-Floor Flat
15 floors	Flat	1,728,958 1,737,637	1,733,298	1.00	1.00
	Tower Y	1,752,270	1,752,270	1.00	1.01
	Tower L	1,586,523 1,607,759	1,597,141	1.00	0.92
20 floors	Flat	2,138,902 2,205,457	2,172,180	1.25	1.25
	Tower Y	1,835,535 1,896,366	1,865,951	1.06	1.08
	Tower L	2,359,304 2,454,446	2,406,875	1.51	1.39
25 floors	Flat	2,987,641 3,102,286	3,044,963	1.76	1.76
	Tower Y	2,698,298 2,747,160	2,722,729	1.55	1.57
	Tower L	2,510,854 2,756,702	2,633,778	1.65	1.52
30 floors	Flat	3,448,457 3,563,071	3,505,764	2.02	2.02
	Tower Y Tower L	3,089,405 3,191,186	3,140,295	1.79	1.81

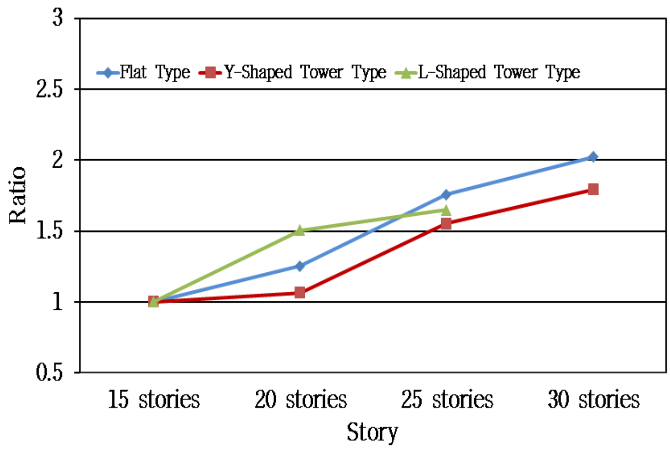


Figure 11. Rate of change for CO_2 emissions based on 15-floor flat.

To analyze the CO_2 emissions of apartment houses by type according to the number of floors, a flat-type 15-floor apartment house was established at reference value 1 to analyze the relative rates of increase or decrease of all other apartment houses. Figure 12 shows the rate of change of CO_2 emissions on the basis of a flat-type 15-floor apartment house. On the 15th floor, the amount of CO_2 emissions of the tower L type was the lowest, at 0.92.

However, on the 20th floor, the amount of CO_2 emissions of the tower L type was the largest, whereas the rate of increase of the tower Y type was the lowest, at 1.08.

Therefore, an eco-friendly design can be achieved: The lowest CO_2 emissions were produced in the tower Y type at floors below the 20th floor, while the tower L type had the lowest CO_2 emissions at floors above the 25th floor.

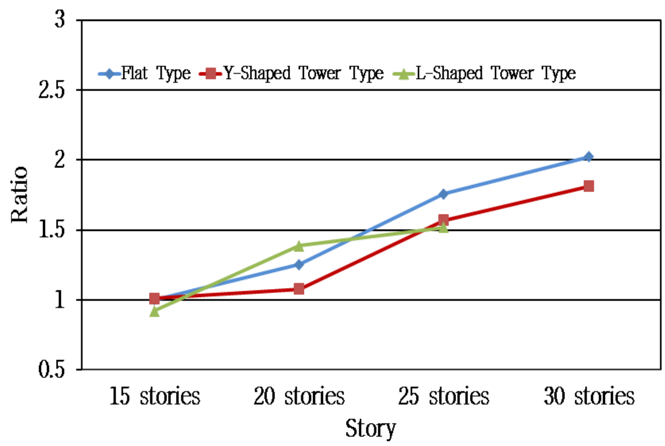


Figure 12. Rate of change for CO_2 emissions based on each reference type.

6. Evaluation of Cost in Apartment Houses

6.1. Evaluation Method

The cost evaluation of apartment houses by type used information from the Korea Public Procurement Service and Korea Price Information (KPI) to establish the unit prices of the primary construction materials [37].

Table 15 lists the cost (US$) evaluation result and its rate of change for apartment houses.

Table 15. Cost evaluation result and change rate per building of apartment houses.

Number of Floors	Type	Cost [$]	Average Cost [$]	Based on Each Reference Type	Based on 15-Floor Flat
15 floors	Flat	896,703 901,429	899,066	1.00	1.00
	Tower Y	949,445	949,445	1.00	1.06
	Tower L	819,684 828,810	824,247	1.00	0.92
20 floors	Flat	1,099,136 1,160,309	1,129,722	1.26	1.26
	Tower Y	992,483 1,022,819	1,007,651	1.06	1.12
	Tower L	1,227,380 1,277,273	1,252,326	1.52	1.39
25 floors	Flat	1,706,697 1,771,057	1,738,877	1.93	1.93
	Tower Y	1,423,665 1,444,463	1,434,064	1.51	1.60
	Tower L	1,285,337 1,401,474	1,343,405	1.63	1.49
30 floors	Flat	1,973,706 2,037,934	2,005,820	2.23	2.23
	Tower L	1,639,493 1,693,531	1,666,512	1.76	1.85

6.2. Evaluation Result

Figure 13 shows a graph of the rate of change in cost, with the cost of a 15-floor apartment house established at the reference value of 1 for each type. The difference in the rate of increase for a flat between the 20th and 25th floors was 0.67, and the material cost increased the most, surpassing the cost of the tower L type.

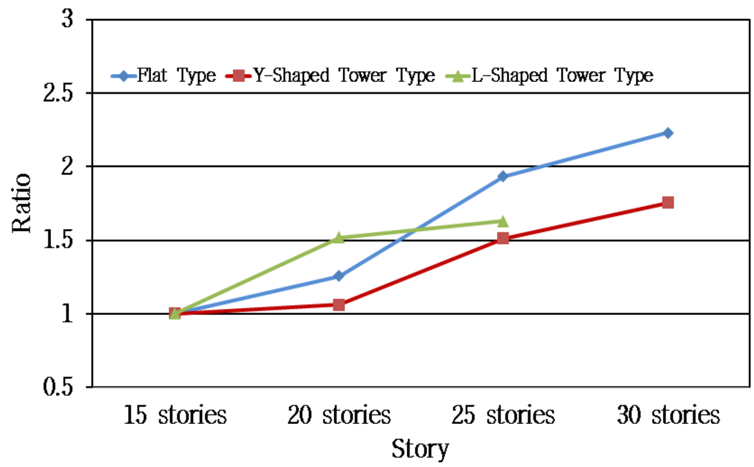


Figure 13. Rate of change for cost based on 15-floor flat.

The difference in the rate of increase for the tower Y type between the 15th and 20th floors was low, at 0.06, but increased rapidly to 0.45 between the 20th and 25th floors. Finally, the difference in the rate of increase for the tower L type between the 15th and 20th floors increased rapidly to 0.52, but decreased as the number of floors increased.

Figure 14 shows a rate of change of material cost based on the 15th floor of a flat. At the 15th floor, the tower L type was evaluated to have the lowest cost, at 0.92; however, its cost at the 20th floor increased rapidly and was evaluated as having the highest cost.

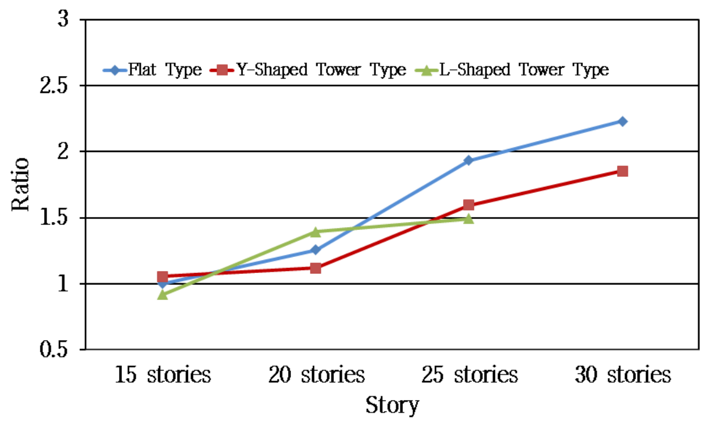


Figure 14. Rate of change for cost based on the 15th floor of a flat.

In floors above the 25th, the costs of flats and tower Y types increased continuously, whereas the tower L type was advantageous in terms of cost as the number of floors increased.

7. Conclusions

This study classified apartment houses in Korea by types and analyzed input material amounts, CO_2 emissions, and cost of primary materials. This study aimed to recommend eco-friendly and economical types of apartment houses; through this study, the following conclusions have been made.

(1) The calculation results for amounts of material used in apartment houses showed that concrete and reinforcement bars were used least for the 15-floor tower L type, but rapidly increased at the 20th floor, thereby outperforming the flat and tower Y types. However, in higher floors above the 20th floor,

material use decreased more for the tower L type than other types. This phenomenon was particularly evident for reinforcement bars.

Therefore, flat and tower Y types of apartment houses were advantageous at lower floors, while the tower L type was advantageous at higher floors in terms of CO_2 emissions and cost.

(2) The evaluation results for CO_2 emissions in apartment houses showed that the most economical types were the 15-floor tower L at 1,597,141 kg-CO_2, the 20-floor tower Y at 1,865,951 kg-CO_2, the 25-floor tower L at 2,633,778 kg-CO_2, and the 30-floor tower Y at 3,140,295 kg-CO_2. Therefore, a flat was advantageous at 20 floors or lower in terms of eco-friendliness, but CO2 emissions increased rapidly as the number of floors increased above the 20th floor. On the other hand, CO_2 emissions rapidly decreased for tower L types as the number of floors increased above the 20th floor; thus, it was evaluated as being the most eco-friendly plan for higher floors.

(3) The results of the evaluation of the cost of apartment houses showed that the cost of a flat was US$899,066 for 15 floors, which was less than the tower Y type, and US$1,129,722 for 20 floors, which was less than the tower L type. However, for 20 floors or higher, the cost increased rapidly. Accordingly, a flat was evaluated to be economically inferior to tower types as the number of floors increased.

(4) The highly useful study results will be utilized as data during the process of determining floor types and number of floors, considering emissions and cost in the construction phase of apartment houses upon the implementation of carbon trading in Korea.

(5) The study has been conducted on buildings in the Republic of Korea only. Therefore, the study results are not applicable to the buildings outside the country. It is planned to improve the reliability of the study by performing quantity analysis and CO_2 emission evaluation on buildings in other countries.

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