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An integrated evaluation of productivity, cost and CO_2 emission between prefabricated and conventional columns

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ABSTRACT

The off-site prefabrication construction method offers several advantages that have positioned it as a good alternative to the conventional method. Recently in South Korea, a form-latticed prefabricated steel reinforced concrete (Form-LPSRC) column was invented as substitute for a conventional steel reinforced concrete (SRC) column. This study evaluates the productivity, cost, and CO_2 emission of Form-LPSRC column with those of SRC column through a case study. Two factory projects utilizing same-size Form-LPSRC and SRC columns are studied. In addition, Web-CYCLONE simulation and equation-based methods are utilized to calculate the productivity, cost, and CO_2 emission of the two column methods. In particular, Web-CYCLONE simulation is used for considering the idle time during the construction process. The Form-LPSRC column improved productivity by 42.5% and provided costs savings of 1.32% compared with the SRC column. Thus, the Form-LPSRC column is excellent for projects where construction duration and cost are of utmost importance. However, the CO_2 emission of the Form-LPSRC column is 72.18% higher than that of the SRC column.

1. Introduction

Off-site construction methods such as prefabrication method have been developed to improve productivity in construction and to reduce cost. Recently, a form-latticed prefabricated steel reinforced concrete (Form-LPSRC) column was developed as an alternative to steel reinforced concrete (SRC) columns in South Korea (Lee and Lee, 2015). An SRC column, which is a type of an encased steel concrete composite column, has been widely applied in high-rise buildings or factory projects. An SRC column consists of I-beam, deformed rebar and concrete as shown in Fig. 1. This type of column has a weakness wherein a minor axis occurs in the column section since only one axis of an SRC column is equipped with the flange (Narayanan, 1988). In addition, since an I-beam steel member is located at the center of the SRC column, the SRC column has inefficient bending resistance. In the limitations, a deformed rebar is placed to improve the structural performance of the SRC column. The Form-LPSRC column can ensure excellent bending resistance without additional deformed rebar reinforcement, by uniformly placing prefabricated steel angles on every column outside of the cross section, as shown in Fig. 1 (Eom et al., 2012; Hwang et al., 2015). In addition, the Form-LPSRC column does not need additional formwork during the construction process since a 1.6 *mm* thick rib-deck is installed for permanent formwork during the prefabrication process (Senkuzo, 2015).

However, a study to clearly analyze how a Form-LPSRC column differs from the existing construction method (i.e., SRC column) has not yet been conducted. For this reason, the Form-LPSRC column method has not been actively applied to actual construction projects. This study is intended to compare the performances of a Form-LPSRC column and an SRC column using a case study.

With increasing public interest in the global warming phenomenon, reduction of carbon dioxide (CO_2) emitted from buildings has become an important topic in the building industry that uses more energy and produces more CO_2 emissions than any other industry (Hong et al., 2012b, 2012c; Kim et al., 2012; Lee et al., 2012; Jeong et al., 2015; Melià et al., 2014; Wang et al., 2015). Most of the previous studies focused on CO_2 emitted during the operation phase of buildings, several recent studies considered the CO_2 emitted during the construction process (Chou and Yeh., 2015;

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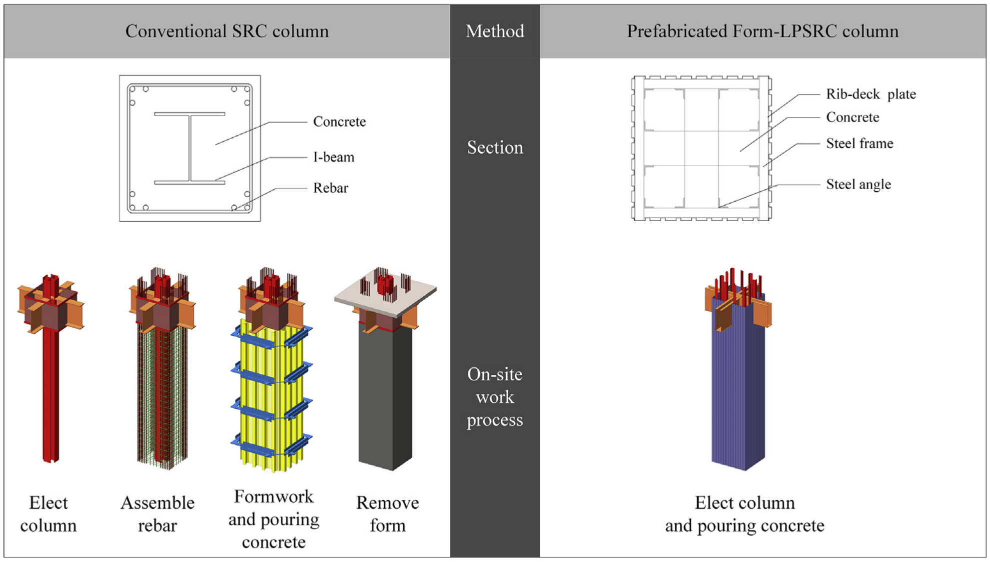


Fig. 1. Overview of the SRC and Form-LPSRC columns.

Hong et al., 2012c, 2014; Jang et al., 2015; Kim et al., 2015; Park and Hong, 2011). Thus, CO_2 emission in the construction process should also be considered as one of the key criteria for selecting the optimal construction method along with productivity and cost.

CYCLONE (CYCLic Operation Networks), a representative construction simulation methodology, has been developed to calculate productivity and cost for repetitive construction processes (Halpin and Riggs, 1992; Halpin, 2005). CYCLON has been used to calculate the productivity and cost of the construction process (Cheng and Feng, 2003; Huang et al., 2004; Han et al., 2006, 2008; Kang et al., 2010; Hong et al., 2011). In addition, the CO_2 emitted during the construction process can be calculated by using CYCLONE. Thus, this study aims to evaluate the productivity, cost, and CO_2 emission of the Form-LPSRC and SRC column methods using the Web-CYCLONE, which is an online web based simulation program developed based on CYCLONE methodology (Halpin, 2003).

2. Materials and methods

The same-sized (i.e., 800 $mm \times 800$ $mm \times 8$ m) Form-LPSRC and SRC columns were respectively applied to "*A*" and "*B*" factory projects executed in South Korea. The case study was conducted based on the data collected at two actual construction projects. As shown in Table 1, the number of columns applied to the two projects differs. However, on the assumption that the same number of columns (i.e., 208 columns) is installed for "*A*" and "*B*" factory projects to conduct the simulation in the identical condition, this study calculated and compared the productivity, cost, and CO_2 emission of 208 Form-LPSRC columns and SRC columns. Fig. 2 shows the process of comparing the productivity, cost, and CO_2 emission of the Form-LPSRC column with those of the SRC column.

Table 1
Overview of the case projects.

Project	"*A*" factory project	"*B*" factory project
Location	Incheon, South Korea	Hwaseong, South Korea
Construction year	2014	2014
Construction method	Form-LPSRC	SRC
Column size	800 $mm \times 800$ $mm \times 8$ m	800 $mm \times 800$ $mm \times 8$ m
Number of columns	208	144

2.1. CYCLONE simulation

The construction project has a characteristic that it cannot be replicated with the same task and resources. For this reason, the construction methods and the combination of resources (i.e., equipment, labor, or materials) used for the construction vary depending on the construction projects (Alvanch et al., 2011). Due to such characteristics, it is essential to analyze all cases with various combinations of resources input to acquire the maximum productivity of a construction process. In addition, since the time required for activities in the construction process changes every time due to the different characteristics of construction projects (i.e., weather conditions, change in resources input, etc.), it is necessary to consider the changes in working and idle time when calculating construction productivity (Hong et al., 2011).

CYCLONE is a construction simulation tool developed to easily calculate the productivity of repetitive tasks in a construction project (Huang et al., 2004; Han et al., 2008; Kang et al., 2010; Song et al., 2010; Hong et al., 2011). CYCLONE simulation calculates the productivity and cost of the construction process considering not only a change in construction duration of each activities but also a change in the resource sets (i.e., equipment, labor, or material) put into the activities. In the CYCLONE simulation, since the construction cost is calculated by multiplying the construction duration by the unit cost of the resources (i.e., equipment and labors) used for the construction, it is possible to calculate the CO_2 emitted during the construction process by multiplying the construction duration by CO_2 emission factors of the resources, representing the CO_2 emitted when the resources are used per unit time (i.e., minute).

As shown in Table 2, the CYCLONE model consists of six elements: normal activity, COMBI activity, queue node, function node, accumulator, and arc (Halpin and Riggs, 1992; Halpin, 2005). Normal and COMBI activities stand for the work tasks performed by the resource sets consisting of construction equipment and labor. Queue nodes refer to a queuing up or waiting for use of resource entities. Arcs show the directional flow of the construction process. Table 2 shows a detailed explanation of each CYCLONE element.

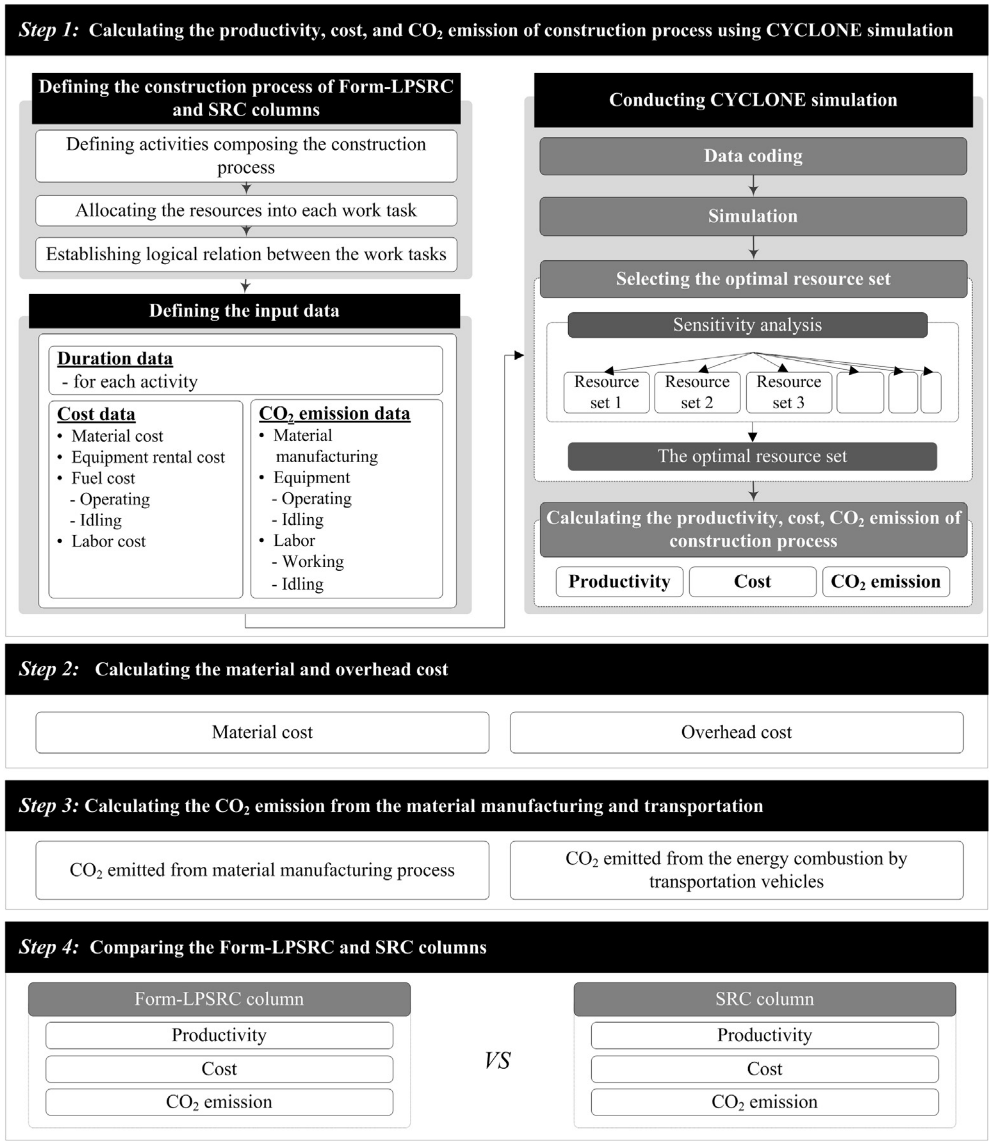
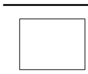
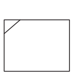
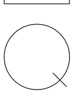
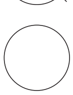
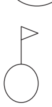


Fig. 2. Process for evaluating the productivity, cost, and CO_2 emission of the Form-LPSRC column with those of the SRC column.

Table 2
CYCLONE elements (Halpin and Riggs, 1992).

Symbol	Name	Function
	Normal Activity	The activities begin processing without delay.
	Combination (COMBI) Activity	The activities can be delayed until the condition for combination is met at each of the preceding Queue Nodes
	Queue Node	This element precedes all COMBI activities and delay statistics are measured.
	Function Node	It is inserted to perform special functions.
	Accumulator (Counter)	It define the number of cycle times.
	Arc	It indicates the direction of entity flow

2.2. Considerations for assessing productivity, cost and CO_2 emission

The productivity, cost, and CO_2 emission of the construction methods may change according to the scope of consideration. Thus, this study identified the scope of consideration, as shown in Fig. 3.

Productivity is an index that indicates to what extent the construction process is completed for unit time (e.g., minute). As shown in Fig. 4, Form-LPSRC and SRC columns entail the same processes in terms of connecting the steel beam, girder, and deck slab to a column member and pouring concrete. Thus, the processes of connecting the steel beam, girder, and deck slab to a column member and pouring concrete were excluded from the construction process in this study. This demonstrates the scope of consideration for calculating the productivity of the Form-LPSRC column defined as the construction process, including from “a” to “b” in Fig. 4(a). The scope of consideration for calculating the productivity of the SRC column was defined as the construction process, including from “a” to “d” in Fig. 4(b). In addition, this study defined the construction process to install one column as one cycle. Productivity, which is calculated by dividing the number of work cycle by the total simulation time as shown in equation (1), can be calculated using CYCLONE simulation in Step 1.

$$P = \frac{N}{duration} \tag{1}$$

where, P is the productivity of the construction process; N is the number of work cycle; and *duration* is the construction duration.

To compare the costs of Form-LPSRC and SRC columns, the overall costs, including material cost, construction cost and overhead costs are considered as shown in Fig. 3. Material cost refers to the cost incurred until construction materials are provided for a construction site. Material suppliers provide the materials for Form-LPSRC and SRC columns, considering all the costs required to produce and provide materials such as the costs of raw material procurement, prefabrication, and transportation. Thus, the material cost can be calculated based on the unit price of the materials provided by material suppliers. Construction cost refers to the cost of equipment and labor used in the construction process of installing Form-LPSRC and SRC columns. The equipment cost includes the rental cost required to lease construction equipment and the energy cost of the energy source used by equipment. The labor cost refers to the cost required to employ labor. The overhead cost, which includes the costs for temporary facilities, utility, testing, project management and bonds, should also be considered. Form-LPSRC column method has a simple on-site work process compared to SRC column method (refer to Fig. 1). Thus, the overhead cost of Form-LPSRC column is expected to be lower than those of SRC column, because Form-LPSRC column requires less on-site management and facilities. However, it is hard to project the overhead cost accurately since the overhead cost may vary across projects and circumstances. RS Means states that 10% and 5% of direct costs are respectively reasonable for the indirect cost for general requirement and overhead, based on the results of an analysis of the building costs for 25 types of buildings (RSMeans, 2013). In the conservative point of view, this study set 15% of direct costs (10% of direct costs for the general requirement and 5% of direct costs for overhead) as the overhead cost, with reference to the construction cost data book published by RS Means. Eventually, the scope of consideration for calculating the cost includes the material cost, construction cost, and overhead cost, as shown in equation (2). The construction cost is calculated using CYCLONE simulation in Step 1, and the material cost and overhead cost are calculated using the equation-based calculation methods in Step 2.

$$\begin{aligned} Cost &= \sum_j MC_j + \sum_j \sum_i CC_{i,j} + OC \\ &= \left(\sum_j MC_j + \sum_j \sum_i CC_{i,j} \right) \times 0.15 \end{aligned} \tag{2}$$

where, MC_j is the material cost of material j; $CC_{i,j}$ is the construction cost of activity i using material j; OC is the overhead cost including general requirement and overhead, and the overhead cost is defined to 15% of direct cost (i.e., material and construction cost).

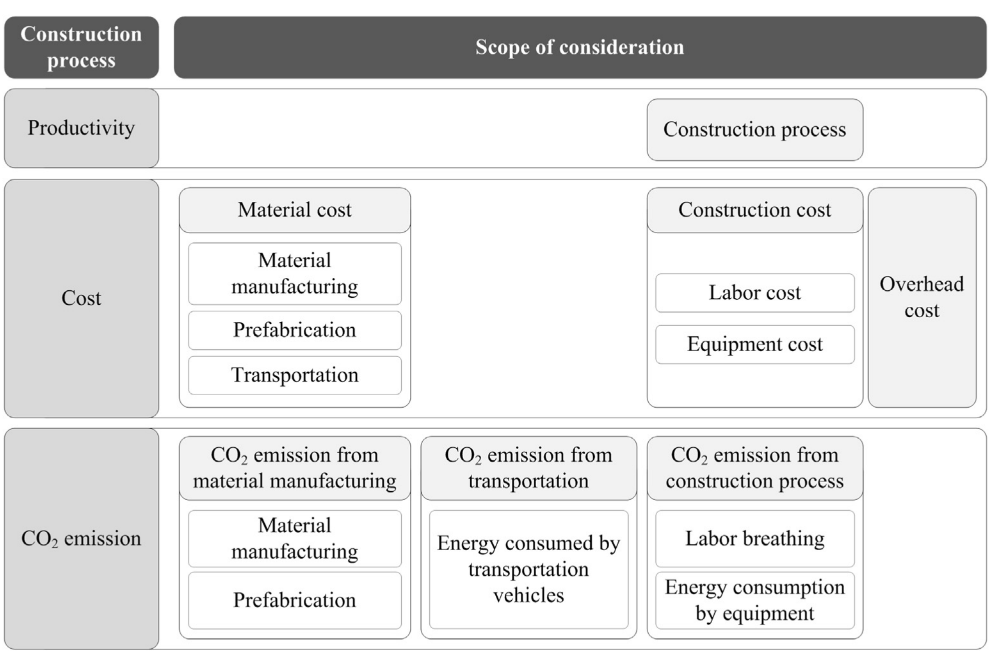


Fig. 3. Scope of consideration for evaluating productivity, cost, and CO_2 emission.

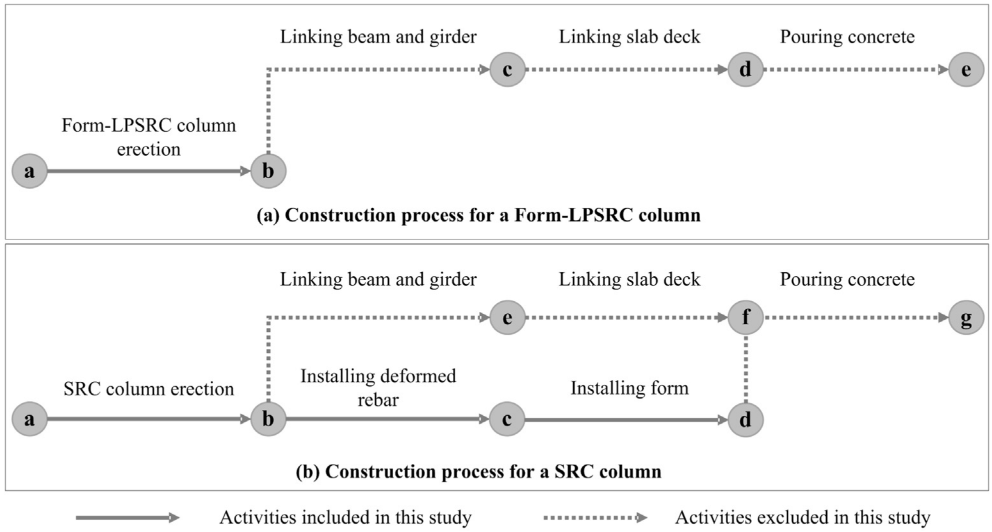


Fig. 4. Construction process for Form-LPSRC and SRC columns.

The scope of consideration for calculating the CO_2 emission for both Form-LPSRC and SRC columns includes the CO_2 emitted from material manufacturing, transportation and construction, as shown in equation (3). A Form-LPSRC column is composed of section steels for structural members and galvanized steel sheets for rib-deck forms. An SRC column is composed of section steels for I-beam and deformed rebar. Thus, CO_2 emissions from manufacturing the section steel, galvanized steel sheet and deformed rebar should be taken into consideration. In addition, a Form-LPSRC column needs prefabrication of materials. Thus, the CO_2 emission from the prefabrication process should also be considered. An SRC column needs formwork for construction of the columns. Thus, the CO_2 emission from the manufacturing process for forms should also be considered. The vehicles that transport the materials for Form-LPSRC and SRC columns to sites cause CO_2 emission. The labor and equipment emit CO_2 in the construction process of installing Form-LPSRC and SRC columns on-site. The CO_2 emission from the construction process is calculated using CYCLONE simulation in Step 1, while the CO_2 emission from the material manufacturing and transportation is calculated using the equation-based calculation methods in Step 3.

$$CO2 = \sum_j MCO2_j + \sum_j TCO2_j + \sum_j \sum_i CCO2_{i,j} \qquad (3)$$

where, $MCO2_j$ is the CO_2 emission from the manufacturing process for material j including the raw material manufacturing and prefabrication; $TCO2_j$ is the CO_2 emission from the transportation for material j; and $CCO2_{i,j}$ is the CO_2 emission of activity i using material j.

2.3. Step 1: Calculating the productivity, cost, and CO_2 emission of the construction process

2.3.1. Defining the construction process

To assess the productivity, cost, and CO_2 emission of the construction process for Form-LPSRC and SRC columns, the activities for Form-LPSRC and SRC columns were defined based on the actual construction data of "A" and "B" case projects, respectively. The CYCLONE model of the construction process for a Form-LPSRC and SRC column were then defined based on the activities, as shown in Figs. 5 and 6.

Fig. 5 shows the CYCLONE model of the construction process for a Form-LPSRC column. As shown in Fig. 4, a Form-LPSRC column only requires a column erection before pouring concrete on site work. Thus, the CYCLONE model is developed to simulate the process of column erection. The resources (i.e., tower crane and crew-1) are applied to the process.

Fig. 6 shows the CYCLONE model of the construction process for a SRC column. As shown in Fig. 4, a SRC column requires three main activities including erecting column, installing rebar, and formwork before pouring concrete on site work. Thus, the CYCLONE model is developed for three main processes. The elements #2 to #6 in Fig. 6 show the process of column erection and related resources. The elements #7 to #15 show the process and resources for assembling rebar. The elements #16 to #21 show the process and resources for formwork. Two equipment and four crews are applied to construct SRC column, and some of equipment and crews can be shared to various activities.

2.3.2. Defining input data

For CYCLONE simulation, the duration data of activities that make up the construction process (Combi and Normal in Figs. 5 and 6) are required. The duration data of activities were collected by measuring the construction duration of each activity in the actual construction site. The duration of activities usually changes due to the bunching effect and variances in travel times. Thus, it is reasonable to use a stochastic value instead of a deterministic value for the CYCLONE simulation (Han et al., 2008). Generally, the input data for construction simulation follows the beta distribution (AbouRizk et al., 1994). However, the number of duration data measured in the case projects was not enough to define the beta distribution. Since the triangular distribution is not largely affected by the number of samples in the data and since its calculation is simple (Hong and Hastak, 2007), this study defined the triangular distribution of the duration based on the construction time of activities measured in the case projects, as shown in Table 3.

Rental, labor, and energy cost data per unit time (i.e., minute) are required for calculating the construction cost. The rental and labor cost data per unit time were obtained from the interview with six field engineers who participated in the case projects. The energy cost data per unit time was obtained by dividing the energy consumption of the construction equipment per unit time by the unit price of the energy source. The energy consumption data per unit

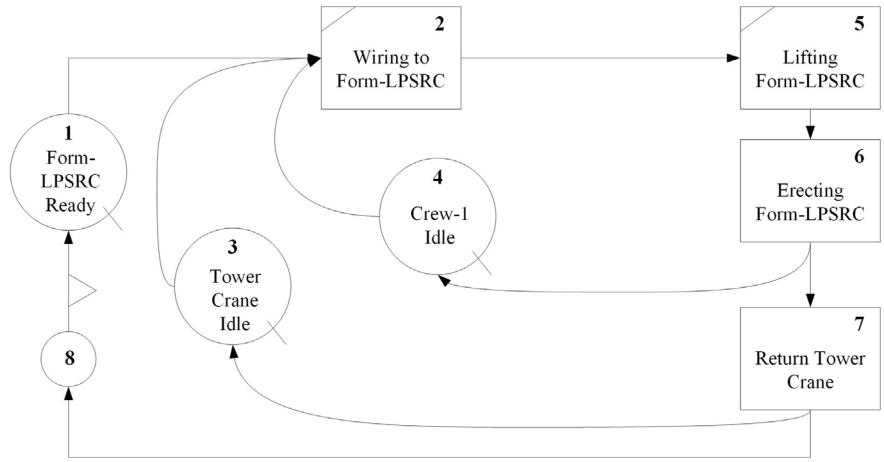


Fig. 5. CYCLONE model of the construction process for a Form-LPSRC column.

time while the construction equipment is in operation were based on the equipment specifications provided by the equipment manufacturers (Genie a Terex Brand, 2015; Hankook Crane and Tech Co., 2015).

Idle time means the time that equipment is not operated and labor do not work. Since equipment 1 and 2 use energy (i.e., electricity) when there is no load, the electricity consumption of equipment during idle time should also be considered. Although there is no empirical information about how much electricity for equipment 1 and 2 is spent when idle, a previous study stated that the motor used 17.8% of total power as the rotational and copper losses on no load condition (Shera et al., 2012). Thus, based on the result of the previous research, this study assumed that idle construction equipment consumes 17.8% of the electricity consumed during operation. The unit price of electricity was based on the 2014 Electric Rates Table provided by Korea Electric Power Company (Korea Electric Power Company, 2015).

CO_2 is emitted from the energy consumed by construction equipment and labor breathing during the construction process. Therefore, the CO_2 emission data of construction equipment and labor are required. The CO_2 emission data of the equipment while in operation were calculated by multiplying the electricity consumption of the operating construction equipment per unit time by the CO_2 emission factor of the electricity. The CO_2 emission data of the equipment during idle time were calculated by multiplying the electricity consumption of the idling construction equipment per unit time (i.e., 17.8% of the electricity consumption of the operating construction equipment) by the CO_2 emission factor of the electricity. The Korea Environmental Industry & Technology Institute (KEITI) presents the CO_2 emission factor of the electricity that indicates the CO_2 emission from manufacturing per unit (i.e., *kWh*) of electricity (KEITI, 2015). This study used the CO_2 emission factor of the electricity (0.495 *kg-CO₂/kWh*) provided by KEITI. The CO_2 emission data of labor used the CO_2 production data resulting from the human breathing during heavy working and idle time, as provided by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 2007). Table 4 shows the cost and CO_2 emission data.

2.3.3. Conducting the CYCLONE simulation

Based on the defined input data, CYCLONE simulation was conducted with the cycle number at 1000 times. Fig. 5 shows the construction process of a Form-LPSRC column that requires Queue Node 1 to Accumulator 8. Fig. 6 shows the construction process of an SRC column that requires Queue Node 1 to Accumulator 22. The productivity, cost, and CO_2 emission of the construction process can change according to the resource sets that are put into the construction process. Thus, it is reasonable to compare the productivities, costs and CO_2 emissions of Form-LPSRC and SRC columns under the condition that the optimal resource sets are applied. This study assessed the productivity, cost, and CO_2 emission of the construction process according to the variability of the resource sets, and selected the optimal resource set. Resource variation was defined considering the project conditions that contain the range of resources available, as shown in Table 5.

Table 6 shows the simulation results for a Form-LPSRC column. In the case of a Form-LPSRC column, the resource set (i.e., Alt. #1) composed of one equipment 1 and one crew 1 was the most superior among 16 resource sets in terms of productivity, cost and CO_2 emission. Under the condition that the optimal resource set was applied, the productivity, cost, and CO_2 emission for a Form-LPSRC column were 0.0151 *Cycle/minute*, 303.4 *\$/Cycle*, and 52.1 *kg-CO₂/Cycle*, respectively.

For the SRC column, 8192 resource sets were established. The optimal resource set for SRC columns was different according to criteria. Thus, this study selected the best resource set individually in terms of productivity, cost and CO_2 emission. Table 7 shows the best five resource sets, among 8192 resource sets, in terms of productivity, cost and CO_2 emission. Under the condition that the optimal resource set was applied, the productivity, cost, and CO_2 emission for an SRC column was 0.0106 *Cycle/minute*, 1263.6 *\$/Cycle*, and 149.2 *kg-CO₂/Cycle*, respectively.

2.4. Step 2: Calculating the material and overhead costs

The cost for both Form-LPSRC and SRC columns should include the material cost and overhead cost as well as construction cost, as mentioned above. The material cost was calculated by multiplying the amount of material by the unit cost of the material, as shown in equation (4). The Form-LPSRC column is produced in a factory and then provided to the site. In the case of the SRC column, the section steel, deformed rebar and form, which are produced in factories by the manufacturers, are provided to the site and then assembled on the site. Consequently, the unit cost of the Form-LPSRC column, section steel, deformed rebar, and form was collected from the manufacturers. The construction costs for Form-LPSRC and SRC columns were calculated by multiplying the results in Tables 6 and 7 (i.e., 303.4 *\$/Cycle* and 1263.6 *\$/Cycle*, respectively) by the number of columns (i.e., 208 *Cycles*). The overhead cost was defined as 15% of direct costs, including material and construction costs, as shown

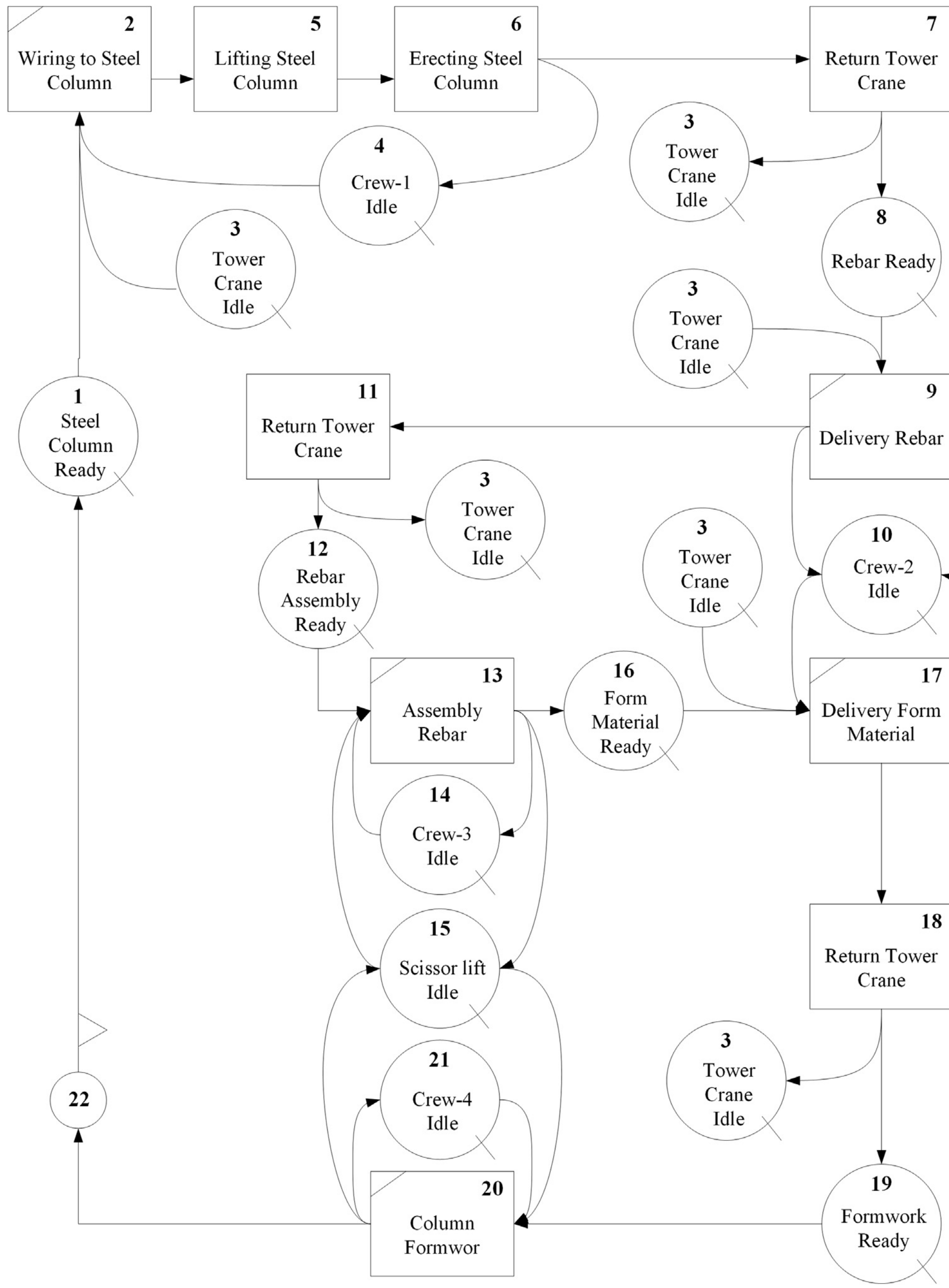


Fig. 6. CYCLONE model of the construction process for an SRC column.

in equation (2). Table 8 shows the cost for both Form-LPSRC and SRC columns, respectively.

$$MC_j = UC_j \times M_j \tag{4}$$

where, MC_j is the material cost for material j; UC_j is the unit cost of material j; and M_j is the amount of material j.

2.5. Step 3: Calculating CO_2 emission from material manufacturing and transportation

The CO_2 emission from the material manufacturing can be calculated by multiplying the amount of materials by the CO_2 emission factors of the materials, as shown in equation (5). The Ministry of Knowledge, Economy (MKE) and the Ministry of Environment (ME) established the life cycle inventory (LCI) of the materials including the section steel, deformed rebar, and galvanized steel sheet composing Form-LPSRC and SRC columns (MKE, 2002; ME, 2005). In addition, the Korea Institute of Civil Engineering and Building Technology (KICT) established the LCI of the form (KICT, 2008). Thus, the CO_2 emission factors of the materials were obtained from the LCI database established by the MKE, ME, and KICT. For the Form-LPSRC column, the CO_2 emission from the prefabrication was calculated by multiplying the amount of materials (i.e., Form-LPSRC column) by the CO_2 emission factor of the prefabrication. The CO_2 emission factor of the prefabrication was calculated at 49.90 *kg-CO_2/ton* by equation (6) (= 60,775 kWh/*month* ÷ 602.89 *ton/month* × 0.495 *kg-CO_2/kWh*). The data, which

Table 3
Data on duration of activities.

Method	Node	Activity	Duration (*min.*)			Resource	Note
			Min.	Most likely	Max.		
Form-LPSRC column	2	Wire to LPSRC column	3.5	5	7	Crew 1	Crew 1
						Equipment 1	1 flagman
	5	Lifting LPSRC column	12	15	20	Crew 1	3 Structural Steel workers
						Equipment 1	1 Safety foreman
	6	Erection LPSRC column	35	40	50	Crew 1	Crew 2
						Equipment 1	2 Laborers
	7	Return tower crane	3	4	5	Equipment 1	Crew 3
SRC column	2	Wire to steel column	3.5	5	7	Crew 1	2 Rodmen
						Equipment 1	1Laborer
	5	Lifting steel column	9	10	15	Crew 1	Crew 4
						Equipment 1	2 Carpenters
	6	Erection steel column	22	25	37	Crew 1	1 Laborer
						Equipment 1	Equipment 1
	7	Return tower crane	3	4	5	Equipment 1	12ton
	9	Delivery rebar	30	35	40	Crew 2	Tower crane
						Equipment 1	1 Operator
	11	Return tower crane	3	4	5	Equipment 1	Equipment 2
	13	Assembly column rebar	180	195	210	Crew 3	Rechargeable
						Equipment 2	Scissor lift
	17	Delivery form material	30	37.5	45	Crew 2	
						Equipment 1	
	18	Return tower crane	3	4	5	Equipment 1	
	20	Column formwork	120	150	180	Crew 4	
						Equipment 2	

Table 4
Cost and CO_2 emission data.

Resource	Cost (*$/hour*)				CO_2 emission data (*kg-CO₂/hour*)	
	Rental cost	Energy cost		Labor cost	Operating	Idle
		Operating	Idle			
Equipment 1	86.09[a]	9.32	1.66	25.74	46.5795	8.29
Equipment 2	3.13	1.07	0.19	–	5.3460	0.95
Crew 1	–	–	–	153.43	0.6190	0.3240
Crew 2	–	–	–	35.23	0.2476	0.1296
Crew 3	–	–	–	83.91	0.3714	0.1944
Crew 4	–	–	–	75.40	0.3714	0.1944

Note.
[a] Exchange rate assumed at 1$ = 1100 KRW.

Table 5
Resource variation for data generation.

Resource	Range of number of equipment and crew	
	Form-LPSRC	SRC
Equipment 1	1 to 4	1 to 4
Equipment 2	–	1 to 8
Crew 1	1 to 4	1 to 4
Crew 2	–	1 to 4
Crew 3	–	1 to 4
Crew 4	–	1 to 4

were related to the amount of electricity used for prefabricating Form-LPSRC columns (60,775 kWh/*month*) and the amount of Form-LPSRC columns produced in a month (602.89 *ton/month*), were obtained from the manufacturer. Table 9 shows the CO_2 emission factors and CO_2 emissions from the material manufacturing. The CO_2 emission from the material manufacturing was calculated by applying the amount of materials and CO_2 emission factors to equation (5). For instance, the CO_2 emission of the section steel composing Form-LPSRC columns was calculated at 466,069 *kg-CO₂* by multiplying the CO_2 emission factor of the section steel (418.75 *kg-CO₂/ton*) by the amount of section steel (1113 *tons*).

$$MCO2_j = EF_j \times M_j \tag{5}$$

$$EF_{LPSRC}^{pre} = \frac{\sum_l EC_{l,LPSRC} \times EF_l}{PM_{LPSRC}} \tag{6}$$

$$TCO2_j = 2\sum_{m=1}\left(\frac{M_j \times TD_{j,m}}{LC_{j,m} \times EE_{m,l}} \times EF\right) \tag{7}$$

where, $MCO2_j$ is the amount of CO_2 emission from the manufacturing process for material j; EF_j is the CO_2 emission factor of material j; M_j is the amount of material j; $EF^{pre}{}_{LPSRC}$ is the CO_2 emission factor of prefabrication for a Form-LPSRC column; $EC_{l,LPSRC}$ is the amount of energy source l used for prefabricating Form-LPSRC columns during a month; EF_l is the CO_2 emission factor of energy source l; PM_{LPSRC} is the amount of prefabricated Form-LPSRC columns during a month; $TCO2_j$ is the CO_2 emission from the transportation for material j; $TD_{j,m}$ is the transportation distance of vehicle m transporting material j; $LC_{j,m}$ is the loading capacity of vehicle m for material j; and $EE_{m,l}$ is the energy efficiency of vehicle m which uses the energy source l.

Hong et al. (Hong et al., 2012a; Hong et al., 2014) suggested a method for calculating the CO_2 emission from transportation, as shown in equation (7). Subsequently, the CO_2 emission from transportation was calculated by applying the amount of materials to equation (7). Here, the transportation distance was set at 30 *km*, which was used in developing the life cycle inventory database in South Korea (KICT, 2008). A 25 ton trailer, 20 ton truck, and 8 ton truck, which use diesel as the energy source, were used for transporting the materials for both Form-LPSRC and SRC columns, as shown in Table 10. The energy efficiency and load capacity of the vehicles were collected from the manufacturer of each vehicle. The CO_2 emission factor of diesel was based on the data (2.62 *kg-CO₂/l*) provided by KEITI (KEITI, 2015).

Table 6
Result of CYCLONE simulation for Form-LPSRC.

Alt.	Resource		Productivity (*Cycle/min.*)	Cost (*$/Cycle*)	CO_2 emission (*kg-CO_2/Cycle*)
	Equipment 1	Crew 1			
#1	**1**	**1**	**0.0151**	**303.4**	**52.1**
#2	2	1	0.0150	438.5	103.9
#3	1	2	0.0150	475.5	53.1
#4	3	1	0.0151	571.7	155.1
#5	2	2	0.0150	608.5	104.6
#6	1	3	0.0151	643.7	53.6
#7	4	1	0.0150	709.5	207.8
#8	3	2	0.0151	741.4	155.9
#9	2	3	0.0151	777.1	105.0
#10	1	4	0.0149	819.4	54.7
#11	4	2	0.0151	876.1	207.5
#12	3	3	0.0151	909.4	156.3
#13	2	4	0.0151	947.6	105.8
#14	4	3	0.0151	1045.0	208.0
#15	3	4	0.0151	1077.8	156.8
#16	4	4	0.0150	1218.0	209.2

Note: The shaded represents the optimal alternatives in each criteria.

Table 7
Result of CYCLONE simulation for SRC.

Alt	Equipment		Crew				Productivity (*Cycle/minute*)	Cost (*$/Cycle*)	CO_2 emission (*kg-CO_2/Cycle*)
	#1	#2	#1	#2	#3	#4			
#1	2	7	2	3	4	3	**0.0106**	1993.1	216.3
#2	3	5	2	3	3	4	0.0106	2134.6	270.4
#3	3	6	2	2	4	4	0.0106	2218.2	279.0
#4	3	8	2	4	4	3	0.0106	2233.3	297.4
#5	3	6	2	3	4	4	0.0106	2278.1	279.9
#6	2	4	1	1	2	2	0.0101	**1263.6**	192.7
#7	2	5	1	1	2	2	0.0101	1268.2	201.2
#8	2	6	1	1	2	2	0.0101	1277.5	210.4
#9	2	7	1	1	2	2	0.0101	1286.7	219.5
#10	2	8	1	1	2	2	0.0101	1290.5	227.8
#11	1	3	1	1	3	2	0.0084	1652.5	**149.2**
#12	1	3	1	2	3	2	0.0084	1732.3	149.7
#13	1	3	1	3	3	2	0.0084	1811.1	150.1
#14	1	3	1	2	2	2	0.0085	1553.8	150.2
#15	1	3	1	2	4	2	0.0085	1919.7	150.3

Note: The shaded represents the optimal alternatives in each criteria.

Table 8
Material, construction, and overhead cost for Form-LPSRC and SRC columns.

Material	Amount of material (*ton*)	Unit cost (*$/ton*)	Cost ($)		
			Material	Construction	Overhead
Form-LPSRC column	1545	2360.8	3,647,391	63,110	556,575
Section steel	1113	1302.0	1,449,126	–	–
Galvanized steel sheet	432	1664.9	719,237	–	–
Prefabrication	1545	957.3	1,479,029	–	–
SRC column	2026	1725.7	3,497,258	262,829	564,013
Section steel	1516	1139.7	1,727,785	–	–
Deformed rebar	510	1177.2	600,372	–	–
Form	14,487[a]	80.7 [b]	1,169,101	–	–

Note: Exchange rate assumed at 1$ = 1100 KRW.
[a] The unit is square meter (m^2).
[b] The unit is US dollar per square meter ($/$m^2$).

3. Results

3.1. Productivity, cost, and CO_2 emission of Form-LPSRC columns

In the case of the Form-LPSRC column, Alt.1 was the optimal resource set, as shown in Table 6. Thus, this study reviewed the productivity, cost, and CO_2 emission of the Form-LPSRC column under the condition that the optimal resource set (Alt. #1) was applied.

Table 11 shows that the productivity of the Form-LPSRC column was calculated at 0.0151 *Cycle/minute*, and that a total of 229.6 h is required to install 208 columns. A total of $ 4,267,077 was required to install 208 columns. Material cost accounted for majority of the costs (85.5%), while construction and overhead costs accounted for 1.5% and 13.0% respectively. The cost exceeding the material cost of section steel was required for prefabrication of Form-LPSRC columns (34.7% of the total cost was incurred in the prefabrication process).

Table 9
CO_2 emission from material manufacturing.

Material	Amount of material (*ton*)	CO_2 emission factor (*kg-CO_2/ton*)	CO_2 emission (*kg-CO_2*)
Form-LPSRC	–	–	1,363,099
Section steel	1113	418.75	466,069
Galvanized steel sheet	432	1898.00	819,936
Prefabrication	1545	49.90	77,094
SRC column	–	–	763,243
Section steel	1516	418.78	634,870
Deformed rebar	510	240.48	122,645
Form	14,487[a]	0.3954[b]	5728

Note: Exchange rate assumed at 1$ = 1100 KRW.
[a] The unit is square meter (m^2).
[b] The unit is kg-CO_2 per square meter (*kg-CO_2/m^2*).

Table 10
CO_2 emission from transportation.

Material	Amount of material (*ton*)	Vehicle	Load capacity (*ton/ea*)	Energy efficiency (*km/l*)	Transportation distance (*km*)	Energy consumption (*l*)	CO_2 emission (*kg-CO_2*)
Form-LPSRC column	1545	25 ton trailer	25	2.5	30	1483.2	3886.0
SRC column	–	–				2270.8	5949.6
Section steel	1516	25 ton trailer	25	2.5	30	1455.4	3813.0
Deformed rebar	510	20 ton truck	20	3.1	30	493.5	1293.1
Formwork	14,487[a]	8 ton truck	600[b]	4.5	30	321.9	843.5

Note.
[a] The unit is square meter (m^2).
[b] The unit is square meter per one truck (*m^2/ea*).

Table 11
Results of Form-LPSRC column.

Category		Unit	Result
Productivity		*Cycle/minute*	0.0151
Construction duration		*hour*	229.6
Cost	Total	*$*	4,267,077 (100.0%)
	Material		3,647,391 (85.5%)
	Section steel		*1,449,126 (34.0%)*
	Galvanized steel sheet		*719,237 (16.9%)*
	Prefabrication		*1,479,029 (34.7%)*
	Construction		63,110 (1.5%)
	Overhead		556,575 (13.0%)
CO_2 emission	Total	*kg-CO_2*	1,377,831 (100.0%)
	Material		1,363,099 (98.9%)
	Section steel		*466,069 (33.8%)*
	Galvanized steel sheet		*819,936 (59.5%)*
	Prefabrication		*77,094 (5.6%)*
	Transportation		3886 (0.3%)
	Construction		10,846 (0.8%)

A total of 1,377,831 *kg-CO_2* appeared to be emitted for 208 columns. As with the cost, majority of the CO_2 emission (98.9%) occurred from material manufacturing, while 0.3% and 0.8% of total CO_2 emissions occurred from transportation and construction, respectively. However, prefabrication did not greatly affect CO_2 emission, unlike cost. In contrast, the galvanized steel sheet accounted for 59.5% of CO_2 emission although it accounts for 16.9% of the total cost. The CO_2 emission factor of the galvanized steel sheet is considerably larger than the CO_2 emission factor of section steel and prefabrication. For instance, the CO_2 emission factor (1898.00 *kg-CO_2/ton*) of the galvanized steel sheet is roughly 4.5 times larger than the CO_2 emission factor (418.75 *kg-CO_2/ton*) of section steel. For this reason, the CO_2 emission of the Form-LPSRC column was most significantly affected by the amounts of galvanized steel sheet.

3.2. Productivity, cost, and CO_2 emission of SRC columns

With the SRC column, the optimal resource set varied according to the productivity, cost, and CO_2 emission. Alt. #1 was the optimal resource set when productivity was the focus, and Alt. #6 was the optimal resource set when cost was emphasized. Alt. #11 was the optimal resource set in terms of CO_2 emission (refer to Table 7). Thus, this study reviewed the productivity, cost and CO_2 emission of SRC columns under the condition that three of the optimal resource sets were applied.

Table 12 shows that the productivity of SRC columns was calculated at 0.0106 *Cycle/minute*, and that a total of 327.0 h is required to install 208 columns. It required $ 4,324,100 to install 208 SRC columns. The material cost accounted for majority of the

Table 12
Results of SRC column.

Category		Unit	Results		
			Productivity-oriented	Cost-oriented	CO_2 emission-oriented
Productivity		*Cycle/minute*	0.0106	0.0101	0.0084
Construction duration		*hour*	327.0	343.2	412.7
Cost	Total	*$*	4,498,596 (100.0%)	4,324,100 (100.0%)	4,417,135 (100.0%)
	Material		3,497,258 (77.7%)	3,497,258 (80.9%)	3,497,258 (79.2%)
	Section steel		*1,727,785 (38.4%)*	*1,727,785 (40.0%)*	*1,727,785 (39.1%)*
	Deformed rebar		*600,372 (13.3%)*	*600,372 (13.9%)*	*600,372 (13.6%)*
	Form		*1,169,101 (26.0%)*	*1,169,101 (27.0%)*	*1,169,101 (26.5%)*
	Construction		414,564 (9.2%)	262,829 (6.1%)	343,729 (7.8%)
	Overhead		586,773 (13.0%)	564,013 (13.0%)	576,148 (13.0%)
CO_2 emission	Total	*kg-CO_2*	814,175 (100.0%)	809,282 (100.0%)	800,228 (100.0%)
	Material		763,243 (93.7%)	763,243 (94.3%)	763,243 (95.4%)
	Section steel		*634,870 (78.0%)*	*634,870 (78.4%)*	*634,870 (79.3%)*
	Deformed rebar		*122,645 (15.1%)*	*122,645 (15.2%)*	*122,645 (15.3%)*
	Form		*5728 (0.7%)*	*5728 (0.7%)*	*5728 (0.7%)*
	Transportation		5950 (0.7%)	5950 (0.7%)	5950 (0.7%)
	Construction		44,982 (5.5%)	40,089 (5.0%)	31,035 (3.9%)

costs (80.9%), while construction and overhead costs accounted for 6.1% and 13.0%, respectively. In addition, *CO_2* emission reached 800,228 *kg*-for 208 columns. As with cost, the majority of CO_2 emission (95.4%) occurred from material manufacturing, while only 0.7% and 3.9% of the total CO2 emission occurred from transportation and construction, respectively. The CO_2 emission of SRC columns was most affected by section steel (79.3%), whereas the form barely affected CO_2 emission although it accounted for 27.0% of the total cost.

As shown in Table 12, when the optimal resource set for one criterion was applied, the results for the other two criteria were not optimal. For instance, when productivity was maximized, cost increased from $ 4,324,100 to $ 4,498,596 while CO_2 emission increased from 800,228 *kg-CO_2* to 814,175 *kg-CO_2*. When cost was minimized, productivity decreased from 0.0106 *Cycle/minute* to 0.0101 *Cycle/minute* while CO_2 emission increased from 800,228 *kg-CO_2* to 809,282 *kg-CO_2*. When CO_2 emission was minimized, productivity decreased from 0.0106 *Cycle/minute* to 0.0084 *Cycle/minute* while cost increased from $ 4,324,100 to $ 4,417,135.

3.3. *Comparison of results between Form-LPSRC and SRC columns*

Table 13 shows the productivity, cost and CO_2 emission of the Form-LPSRC and SRC columns under the condition that the optimal resource sets were applied. The Form-LPSRC column was 42.45% higher in productivity than the SRC column. A total of 229.6 h of construction duration was required to install 208 Form-LPSRC columns, whereas a total of 327.0 h was required to install 208 SRC columns. Thus, when Form-LPSRC columns are applied in lieu of SRC columns, construction duration can be reduced by 97.5 h.

The Form-LPSRC column led to a cost reduction by cutting down the amount of section steel to be used, whereas prefabrication process caused a considerable cost increase. For this reason, the material cost of the Form-LPSRC columns was 4.29% higher than the material cost of the SRC columns. However, the construction cost of the Form-LPSRC columns was reduced to 75.99% by improving productivity and reducing the amount of equipment and labor. Eventually, if Form-LPSRC columns are installed in lieu of SRC columns, the amount of $57,024 (1.32%) can be saved.

With regard to CO_2 emission, the SRC column was better than the Form-LPSRC column. The CO_2 emissions from the transportation and construction processes for Form-LPSRC columns were lower than those for SRC columns. However, the CO_2 emission from the material manufacturing of Form-LPSRC columns was 78.59% higher than that of SRC columns. Since the CO_2 emission from the material manufacturing process was overwhelmingly higher than the CO_2 emission from the transportation and construction, the CO_2 emission of Form-LPSRC columns was 72.18% higher than the CO_2 emission of SRC columns.

As the SRC columns failed to have the optimal resource set to satisfy all of the productivity, cost, and CO_2 emission parameters, the results shown in Table 13 cannot be simultaneously obtained. For instance, where the optimal resource set to ensure the minimum cost is applied to the construction of SRC columns, a total of

Table 13
Results with the optimal resource set.

Category		Unit	Construction method		Improvement rate (C)[a]
			Form-LPSRC (A)	SRC (B)	
Productivity		*Cycle/minute*	0.0151	0.0106	42.45%
Construction duration		*hour*	229.6	327.0	29.80%
Cost	Total	*$*	4,267,077	4,324,100	1.32%
	Material		3,647,391	3,497,258	−4.29%
	Construction		63,110	262,829	75.99%
	Overhead		556,575	564,013	1.32%
CO_2 emission	Total	*kg-CO_2*	1,377,831	800,228	−72.18%
	Material		1,363,099	763,243	−78.59%
	Transportation		3886	5950	34.68%
	Construction		10,846	31,035	65.05%

Note.
[a] C = (B-A)/B.

343.2 h of construction duration is required to install 208 SRC columns as shown in Fig. 7. Thus, where the minimum cost is targeted, construction duration can be reduced by 113.7 h (33.11%) with the use of Form-LPSRC columns. Where the maximum productivity is targeted, the cost can be reduced by $231,519 (5.15%) with the use of Form-LPSRC columns while the CO_2 emission can increase by 563,657 *kg-CO₂* (69.23%).

4. Discussion

This study compared the productivity, cost and CO_2 emission of Form-LPSRC and SRC columns to identify the characteristics of the Form-LPSRC column, which has been recently invented as an off-site construction method. In terms of productivity, the Form-LPSRC columns were considerably better than the SRC columns. In terms of cost, the Form-LPSRC columns were also better than the SRC columns. Thus, the use of Form-LPSRC columns instead of SRC columns can lead to reduced cost and construction duration. In particular, Form-LPSRC columns can reduce construction duration by at least 29.80% compared with SRC columns. Thus, Form-LPSRC columns are expected to be useful in projects that put a high value on shortening duration at a low cost.

However, in terms of CO_2 emission, Form-LPSRC columns are considerably inferior to SRC columns. The CO_2 emission of the Form-LPSRC columns was higher than the CO_2 emission of the SRC columns, a finding that was attributed to the use of a galvanized steel sheet. Form-LPSRC columns use galvanized steel sheet for 1.6 *mm* thick rib-deck form. The CO_2 emission factor of the galvanized steel sheet (1898.00 *kg-CO₂/ton*) is roughly 4.5 times higher than the CO_2 emission factors of section steel and deformed rebar (418.78 and 240.48 *kg-CO₂/ton*, respectively). For this reason, the CO_2 emission (819,936 *kg-CO₂*) from 432 tons of galvanized steel sheet was roughly 1.8 times higher than the CO_2 emission (466,069 *kg-CO₂*) from 1113 tons of section steel (refer to Table 9). Thus, it is necessary to find a material that will replace galvanized steel sheet to improve the environmental performance of a Form-LPSRC column. For example, 1.6 mm thick plat steel sheet have been developed to replace the galvanized steel sheet referring to the results of this study. The unit weight of developed plat steel sheet (i.e., 19.0 kg/m^2) is 10% lighter than those of galvanized steel sheet (21.6 kg/m^2), and the CO_2 emission factors of plat steel sheet is identical with general section steel (418.78 *kg-CO₂/ton*). If the plat steel sheet is applied to the case project, 819,936 *kg-CO₂* from 432 tons of galvanized steel sheet can be reduced to 165,569 *kg-CO₂* from 393 tons of plat steel sheet. Eventually, total CO_2 emission of Form-LPSRC column is expected to 722,464 *kg-CO₂*, and it shows a reduction of 9.72% compared to CO_2 emission (800,228 *kg-CO₂*) from SRC column.

Meanwhile, this study proposed an assessment method based on CYCLONE simulation. The proposed method assesses the

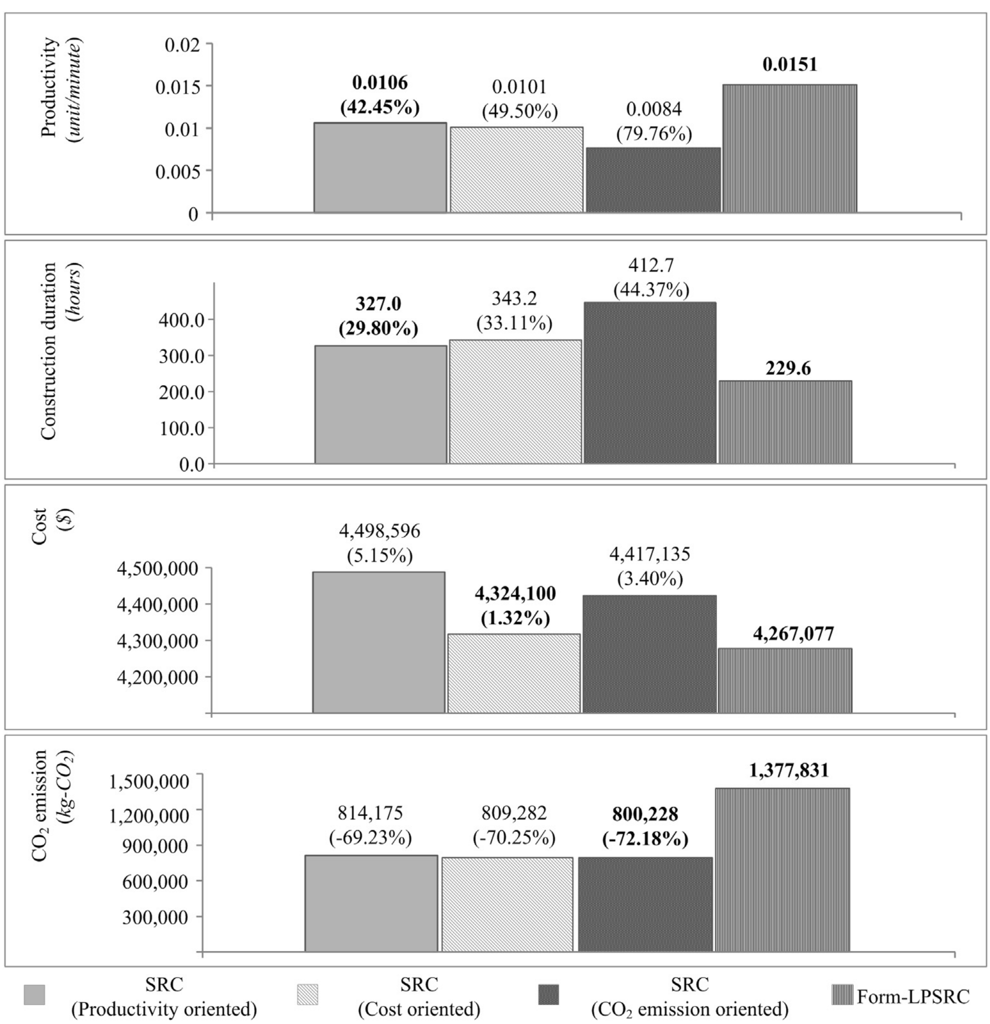


Fig. 7. Comparison of the results of Form-LPSRC and SRC columns.

productivity by reflecting the completion time of construction activity, and then the cost and CO_2 emission by reflecting the working and idling time of construction equipment and labor. The result from the case study showed that it would be possible to easily and accurately assess productivity, cost, and CO_2 emission of the construction process. Thus, the proposed method is expected to be used in establishing an optimal construction plan by simultaneously assessing the productivity, cost, and CO_2 emission of the construction process although it requires additional time and effort in defining all activities of construction processes and modelling the defined activities using CYCLONE elements.

5. Conclusions

The Form-LPSRC column has been invented as an alternative to the SRC column in South Korea. This study compared the productivity, cost, and CO_2 emission of Form-LPSRC and SRC columns to identify the characteristics of the Form-LPRSC column. To this end, a case study was conducted targeting two factory projects that use the same-sized Form-LPSRC and SRC columns.

Web-CYCLONE simulation can calculate the productivity, cost, and CO_2 by considering not only the working and idle time in construction process but also a change in construction duration of each activities. Thus, Web-CYCLONE was used to evaluate the productivity, cost and CO_2 emission of the construction process. The material and overhead costs as well as the CO_2 emission from the material manufacturing and transportation processes were calculated using the equation-based methods presented by the existing studies.

The resource set (i.e., equipment and labor) applied to the construction process can affect productivity, cost and CO_2 emission. Thus, this study calculated and compared the productivity, cost, and CO_2 emission of the Form-LPSRC and SRC columns under the condition that the optimal resource set was applied. The productivity, cost, and CO_2 emission of Form-LPSRC columns were calculated at 0.0151 *Cycle/minute*, $ 4,267,077, and 1,377,831 *kg-CO₂*, respectively. The productivity, cost and CO_2 emission of SRC columns were calculated at 0.0106 *Cycle/minute*, $ 4,324,100, and 800,228 *kg-CO₂*, respectively.

In terms of productivity, Form-LPSRC columns were 42.45% more productive than the SRC columns. The productivity improvement reduced the construction duration by 97.5 h. In addition, the Form-LPSRC columns were more cost-efficient by 1.32% than SRC columns due to the cost savings in the construction process. However, the galvanized steel sheet adopted to improve productivity considerably increased the CO_2 emission of the Form-LPSRC. Although Form-LPSRC columns reduced the CO_2 emission from transportation and construction, their CO_2 emission was 72.18% higher than that of SRC columns, owing to an increase in the CO_2 emission from the material manufacturing process. Thus, Form-LPSRC columns place importance on the reduction of construction duration or cost. However, the use of Form-LPSRC columns is not appropriate for projects that put a high value on minimizing environmental impact. To improve the environmental performance of a Form-LPSRC column, it is necessary to conduct a study on replacing the galvanized steel sheet with materials that have a low environmental impact.

This study identified the characteristics of the Form-LPSRC column, an off-site construction method, by comparing it with the SRC column. A variety of off-site construction methods aside from the Form-LPSRC column are being continuously developed. The characteristics of new off-site construction methods should be identified in further studies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.11.035.

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