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Effects of Half-Precast Concrete Slab System on Construction Productivity

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Abstract: A half-precast concrete slab system (HPCSS) is reported to exhibit excellent structural performance when compared with traditional slab systems. However, there is a lack of extant research examining the construction issues of an HPCSS. Thus, in this study, we analyze the construction process and productivity of applying an HPCSS by using a simulation method with the data collected from an actual construction case. The results indicate that (i) the construction productivity of HPCSS is 1.7 times that of a traditional slab system, (ii) the cost per productivity unit of HPCSS exceeds that of a traditional slab system, and (iii) critical resources affecting the HPCSS productivity include form crew and rebar crew. The results of this study suggest that it is possible to develop an optimal construction plan of a construction site in which an HPCSS is installed, and that the HPCSS can be actively applied in the future.

Keywords: half-precast concrete slab system; construction productivity; construction simulation

1. Introduction

The construction industry is a highly labor-intensive industry facing several issues, including low productivity and construction quality. In order to overcome such problems, several researchers and practitioners have attempted to develop various methods to facilitate mechanical or manufactured procurements for a part of a facility, and this has subsequently led to the proliferation of automation technology in construction. That is, automation construction technologies are used in the construction of facilities, and the use of construction machines instead of construction laborers has led to high effectiveness and quality in assembling several parts of a facility.

In this context, precast concrete (PC) slab systems have been proposed by various researchers because of their advantages in terms of quality, convenience, and construction period. Recently, a half-PC slab (or composite slab) was developed to replace existing construction methods, and to improve the performance of a PC slab system. In general, a half-PC slab system (HPCSS) is defined as a slab system that is pre-stressed and used with slab topping concrete. The structural performance of an HPCSS is known to be higher than that of normal concrete in terms of crack and deflection control because of the manufacturing process employed in controlled environments in a factory [1].

Although several researchers have examined the structural performance of HPCSSs, there is a paucity of research investigating issues concerning construction engineering and management. That is, it is necessary to identify (i) the manner in which relevant work activities are influenced by the application of HPCSS, (ii) the type of work activities comprising the HPCSS that has the maximal impact on determining project success, and (iii) the type of resources required to carry out the aforementioned activities that should be carefully considered to achieve effective construction work. In this context, the aim of the present study involves analyzing the differences between the construction productivity of an HPCSS and that of a traditional slab system. In addition, the study focuses on detailing issues related to an HPCSS based on the results of construction productivity analysis.

Essentially, in the study, the construction productivity of an HPCSS is analyzed to compare an HPCSS and a traditional slab system (i.e., a cast-in-place slab system or CIPSS). This involves selecting and analyzing an actual construction that is built by using both slab systems experimentally to gather the data necessary to compare the construction process and productivity of the HPCSS with the corresponding parameters of a CIPSS. A discrete event simulation technique based on the collected data is used to measure the performance of each slab system in terms of construction productivity, including installation time, resource utilization, and cost effectiveness.

2. State of the Art

Several studies have introduced methods to enhance the structural performance of concrete members. Recent studies have proposed cement-based bonded overlay techniques (i.e., HPCSS) to enhance the structural performance of a PC slab system by topping a layer of cast in-situ reinforced concrete with various materials, including steel fibers and polyvinyl alcohol fibers [2–4]. The purpose of these studies involved adding materials to improve the load-carrying capacity and stiffness of the HPCSS, and their results revealed that the structural performance of the HPCSS was highly dependent on the bonding between the topped layers and the substrate [3].

Most previous studies related to composite slabs have focused on evaluating their structural performance. However, to the best of the authors' knowledge, very few studies have explored the effect of applying an HPCSS from a construction engineering and management (CEM) viewpoint. A careful review of previous studies that focus on the CEM aspects of precast technology, including HPCSS, indicates that the research objective and scope of the extant studies can be divided into the three following categories: (i) production management of precast members [5–8], (ii) benefit analysis of precast technology in terms of waste management, environment, time, and cost [9–11], and (iii) effective installation of precast members [12–14]. With respect to the first category, Chen et al. [5] examined the issue of improving the current production process of the precast elements based on expert opinions. Ko and Wang [6] and Li et al. [7] proposed a decision support system using genetic algorithms to aid project managers in arranging precast member production plans. Yin et al. [8] developed a precast production management system using radio-frequency identification (RFID) to facilitate the production of precast members by considering production quantity, material quantity, and inspection and inventory information. With respect to research related to benefit analysis in conjunction with the application of a precast technique, Ahmed and Avetisyan [9] analyzed the benefits of applying precast normal weight wall panels in terms of the construction time and costs. Dong et al. [10] measured carbon emissions from the application of a precast method with high-rise building construction work. Shen et al. [11] analyzed the benefits of the precast method in terms of reducing waste. With respect to the effective installation of precast members, Li et al. [12] suggested a new system to train precast installation workers to be productive while ensuring awareness of the risks of precast installation works. Nath et al. [13] proposed a method to generate shop drawings of precast members by using building information modeling (BIM) technique. Pan et al. [14] proposed a new technique termed the "Full-span precast launching method" to develop bridge construction technology based on the results of high-speed rail project case studies.

As mentioned previously, there is a lack of studies examining the precast method from the CEM viewpoint, while very few extant studies have focused on improving the production efficiency and delivery issues of precast elements. In addition, although HPCSS was developed to compensate for the several problems of a precast slab system, to the best of the authors' knowledge, very few studies have explored the construction aspects of HPCSS. Hence, the present study focuses on the manner in which an HPCSS application affects related construction works and construction productivity when compared with those of a conventional CIPSS.

3. Case Study of Half-Precast Slab System Construction Work

As mentioned previously, the construction productivity of an HPCSS is based on the comparison results between an HPCSS and a CIPSS. Thus, it is necessary that a case study should be conducted based on an actual project that is constructed using both slab systems (i.e., HPCSS and CIPSS).

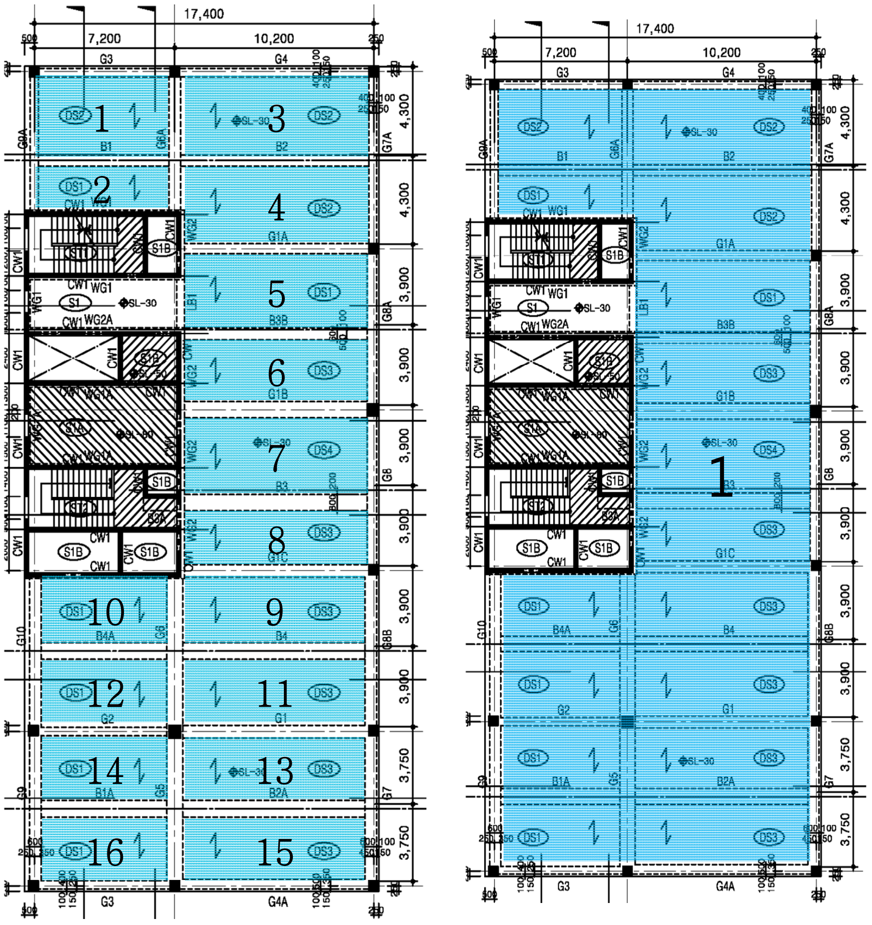
3.1. Case Introduction

Table 1 lists the profile of our selected construction project case. As can be inferred from the table, the building in question was located in Gwangju Metropolitan City, comprising six floors (five floors and one underground floor). With respect to the structure system, (i) the main structure system design was based on the reinforced concrete system, (ii) HPCSS was applied to the slab work at the 5th floor, and (iii) the other floors (i.e., 2nd to 4th floors) were constructed using CIPSS.

Table 1. Details of the case considered in the study.

Items		Major Features
Project name		K Building construction project
Location		Gwangju Metropolitan City, South Korea
Type of building		Office building
Type of structure		Reinforced Concrete (RC) system
Construction area		2138.56 m^2
Gross floor area		6610.98 m^2
Floor plan	Number of Floors	6 floors (five floors and one underground floor)
	HPCSS installed	5th floor
	CIPSS installed	2nd to 4th floors
Floor area installed by HPCSS		564.2 m^2

Figure 1 shows the floor construction plan with the use of each slab system (i.e., HPCSS and CIPSS). As shown in the figure, each floor has a similar space plan involving the design of two separated spaces (i.e., service area and office area), and HPCSS and CIPSS were applied to construct the office area. Figure 1a shows the plan of the 5th floor that was designed such that it was constructed using 16 HPCSS units, while the 2nd to 4th floors were constructed using the traditional slab system (i.e., CIPSS), as shown in Figure 1b. The construction productivity of each slab system was deduced based on the data including resource and duration information (Table 2) collected during the installation work of each system on the same area, and thus, the construction productivity of both slab systems could be considered reliable.



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

Figure 1. Floor plans for half-precast concrete slab system (HPCSS) and a cast-in-place slab system (CIPSS) for the case project: (**a**) 5th floor plan; (**b**) 2nd–4th floor plan.

3.2. Installation Process of Each Slab System

With respect to buildings that adopt a reinforced structure system, the structure system typically comprises four basic elements including column, beam and girder, wall, and slab. In addition, a case showed that there was no difference in terms of installation work of the column, beam, girder, and wall, irrespective of the type of slab works (i.e., HPCSS and CIPSS). That is, in advance of slab installation, it is necessary to complete a common process (CP) of the three following work activities: (i) preparation, (ii) column and beam installation, and (iii) wall installation.

As shown in Figure 2, (i) preparation includes four tasks including marking (CP 1), horizontal stand installation (CP 2), rebar delivery (CP 3), and form and support delivery (CP 4). This is followed by the three following work tasks to complete column and beam installation activity: column rebar installation (CP 5), column form installation (CP 6), and beam form installation (CP 7). With respect to the final common activity, wall installation work requires three common work tasks including wall form installation (one side) (CP 8), wall rebar installation (CP 9), and wall form completion (CP 10). With respect to common work tasks (CPs 1 to 10), form labor, steel labor, and a tower crane are continuously input to implement the work tasks.

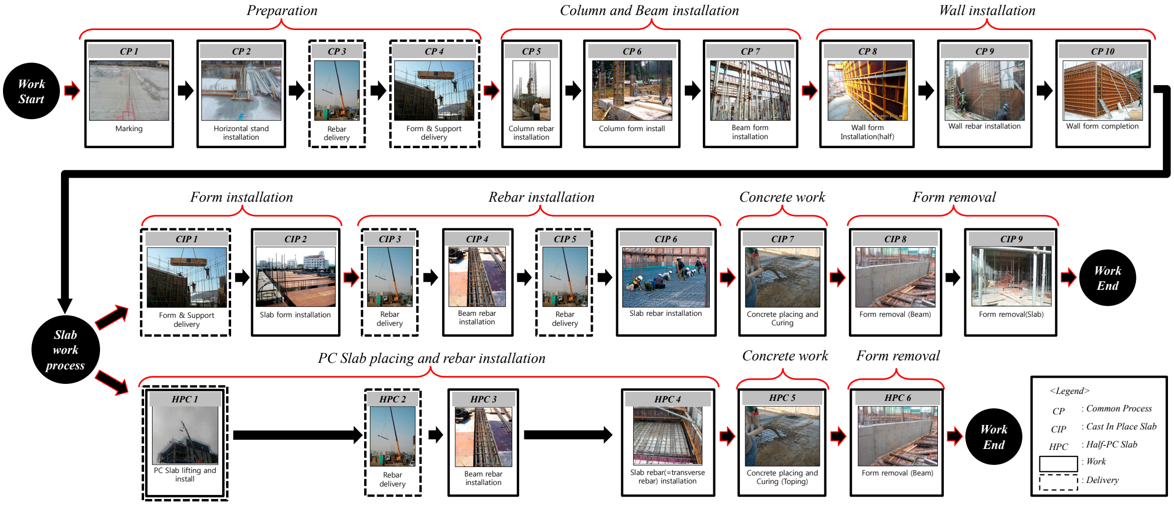


Figure 2. Work process of HPCSS and CIPSS.

After completing the common process, different slab work processes are initiated based on the type of slab system (i.e., HPCSS and CIPSS), as shown in Figure 2. If a conventional slab system (i.e., CIPSS) is applied, then the four following work activities are required: (i) form installation, (ii) rebar installation, (iii) concrete work, and (iv) form removal. As shown in the figure, form installation consists of two work tasks including form and support delivery (CIP 1) and slab form installation (CIP 2). Rebar installation requires two works and two deliveries, namely, beam rebar delivery (CIP 3), beam rebar installation (CIP 4), slab rebar delivery (CIP 5), and slab rebar installation (CIP 5). Following the rebar installation work, concrete placing and curing (CIP 7) is conducted, and this is followed by form removal works for the beam and slab (CIPs 8 and 9). With respect to the CIPSS work process, existing resources such as form and rebar labor and a tower crane are constantly input, and the concrete labor and pump car are freshly input to perform the concrete placement task.

The three following work activities are required to apply an HPCSS: (i) slab placing and rebar installation (HPCs 1 to 4), (ii) concrete work (HPC 5), and (iii) form removal (HPC 6). The differences between HPCSS and CIPSS are identified from the process of slab placing and form removal works. That is, the application of HPCSS allows for the simplification and removal of two work tasks when compared with that of the CIPSS process. First, the form installation and slab rebar installation tasks are eliminated and simplified, and following concrete curing, there is no need for the slab form removal task in the HPCSS process.

4. Simulation Modeling and Implementation

The measurement of the construction productivity of HPCSS and CIPSS was conducted by using the cyclic operation network (CYCLONE) method developed by Halpin and Riggs [15]. This method is widely used in related research fields. Furthermore, CYCLONE is a discrete-event simulation method that focuses on construction work tasks, and thus, this method is widely applied to model repetitive construction work. In addition, CYCLONE is utilized as a management tool to analyze construction productivity based on the logical connections between work tasks, duration, and resources, and thus, CYCLONE can be used to determine the influence of specific work tasks on the overall construction productivity in conjunction with variations in duration and resources assigned to each work task [16,17]. More information on CYCLONE including modeling elements can be found in the study by Halpin and Riggs [15].

4.1. Simulation Modeling

Using CYCLONE and information with respect to the case study including the work processes (i.e., Figure 2) and their precedence relationships, we developed CYCLONE models of CIPSS and HPCSS, as shown in Figures 3 and 4, respectively. As shown in the figures, the two simulation models consist of the two following parts: (i) CP (i.e., elements denoted by the green area in Figure 3) and CIPSS (i.e., elements denoted by the red area in Figure 3) parts in the model for the traditional slab system installation process and (ii) CP (i.e., elements denoted by the green area in Figure 4) and HPCSS (i.e., elements denoted by the blue area in Figure 4) parts in the model for the targeted slab system installation process. In both figures, (1) common work activities (depicted as CP1 to CP10 in Figure 2) are represented by Nodes 1 to 17 in Figures 3 and 4, and (2) indigenous work activities (explained based on CIP 1 to 9 and HPC 1 to 6 in Figure 2) are represented by (i) Nodes 18 to 30 in Figure 3 for CIPSS and (ii) Nodes 18 to 27 in Figure 4 for HPCSS. Moreover, it is assumed that construction for a floor is completed after the completion of concrete curing and form removal tasks, which follow tasks of concrete placing work. However, both simulation models did not include two tasks after concrete placement, namely, concrete curing and form removal works, because it is not necessary to input specific resources for the concrete curing work, and this otherwise creates noise in analyzing other labor crew productivities and idleness. In addition, form removal work cannot be initiated for a long time (i.e., typically 4 to 13 working days), until concrete curing is finished, and this subsequently influences crew productivity measurement.

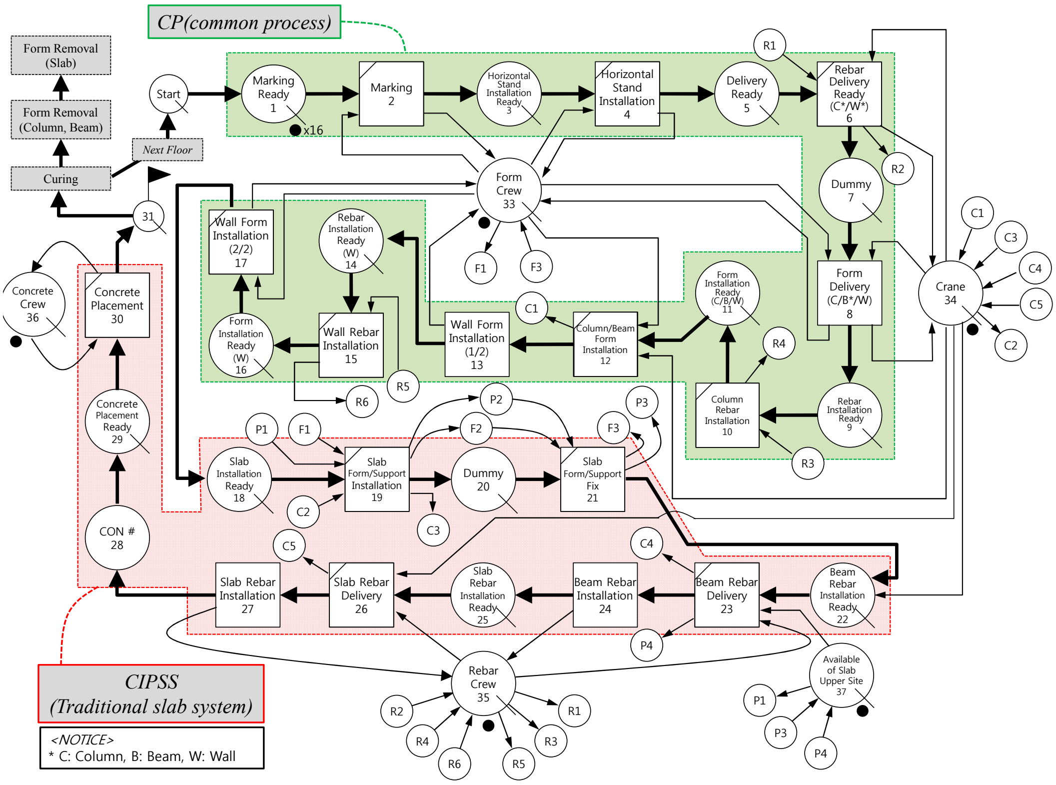


Figure 3. Cyclic operation network (CYCLONE) model for CIPSS installation work.

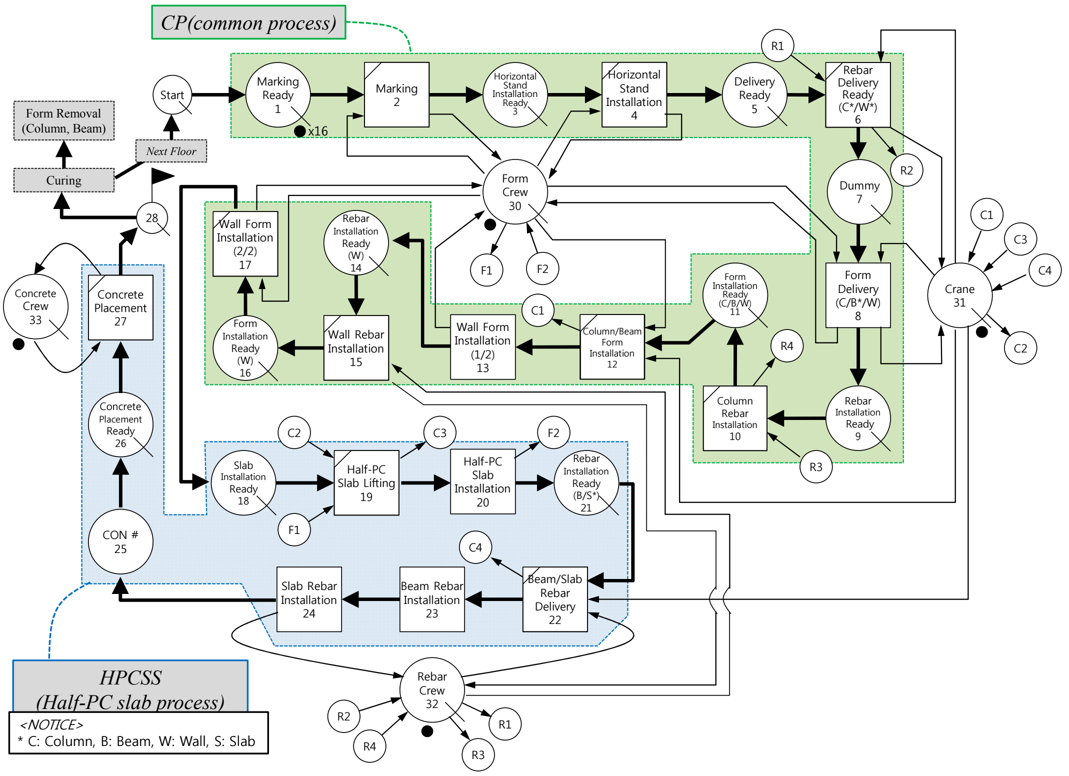


Figure 4. CYCLONE model for HPCSS installation work.

4.2. Simulation Model Implementation and Validation

Here, we remark that it is necessary to define information related to duration and resources with CYCLONE modeling elements COMBI, NORMAL, and QUEUE nodes to implement the CYCLONE simulation. The coding directions of CYCLONE indicated that (i) the duration data for each work task that is connected to another, in conjunction with the precedence relationship, is located at the COMBI or NORMAL nodes and (ii) the resource type and quantity of each work task are located at the QUEUE node. Information related to duration and resources is stochastically collected based on construction records or specifications of each task while the duration data of newly adopted work tasks are often gathered based on expert opinions (i.e., a deterministic method). Extant research indicates that it is possible to acquire reliable data on work duration if it is possible to derive various probabilistic distributions including normal, beta, and triangular distributions from raw data. Furthermore, it is widely known that a beta distribution is appropriate for work duration simulation data [18]. However, it is not possible to follow the beta distribution in this study due to practical limitations in terms of the low number of HPCSS cases. Conversely, a triangular distribution is not significantly affected by the number of samples in the data, and thus, it can ensure that the collected data is reliable and accurate [17,19,20].

Therefore, duration data of work tasks on CP and CIPSS are set by using a triangular distribution based on information to construct the 2nd, 3rd, and 4th floors of the building of interest (“case building”). Similarly, duration data of the work tasks on HPCSS are defined using information on installing 16 half-PC slabs on the 5th floor. In addition, resource data for each work task corresponding to CP, CIPSS, and HPCSS are derived from construction records of the case building.

Table 2 lists the resource and duration input data for each work task shown in Figures 3 and 4. For example, from the table, we note that marking (Node 2) and horizontal stand installation (Node 4) most probably required 8 h based on the construction record of the case project. In addition, the duration of concrete placement (Node 27 in HPCSS and Node 30 in CIPSS) is set at 8 h by comparatively using a deterministic method.

Table 2. Resource and duration data for each work task.

Remark	Node	Work Tasks	Resource		Duration (hours)		
			Crew	Equipment	Minimum	Most Likely	Maximum
CP	2	Marking	Form	-	7	8	9
	4	Horizontal stand install	Form	-	7	8	9
	6	Rebar delivery (C/W)	Rebar	Crane	0.75	1	1.25
	8	Form delivery (C/W/B)	Form	Crane	2.5	3	3.5
	10	Column rebar installation	Rebar	-	15	16	17
	12	Column/beam form installation	Form	Crane	26	28	30
	13	Wall form installation (1/2)	Form	-	3	4	5
	15	Wall rebar installation	Rebar	-	7	8	9
	17	Wall form installation (2/2)	Form	-	3	4	5
CIPSS	19	Slab form/support delivery	Form	Crane	3	4	5
	21	Slab form installation	Form	-	52	56	60
	23	Beam rebar delivery	Rebar	Crane	2.5	3	3.5
	24	Beam rebar installation	Rebar	-	22	24	26
	26	Slab rebar delivery	Rebar	Crane	2.5	3	3.5
	27	Slab rebar installation	Rebar	-	22	24	26
	30	Concrete placement	Concrete	Pump Car	-	8	-
HPCSS	19	Half-PC slab lifting	Form	Crane	15	16	17
	20	Half-PC slab installation	Form	-	7	8	9
	22	Beam/Slab rebar delivery	Rebar	Crane	2.5	3	3.5
	23	Beam rebar installation	Rebar	-	22	24	26
	24	Slab rebar installation	Rebar	-	7	8	9
	27	Concrete placement	Concrete	Pump Car	-	8	-

The simulation was implemented with the simulation models, and input data represented by Figures 3 and 4 and Table 2 to analyze the construction productivity for types of work tasks and resources. The simulation results show that (i) first, the required cycle time for constructing each floor is calculated as 174.6 h and 103.3 h for CIPSS and HPCSS, respectively, (ii) construction productivity corresponds to 0.0057 (cycle/h) and 0.0097 (cycle/h) for CIPSS and HPCSS, respectively, and (iii) finally, these results can be interpreted as the delivery of higher productivity by HPCSS. A detailed explanation of these results is described in the "Findings and discussion" section.

In order to conduct a simulation study of the effects of HPCSS on construction productivity, it is necessary to verify if the developed simulation model can adequately reflect actual construction data [20]. In the study, this verification was conducted based on comparing two types of data, namely, "collected data" from the actual case and "simulated data" from each model. That is, the study explores the following: (i) the extent to which the actual and simulated durations are identical for each work task and (ii) the manner in which events during the simulation chronologically occurred when compared with the actual construction process.

Table 3 lists the percentage difference between the simulated and actual durations for each work task. For example, with respect to Node 2 (i.e., "marking" in Table 2), the simulated and actual durations correspond to 7.9 h and 8.0 h, respectively, and subsequently, the percentage difference of sum is estimated as 1.935% (i.e., $|0.1019 - 0.1000|/0.1000 \times 100$). A similar method is used to determine that after calculating the percentage difference of the sub-totals for all tasks (i.e., Nodes 2 to 30 for CIPSS and Nodes 2 to 27 for HPCSS), the lowest value corresponds to 0.443% for Node 27 for CIPSS, while the highest value corresponds to 23.871% for Node 6 for CP. Furthermore, (i) Nodes in the CP process (i.e., Nodes 2 to 17) exhibit an average difference of 85.723%, (ii) Nodes in CIPSS display an average difference of 3.096%, and (iii) Nodes in HPCSS exhibit an average difference of 12.710%. The results indicate that the developed models could be interpreted as being reliable in terms of the accuracy of construction duration.

Table 3. Simulated and actual durations for each work task.

Remark	**Node**	**Durations From Simulation**		**Duration from Case Study**		**Percentage Difference (%) (=∣aa − bb∣/ bb × 100)**
		Measured (a)	**Rate of (a) on Sum (aa)**	**Measured (b)**	**Rate of (b) on Sum (bb)**	
CP	2	7.9	0.1019	8.0	0.1000	1.935
	4	7.8	0.1006	8.0	0.1000	0.645
	6	1.2	0.0155	1.0	0.0125	23.871
	8	2.8	0.0361	3.0	0.0375	3.656
	10	14.9	0.1923	16.0	0.2000	3.871
	12	27.9	0.3600	28.0	0.3500	2.857
	13–17	15	0.1935	16.0	0.2000	3.226
	sum	77.5	1.0000	80.0	1.0000	
			Average			5.723
CIPSS	19	3.9	0.0324	4.0	0.0328	1.286
	21	55.4	0.4598	56.0	0.4590	0.160
	23	2.5	0.0207	3.0	0.0246	15.629
	24	24.1	0.2000	24.0	0.1967	1.667
	26	3	0.0249	3.0	0.0246	1.245
	27	23.6	0.1959	24.0	0.1967	0.443
	30	8	0.0664	8.0	0.0656	1.245
	Sum	120.5	1.0000	122.0	1.0000	
			Average			3.096
HPCSS	19–20	18.6	0.3131	24.0	0.3582	12.584
	22	3	0.0505	3.0	0.0448	12.795
	23	23.7	0.3990	24.0	0.3582	11.385
	24	6.1	0.1027	8.0	0.1194	13.994
	27	8	0.1347	8.0	0.1194	12.795
	Sum	59.4	1.0000	67.0	1.0000	
			Average			12.710

Figure 5 compares the simulation results and actual case records, which enables us to examine as to whether the operation of the developed simulation model is identical to the actual work process. That is, the figure lists the HPCSS events that (i) are chronologically completed during the implementation of simulation (i.e., the top panel of the figure) and (ii) chronologically reported from actual construction records (i.e., bottom panel of the figure). In addition, based on COMBI (Nodes 19, 22, and 27) and NORMAL (Nodes 20, 23, and 24) elements with defined durations, the figure captures the simulated events from the initial task of half-PC installation (i.e., Node 19 in Figure 4) assuming that the initiation time of node 19 is converted to zero. The principal results of comparison are as follows:

As shown in the figure, the installation of the first HPC slab unit is performed in conjunction with the following five tasks: HPC slab lifting (chronological list 1), HPC slab installation (chronological list 2), rebar delivery (chronological list 3), beam rebar installation (chronological list 5), and slab rebar installation (chronological list 7). Under this condition, the simulation time for the aforementioned tasks corresponds to 3.6 h while actual construction time for the first HPC slab unit from the record corresponds to 4.0 h, as denoted by "A" in the figure. Similarly, the installation work for the second HPC slab unit is completed in 6.6 h as per the simulation result and 6.0 h as per the actual record (Refer to "B" in Figure 5). This result suggests that the time to complete the first slab as measured by the simulation is less than the time indicated by the actual record (i.e., 0.6 h), while the time to complete the second slab unit in the actual record is less than that in the simulation by a maximum of 0.6 h. In addition, the time to complete the installation of the last slab (i.e., 16th slab) is 41.2 h as per the simulation and 48 h per by the actual record. According to Hong et al. [19], a simulation model developed using the actual data can yield (i) productivity rates that are closer to that in an ideal situation and (ii) lower uncertainty. Subsequently, the results of the simulation are superior in consistency when compared with those obtained from the actual data. From this viewpoint, the actual record reveals a buffer between the two works, as indicated by "C" in Figure 5, although this buffer does not exist in the simulation result. Consequently, this indicates that the simulated completion time of the final unit is less than that in the actual record.

Moreover, the simulation result indicates that the work tasks for the first and second units of slabs are simultaneously ongoing, and this is also observed in the operations from the actual construction record (Refer to "D" in Figure 5). Thus, the aforementioned results indicate that the developed simulation models are sufficiently accurate to be of value in further analysis.

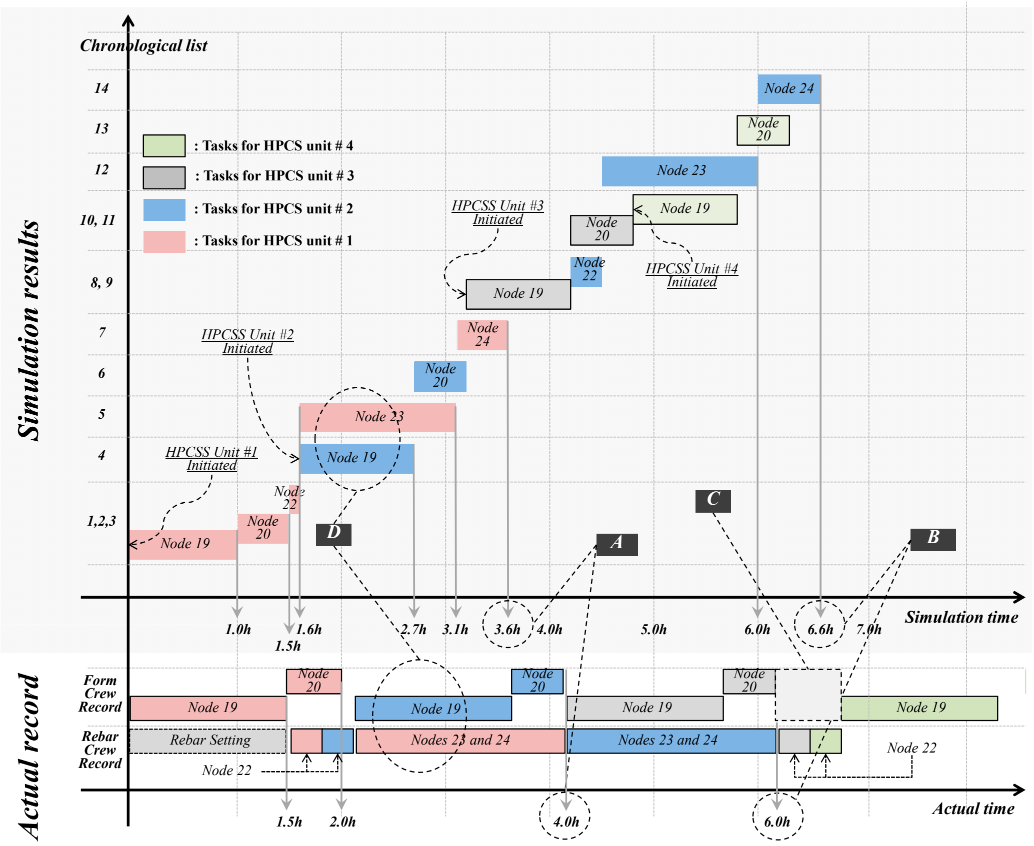


Figure 5. Chronological list of simulation results and actual records.

5. Findings and Discussion

The work productivities of each set of crew and equipment are explored based on the simulation statistics, to identify the advantages and disadvantages of HPCSS over those of CIPSS. The results indicate that the most idle resources in the two slab methods correspond to "concrete crew" (95.42% idle for CIPSS and 92.26% idle for HPCSS in Table 4) followed by "crane" (70.97% for CIPSS and 41.71% for HPCSS), "rebar crew" (50.79% for CIPSS and 34.98% for HPCSS), and "form crew" (0.03% for CIPSS and 0.22% for HPCSS in Table 4). In summary, the types of resources for installing HPCSS exhibit relatively less idle states, and this suggests that each crew and equipment for HPCSS work in a smoother manner with less interruption when compared with the case of CIPSS. Furthermore, the relatively low idle state also indicates that it is necessary to consider additional work crew or equipment in terms of improvements in work productivity.

In addition to the basic analysis shown above, we conduct a sensitivity analysis to examine changes in productivity due to the changes in input resources. The sensitivity analysis determines the optimal combination of resource inputs and identifies resources that have a significant influence on the work productivity of HPCSS and CIPSS. Conversely, a cost data survey of the input resources is used to analyze work productivity with respect to the input cost.

Table 4. Simulation results in terms of percent of idleness of a resource.

Division	Node	Resource	Average Units Idle	Times not Empty	Average Wait Time	% Idle
CIPSS	33	Form Crew	0	0	0	0.03
	34	Crane	0.8	124	1.3	70.97
	35	Rebar Crew	0.5	88.7	1.1	50.79
	36	Conc. Crew	1	166.6	83.3	95.42
HPCSS	30	Form Crew	0	0.2	0	0.22
	31	Crane	0.5	43.1	0.5	41.71
	32	Rebar Crew	0.4	36.1	0.6	34.98
	33	Conc. Crew	0.9	95.3	47.6	92.26

The change in the work crew for the sensitivity analysis is determined by analyzing the construction record. That is, based on the actual working daily report, the form crew is input from at least one team, up to a maximum of three teams, such that the change in the form crew amount is determined from 1 to 3. The same method is applied to determine the change in the crane from 1 to 2, the rebar crew from 1 to 3, and the concrete crew from 1 to 2. This process generated 36 scenarios based on the resource combination (Table 5).

Table 5. Sensitivity analysis results based on resource combination scenarios.

Scenario	Resource Information				Construction Productivity (Cycle/Simulation Time) (a)		Install Time (h/cycle) (b)		Cost Productivity (US$/Simulation Time) (c)	
	Form Crew	Crane	Rebar Crew	Conc. Crew	HPCSS	CIPSS	HPCSS	CIPSS	HPCSS	CIPSS
1	1	1	1	1	0.0097	0.0057	103.09	175.44	3.2303	2.8323
2	1	1	1	2	0.0096	0.0057	104.17	175.44	3.4046	3.0213
3	1	1	2	1	0.0108	0.0066	92.59	151.52	5.3180	4.8846
4	1	1	2	2	0.0112	0.0068	89.29	147.06	5.7779	5.2969
5	1	1	3	1	0.0107	0.0069	93.46	144.93	6.9914	6.8161
6	1	1	3	2	0.0107	0.0070	93.46	142.86	7.2896	7.1034
7	1	2	1	1	0.0100	0.0056	100.00	178.57	4.6733	3.9409
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
13	2	1	1	1	0.0102	0.0062	98.04	161.29	3.4625	3.1654
14	2	1	1	2	0.0102	0.0062	98.04	161.29	3.7154	3.3955
15	2	1	2	1	0.0125	0.0075	80.00	133.33	6.2629	5.6630
16	2	1	2	2	0.0123	0.0074	81.30	135.14	6.4674	5.8446
17	2	1	3	1	0.0131	0.0079	76.34	126.58	8.6763	7.8726
18	2	1	3	2	0.0131	0.0079	76.34	126.58	9.0204	8.1598
19	2	2	1	1	0.0130	0.0067	76.92	149.25	6.2096	4.8077
20	2	2	1	2	0.0130	0.0067	76.92	149.25	6.5034	5.0314
21	2	2	2	1	0.0181	0.0082	55.25	121.95	5.7748	7.8539
22	2	2	2	2	0.0184	0.0083	54.35	120.48	6.1043	8.2234
23	2	2	3	1	0.0198	0.0087	50.51	114.94	7.9178	6.9925
24	2	2	3	2	0.0197	0.0087	50.76	114.94	8.1189	7.1771
25	3	1	1	1	0.0105	0.0063	95.24	158.73	3.6477	3.2936
26	3	1	1	2	0.0104	0.0063	96.15	158.73	3.8688	3.4920
27	3	1	2	1	0.0127	0.0075	78.74	133.33	6.4744	5.7538
28	3	1	2	2	0.0128	0.0076	78.13	131.58	6.8355	6.0794
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
34	3	2	2	2	0.0199	0.0087	50.25	114.94	6.6799	5.8298
35	3	2	3	1	0.0223	0.0094	44.84	106.38	9.0139	7.5675
36	3	2	3	2	0.0217	0.0093	46.08	107.53	9.0530	7.7583

Table 5 lists the results of the sensitivity analysis. As can be observed from the table, the simulation results for each scenario are categorized into the three following aspects: "construction productivity" (column (a)), "installation time" (column (b)), and "cost productivity" (column (c)). We note that the construction productivity of HPCSS is generally higher than that of CIPSS. In other words, the HPCSS productivity ranges from 0.0223 (cycle/simulation time, scenario 35) to 0.0096 (cycle/simulation time, scenario 2), and the CIPSS productivity ranges from 0.0094 (cycle/simulation time, scenario 35) to 0.0057 (cycle/simulation time, scenarios 1 and 2). Corresponding to column (a) in Table 5, Figure 6 shows the productivity chart for each slab system for each scenario. As shown in the figure, (i) HPCSS productivity increases with increase in the resource input, and (ii) CIPSS productivity exhibits a relatively moderate increase despite additional resource input. Moreover, the installation time based on the scenario exhibits a similar tendency relative to construction productivity.

The cost data of each crew and equipment are examined to analyze the cost per unit time based on the scenarios. The estimation of the unit cost for each crew involved the following: (i) analyzing the detailed construction labor of each crew via analysis of the construction records, and (ii) considering the acquisition of daily labor costs from Korea price information (KPI) [21]. Based on this method, the unit cost of each crew is calculated as follows: (i) unit cost of form crew = 3.99 (US\$/m^2 × hour), (ii) unit cost of rebar crew = 80.86 (US\$/ton × hour), and (iii) unit cost of concrete crew = 12.15 (US\$/m^3 × hour). The rental cost of the tower crane (25 Ton) is calculated as 68.75 (US\$/hour) based on KPI (KPI 2016). The cost productivity based on each resource combination is calculated based on the above cost data. As listed in Table 5, the highest cost performance of HPCSS is observed to be 5.7748 (US\$/simulation time) for scenario 21, while the cost productivity of CIPSS corresponds to 2.8323 (US\$/simulation time) for scenario 1.

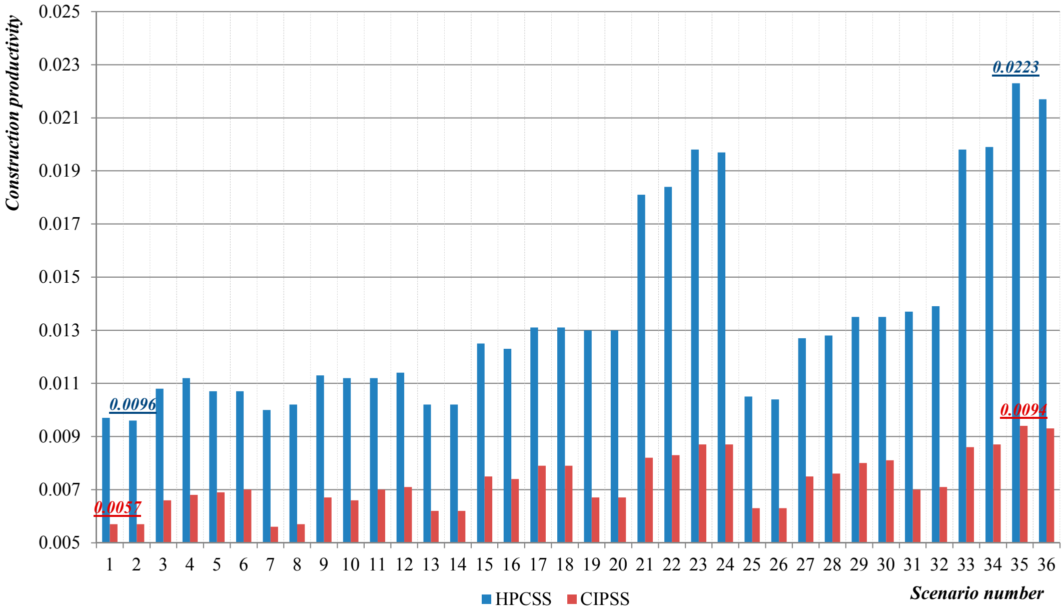


Figure 6. Construction productivity for each scenario.

Figure 7 shows the "cost productivity" (i.e., column (c) values/column (a) values in Table 5) based on the above simulation results. As shown in the figure, scenario 21 of HPCSS corresponds to the highest cost productivity (i.e., 319.35 US\$/cycle), and the highest value of cost productivity for CIPSS corresponds to 497.75 (US\$/cycle) for scenario 1. Overall, the cost productivity value of HPCSS is superior to that of CIPSS while HPCSS and CIPSS tend to differ in scenarios 20 to 23. That is, the cost productivity value of CIPSS deteriorated under conditions in which the rebar crew was added and concrete crew was reduced by one crew set (i.e., conditions from scenario 20 to scenario 21). In contrast, the cost productivity is optimized for HPCSS.

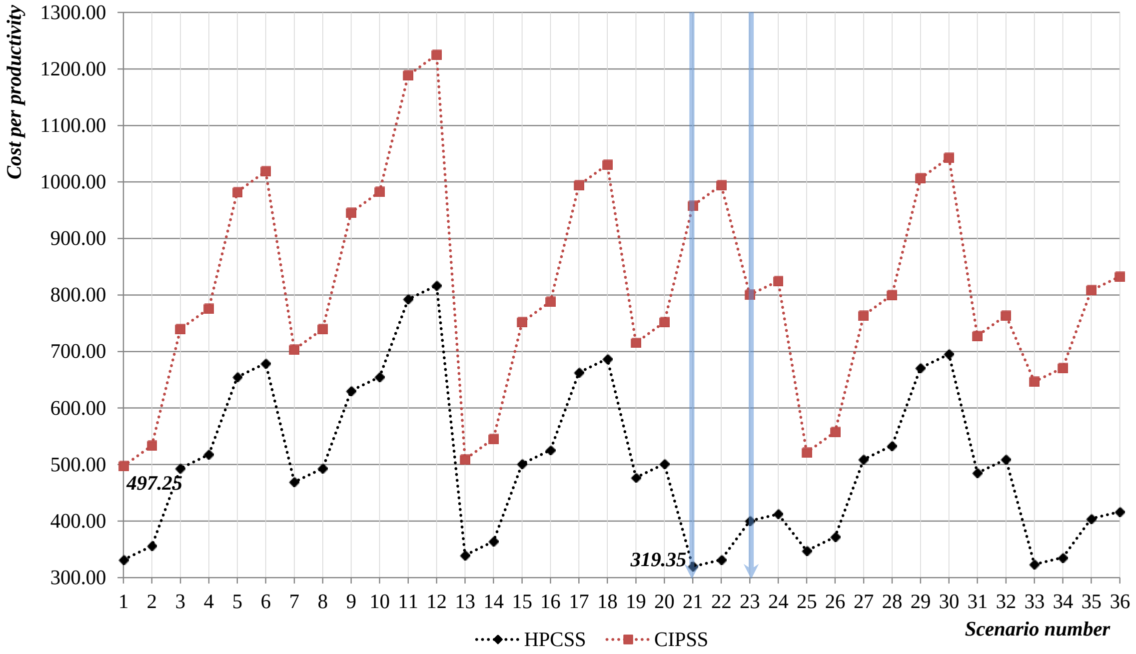


Figure 7. Cost productivity of each scenario.

From the above results, we note that the productivities of HPCSS and CIPSS are affected by the types of resources. Therefore, multivariate analysis of variance (MANOVA) method is applied to further analyze the manner in which the four resources analyzed in the study affect the work productivity of HPCSS and CIPSS. In particular, MANOVA is useful when applied in conjunction with experimental designs, that is, research designs in which a researcher directly controls one or more independent variables to determine the effect on the dependent variables [22]. Four independent variables are defined to apply MANOVA (form crew, crane, rebar crew, and conc. crew), and two dependent variables are defined as HPCSS and CIPSS work productivity (i.e., column (a) of Table 5). The MANOVA test was implemented by using SPSS Ver. 22 software in our study.

Table 6 lists the key results of the MANOVA test. From the table, we note that the resources affecting the HPCSS work productivity are form crew ($F = 6.775$, Sig. = 0.003 ($p < 0.01$)) and rebar crew ($F = 6.775$, Sig. = 0.003 ($p < 0.01$)); the crane and concrete crew are not affected because all the significance levels are greater than 0.1. Similarly, the crane ($F = 2.606$, Sig. = 0.035 ($p < 0.05$)) is the only factor that affects the work productivity of CIPSS.

Table 6. Results of multivariate analysis of variance (MANOVA) test.

Subject effects	Dependent Variable	df	Mean Square	*F*	Sig.
Construction productivity (HPCSS)	Form crew	26	0.878	6.775	0.003
	Crane	26	0.295	1.990	0.141
	Rebar crew	26	0.878	6.775	0.003
	Conc. crew	26	0.218	0.588	0.860
Construction productivity (CIPSS)	Form crew	21	0.833	1.795	0.132
	Crane	21	0.341	2.606	0.035
	Rebar crew	21	0.857	2.000	0.093
	Conc. crew	21	0.206	0.619	0.844

6. Conclusions

Previous studies have mostly focused on actively developing various precast concrete slab systems to solve the problems of reducing the functional manpower, aging skilled workers, and improving construction quality. The systems reportedly possess advantages in terms of improving construction quality, as well as improving workability and shortening construction periods. In general, the results of these studies indicate that HPCSS displays excellent structural performance and facilitates easy construction because it does not require supports, when compared with the existing CIPSS. Despite these advantages, extant studies on HPCSS mostly focus on the structural performance of HPCSS, and subsequently, there is a paucity of studies examining the construction issues involved in HPCSS. Thus, the present study involved analyzing detailed construction issues, including the construction process and work productivity aspects arising from the application of HPCSS. The study focused on the detailed data of construction cases in which HPCSS and CIPSS are applied simultaneously. For this purpose, discrete event simulation and multivariate data analysis techniques were used.

The simulation results indicate the following: (i) the work productivity of HPCSS is 1.7 times that of CIPSS (i.e., 0.0097 (HPCSS)/0.0057 (CIPSS) = 1.701754, Table 5), and (ii) the percentage idle state of the concrete crew, crane, and rebar crew is high in both systems (Table 5). Our sensitivity analysis, based on the simulation results, indicates that the work productivity of HPCSS generally increases with increase in the resource input, and the productivity of CIPSS increases in a relatively moderate manner (Figure 6). When the installation cost is considered, HPCSS is generally superior to CIPSS in terms of cost per productivity unit (Figure 7). Further, the MANOVA test results indicate that the resources that affect the productivity of HPCSS are form crew and rebar crew, while the use of the crane affects CIPSS productivity (Table 6).

We believe that the results of the study can be used to develop an optimal construction plan for a construction site in which HPCSS is installed and that HPCSS will find increased application in future.

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References

1. Lee, J.; Yoon, J.; Kang, H. Combined half precast concrete slab and post-tensioned slab topping system for basement parking structures. *J. Struct. Integr. Maint.* **2016**, *1*, 1–9. [CrossRef]
2. Cho, C.; Kappos, A.; Moon, H.; Lim, H. Experiments and failure analysis of SHCC and reinforced concrete composite slabs. *Eng. Fail. Anal.* **2015**, *56*, 320–331. [CrossRef]
3. Mansour, F.; Bakar, S.; Ibrahim, I.; Marsono, A.; Marabi, B. Flexural performance of a precast concrete slab with steel fiber concrete topping. *Constr. Build. Mater.* **2015**, *75*, 112–120. [CrossRef]
4. Said, S.; Razak, H.; Othman, I. Flexural behavior of engineered cementitious composite slabs with polyvinyl alcohol fibers. *Constr. Build. Mater.* **2015**, *75*, 176–188. [CrossRef]
5. Chen, J.; Yang, L.; Tai, H. Process reengineering and improvement for building precast production. *Autom. Constr.* **2016**, *68*, 249–258. [CrossRef]
6. Ko, C.; Wang, S. GA-Based decision support systems for precast production planning. *Autom. Constr.* **2010**, *19*, 907–916. [CrossRef]
7. Li, S.; Tserng, H.; Yin, S.; Hsu, C. A production modeling with genetic algorithms for a stationary precast supply chain. *Expert Syst. Appl.* **2010**, *37*, 8406–8416. [CrossRef]
8. Yin, S.; Terng, H.; Wang, J.; Tsai, S. Developing a precast production management system using RFID technology. *Autom. Constr.* **2009**, *18*, 677–691. [CrossRef]
9. Ahmed, A.; Avetisyan, H. Reducing time and cost of construction projects by improving the properties of precast normal weight wall panels. *Procedia Eng.* **2016**, *145*, 1066–1073. [CrossRef]
10. Dong, Y.; Jaillon, L.; Chu, P.; Poon, C. Comparing carbon emissions of precast and cast-in-site construction method—A case study of high-rise private building. *Constr. Build. Mater.* **2015**, *99*, 39–53. [CrossRef]

11. Shen, L.; Tam, V.; Li, C. Benefit analysis on replacing in situ concreting with precast slabs for temporary construction works in pursuing sustainable construction practice. *Resour. Conserv. Recycl.* **2009**, *53*, 145–148. [CrossRef]
12. Li, H.; Lu, M.; Chan, G.; Skitmore, M. Proactive training system for safe and efficient precast installation. *Autom. Constr.* **2015**, *49*, 163–174. [CrossRef]
13. Nath, T.; Attarzadeh, M.; Tiong, R.; Chidambaram, C.; Yu, Z. Productivity improvement of precast shop drawings generation through BIM-Based process re-engineering. *Autom. Constr.* **2015**, *54*, 54–68. [CrossRef]
14. Pan, N.; Chiu, T.; Chen, K. Full-span precast launching method analysis with dynamic simulation—Case studies of Taiwan high-speed rail project. *Autom. Constr.* **2008**, *17*, 592–607. [CrossRef]
15. Halpin, D.W.; Riggs, L.S. *Planning and Analysis of Construction Operations*; Wiley: New York, NY, USA, 1992.
16. Han, S.; Lee, S.; Hong, T.; Chang, H. Simulation analysis of productivity variation by GPS implementation in earthmoving operations. *Can. J. Civ. Eng.* **2006**, *33*, 1105–1114. [CrossRef]
17. Hong, T.; Hastak, M. Simulation study on construction process of FRP bridge deck panels. *Autom. Constr.* **2007**, *16*, 620–631. [CrossRef]
18. AbouRizk, S.M.; Halpin, D.W.; Wilson, J.R. Fitting beta distributions based on sample data. *J. Constr. Eng. Manag.* **1994**, *120*, 288–305. [CrossRef]
19. Hong, T.; Cho, K.; Hyun, C.; Han, S. Simulation based Schedule estimation model for ACS-Based core wall construction of high-rise building. *J. Constr. Eng. Manag.* **2011**, *137*, 393–402. [CrossRef]
20. Cho, K.; Hong, T.; Hyun, C. Space zoning concept-based scheduling model for repetitive construction process. *J. Civ. Eng. Manag.* **2013**, *19*, 409–421. [CrossRef]
21. Korea Price Information. Available online: http://www.kpi.or.kr/ (accessed on 2 March 2017).
22. Hair, J.; Black, W.; Babin, B.; Anderson, R.; Tatham, R. *Multivariate Data Analysis*, 6th ed.; Pearson Education: Upper Saddle River, NJ, USA, 2006.