ANALYSIS OF THE PROCESS OF FABRICATION OF STEEL STRUCTURES USING AN AUTOMATIC CONSTRUCTION SYSTEM

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ABSTRACT: An automatic construction system in Korea is now at the stage of the full automation like in Japan, and an actual pilot project is going to be built in 2009. However, in developing a new construction system that has never been implemented before, there is a need to assess the performance and to consider the uncertainty of the system. The program evaluation and review technique (PERT) allows dealing with this uncertainty. Thus, this paper implements an analysis of the process of steel fabrication and makes suggestions for time-related problems arising from the analysis. The time required for steel erection by the automatic system was compared with that in the traditional method. In the result, finding out another construction process and improving robot performance were proposed to resolve the problems. The results will contribute to promoting the development of an efficient system for the new automatic construction system.

Keywords: Steel fabrication, Automatic construction system, Time, Construction process analysis, Program evaluation and review technique (PERT)

1. INTRODUCTION

In data presented by the US Bureau of Labor Statistics [1] structural steel was ranked fourth, with 58.2 fatalities per 100,000 workers, in construction-related accidents. About 33% of all fatalities in the construction industry are related to falls. In steel erection, 65% of fatalities are the result of falls [2]. Shim [3] has reported that the number of workers on construction sites in Korea would be in insufficient, 423,000 for demand required in 2010. An automatic construction system has been considered as one of the solutions to alleviate the above problems.

In the early 1990s, several Japanese construction firms developed fully automatic construction systems. A number of benefits were proved by these systems, including improved construction productivity, less dependence on labor, and improved safety and quality. Recently, the Korean government has been strongly supporting research into a robot-based construction automation system (RCA) in frameworks of high-rise buildings. The system consists of a robot and numerous kinds of attachments and plays a role in connecting the joints in a steel structure. It enables workers to complete steel fabrication works without climbing high. Moreover, the robot for assembling joints replaces skilled labor fast and in an accurate manner. It is a helpful alternative for the shortage of skilled labor and the high accident rate on steel structure sites.

On the other hand, it is true that there are differences between the RCA system and the Japanese fully automatic construction system due to inherent construction conditions, such as different preferences for technical methods. It means that the RCA is a system applied first in the world. Because of rare historical data and restricted information, the automatic system remains unpredictable. In particular, fabrication work on a steel structure becomes the work area of most concern to the robot application in the RCA system.

Therefore, the purpose of this study was to analyze the construction process of steel fabrication work using the RCA system in order to identify nonefficient tasks and/or conflicts. The comparison of individual processes and total times calculated from both traditional construction and the RCA system will be meaningful for understanding the efficiency of the process analyzed. As a result, this study contributes to promoting the development of an efficient system for the new automatic construction system.

2. BACKGROUND

2.1 Previous Construction Automation

Japan plays a leading part in automatic construction using robots [4]. As shown in Table 1, in the 1980s, Japan achieved great results in individual robots for construction sites. Moreover, complete automatic systems for building construction were developed from the early 1990s. Many buildings were constructed by the automatic systems of various general contractors such as Obayashi

Corporation and Shimizu Corporation [5]. Although a complete automatic system for building construction contributes to improving the image of the construction industry and alleviating staffing problems, it still has the problems of very large operating costs and the difficulty of developing equipment for practical applications [6].

Table 1. Previous systems for automation

Period	Characteristic	Techniques
1980s	Introduction of robots on building sites	Spraying Smoothing concrete Distributing materials Installing facades
1990s	Fully automatic construction system	SMART (Shimizu manufacturing system by advanced robotics technology) ABCS (automated building construction system)
2002	Humanoid robots	Fitting interior walls Helping to carry slabs Driving forklift trucks

2.2 Robot-based Automatic Systems in Korea

In Korea, automatic equipment and robots which could substitute for labor in specialized tasks such as installing facades and smoothing concrete have been developed and applied to some construction sites since 1990 [7]. Recently, research has started on a fully automatic construction system which automatically builds a whole structure as one work [8].

Traditional construction in steel fabrication has problems that cause the steel workers to carry out their job in dangerous conditions and require a significant amount of skilled labor. The automatic construction system is one of the alternatives to solving the existing problems for improved construction circumstances.

The system under construction has benchmarked fully automatic Japanese construction systems such as the SMART system, but also considered the characteristics of the Korean construction industry. The differences between Korea and Japan are shown in Table 2. Because earthquake is less serious a risk in Korea than in Japan, it allows a preference for H-section girders. The RCA system plans to use a bolting robot instead of a welding robot for connecting. The system also uses a tower crane for lightening a construction factory (CF), whereas the Japanese system inserts cranes in CF.

Table 2. Differences between systems in Korea and Japan

Categories	Korea	Japan
Member	H-section girder	CFT (concrete-filled tube)
Robot	Bolting	Welding
Lifting	Tower crane	Crane in CF
Level of Automation	Selective	Full

As shown Figure 1, the automatic system is composed of eight components: 1) the construction factory (CF), attached to core produced in advance, protects the inside from outer conditions such as rain and snow, 2) the intelligent tower crane uses an RFID reader to find steel members fast, then lifts steels to the working floor; the auto shackle device of the tower crane enables workers to avoid climbing to the top of the steel structure to unhook, 3) the robot crane moves the robot system to the girders horizontally, 4) the mobile manipulator moves the robot system to the girders vertically, 5) the cabin, in which a person assists the robot, is a control tower for the robot, 6) a sensor makes a robot perceive the holes in the joint and traces its location during movement, 7) an anchoring device settles the robot system to the steel member, 8) an end effector, like human hands, assembles bolts and nuts for connecting a joint.

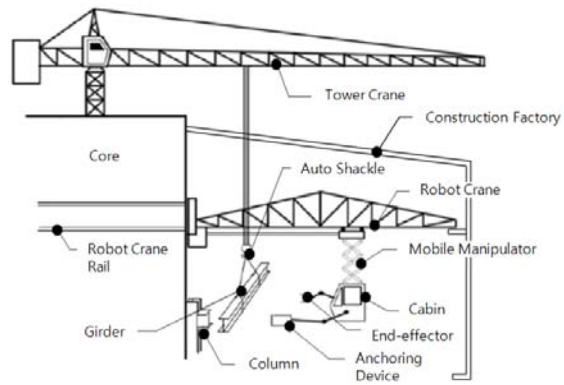

Figure 2. Components of a robot-based construction automation system [see ref. 9]

Also, structural members are designed for the goal of supporting the automatic construction system. Figure 3 shows the main idea of member design applied in the RCA system. In the connection between bracket and girder, application of Y-shape plates opened upward enables easy insertion of the girder web into the distance between plates without human hands. A rope guides the girder to the bracket precisely through the hole attached in the bracket's flange. Its key role is helping to position girders to columns easier and faster than can be done by traditional design. When workers use this design, they have no need to work at high elevation temporarily to position a girder. It gives the benefit not only of safety but also of positioning time. In actuality, the detailed results were proved by a mock-up test for the design.

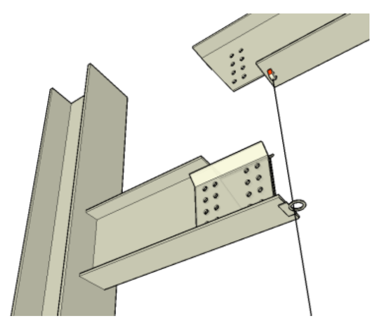

Figure 3. Joint design for girder installation

The RCA system is different from the traditional work method, even from the fully automatic Japanese construction system. Because it has never performed before, historical data by the traditional method is not available. This means that the new system has much uncertainty in schedule, cost, quality, and safety. An actual pilot project is going to be built to eliminate the uncertainty at the research stage.

3. CONSTRUCTION PROCESS ANALYSIS

3.1 Outline of Pilot Project

The pilot project for testing the RCA in Korea starts in 2009 and will be completed in 2010. However, the process for steel fabrication has not yet been established in detail because it is newly developed. Given this limitation, this study proposes a rational process and calculates the time according to the process. It helps identify nonefficient works and/or conflicts which may occur during real construction.

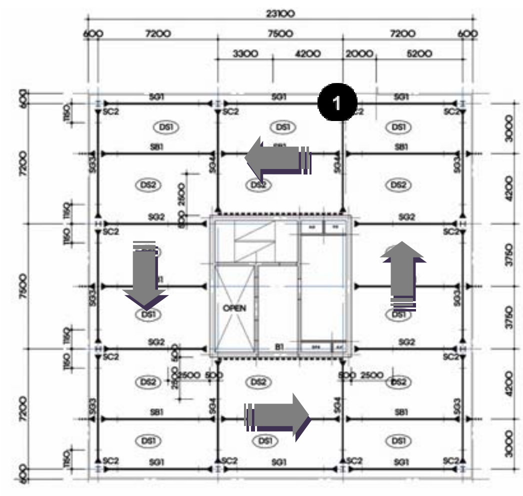

Figure 4. Plan of pilot project

There are some conditions to be defined before analyzing the process of steel erection. Figure 4 is a floor plan of the pilot project. There are 12 columns and 28 girders and beams on each floor. Table 3 is a summary of the pilot project. The building is built with a height of 3.4 m per floor and with seven stories. The work area is 567 m^2. A tower crane is installed at the center of the core. The work starts from the first column and rotates anticlockwise. Labor consists of five people as a crew, and human and robot collaborate the erection. The working hours in a day are assumed to be from 7:30 to 17:30, a total of nine hours. The installation of the girder applies the joint design mentioned above for automation procedure. The building is erected story-by-story. Inspection and weather effects are not considered in this process. Breakdown of the robot is not included in the considerations. Welding is also excluded in this study. The maximum speed of the robot movement is 30 m/min.

Table 3. Summary of pilot project

Categories	Conditions	Remark
Floor	7 stories	3.4 m height per floor
Work time a day	7:30~17:30	Total 9 h
Work area	One floor	567 m^2
Labor	A crew	5 people
Robot	A bolting robot	Including a cabin
Tower crane	1 EA	RFID, Auto shackle

3.2 Fabrication Work Process

Steel erection of a building structure consists of seven main activities: preparation, column erection, girder positioning, girder bolting, plumbing, column fastening, and girder fastening. Figure 6 represents an analysis of the detailed processes identified by the traditional erecting method and the RCA system. In the traditional construction process, ironworkers begin to erect girders after they finish all columns. In girder connection, two workers climb up on each column and position the hoisted girder between the columns. At this stage not all the bolts required at the connection points are installed, and the ones installed are tightened with a hand wrench shown in the shaded area in Figure 5. After 28 repeats of hoisting, fitting, and tightening, workers plumb the frame to adjust the steel angle correctly. The remaining bolts are installed and are fastened using an impact wrench, together with the bolts previously installed.

In contrast, in the RCA system a crew assembles the columns one by one as in the traditional way. Workers start to connect the columns with the girders using the joint design for girder installation. At this stage, ironworkers have no need to bolt in joints. Once a girder is positioned, the bolting robot moves to a joint and then inserts bolts in four holes and goes to the overside to connect nuts to bolts. After this point, the work for steel erection is divided into two separate operations, by human and robot. The human continues to position girders, while the robot inserts bolts and tightens nuts. Because the working speed of humans is much faster, there are no interferences at all. However, plumbing can't start until the robot finishes the last bolting. In the fastening stage, the robot again implements the final fastening work.

The main feature of both processes is that the traditional and the RCA system operate in series and in parallel, respectively. That means that the traditional process has a single piece flow and the automatic system has two different styles of work flow. Therefore, the latter has to control the process more carefully than the former to obtain efficient flow.

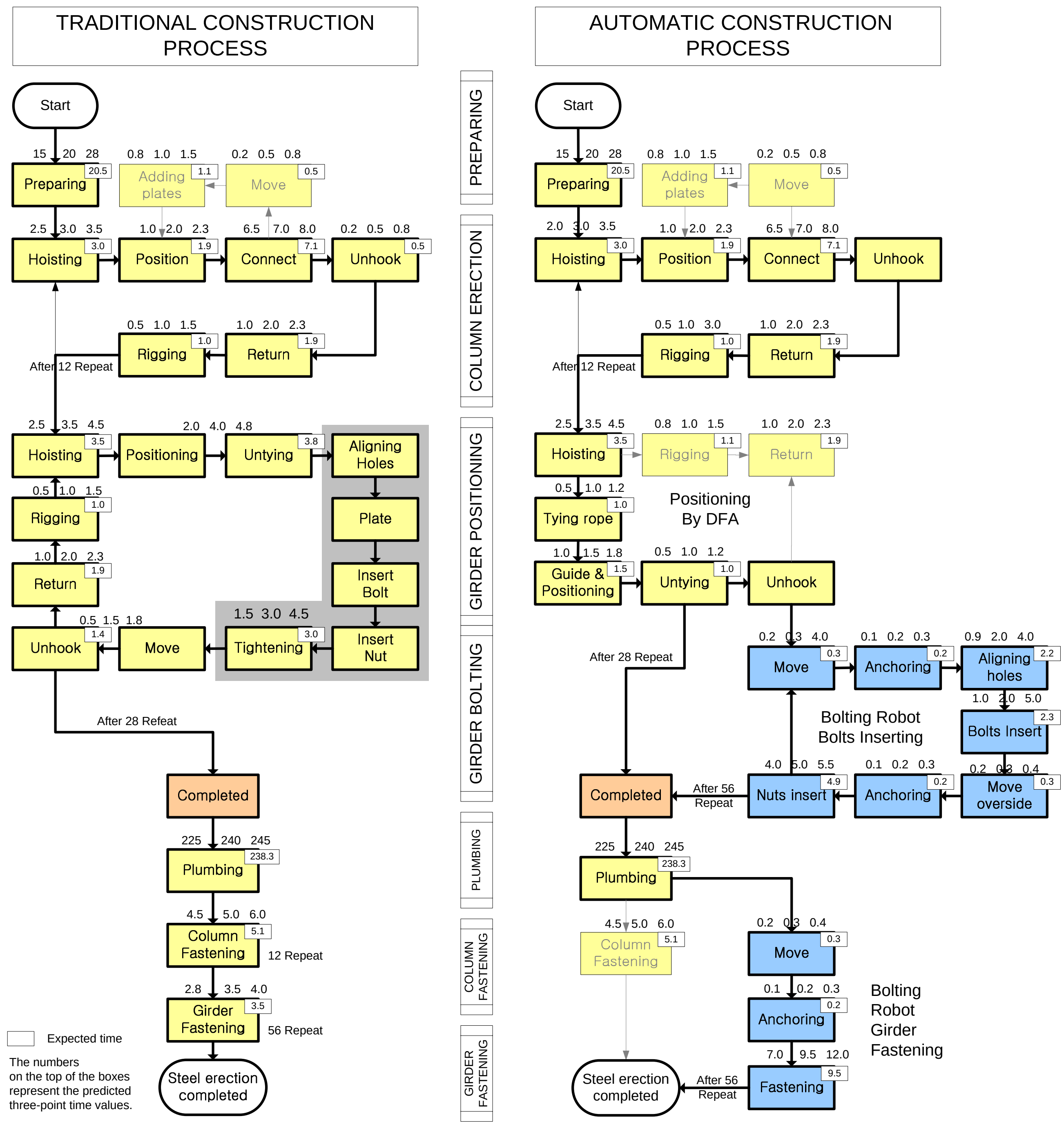

Figure 5. Workflows of traditional process and robot-based construction automation (RCA) system

3.3 Fabrication Time

The program evaluation and review technique (PERT) is one of the well known techniques for quantifying the impact of such uncertainty. In forecasting fabrication work time in this study, PERT is applicable because it is relatively convenient and easy to use. It also recognizes the probabilistic, rather than deterministic, nature of the operations involved in high-risk activities [10]. Although PERT has some limitations, such as assuming that all activities are independent and valid on beta distribution, it is still effective to predict time with three-point time values. There are four steps in estimating time: 1) individual activity time, 2) CPM calculations, 3) distribution of project duration, and 4) analysis of project completion probabilities.

Individual activity time needs three-time values with most optimistic, most frequent, and most pessimistic. In this study, they were collected by the ways shown in Table 4. The time by labor was calculated from a video recorded on a construction site, C Medical Center, Seoul, Korea [11]. A mock-up test for the joint design of girder installation provided a lot of data for task time by minutes. Lastly, robot movement was guessed by interview with the developers. But, it is noted that the data could change, because the system is at the level of research.

Table 4. Method of survey for three-point time values

Object	Method of research
Human force	Interview with workers Analysis of a video-recorded steel fabrication cases
Joint design for girder installation	Mock-up test
Robot movement	Interview with developers

Table 5. Values of three-point time in the traditional steel fabrication work process

Sector	Activity	Activity time (min)		
		a	m	b
Preparing	Preparing	15.0	20.0	28.0
Column Connection	Hoisting Steel	2.5	3.0	3.5
	Position	1.0	2.0	2.3
	Connect	6.5	7.0	8.0
	Crane Return	1.0	2.0	2.3
	Rigging	0.5	1.0	1.5
Girder Positioning	Hoisting Steel	2.5	3.5	4.5
	Position Untying	2.0	4.0	4.8
	Move Unhook	0.5	1.5	1.8
	Return	1.0	2.0	2.3
	Rigging	0.5	1.0	1.5
Girder Bolting	Aligning Holes Plate Insert Bolt Move Insert Nut Tightening	1.5	3.0	4.5
Plumbing	Plumbing	225.0	240.0	245.0
Column Fastening	Column Fastening	4.5	5.0	6.0
Girder Fastening	Girder Fastening	2.8	3.5	4.0

Table 5 shows the values of three-point time in steel erection by the traditional method. Preparing time consists of finding materials, tying ropes, rigging, attaching plates, and setting out. Hoisting steel time is between 2.5 and 4.5 min, 3.0 min being the most frequent (most likely) duration in lifting. Some tasks became a group due to mixing of behavior, such as position and untying. In the traditional work method, the time is stable because the activities have been performed since steel structures started. Although the girder position and girder bolting works are implemented together in the same time, these activities were separated for comparison in Table 6.

Table 6 describes the values of time estimated for predicting the performance of the RCA system. Among the repeatable tasks, the longest task is girder fastening by the bolting robot. In the RCA process, the time of girder positioning is slightly shorter than in the traditional method because of the use of joint design for girder installation.

Table 6. Values of three-point time in automatic construction system

Sector	Activity	Activity time (min)		
		a	m	b
Preparing	Preparing	15.0	20.0	28.0
Column Connection	Hoisting Steel	2.0	3.0	3.5
	Position	1.0	2.0	2.3
	Connect	6.5	7.0	8.0
	Crane Return	1.0	2.0	2.3
	Rigging	0.5	1.0	3.0
Girder Positioning	Hoisting Steel	2.5	3.5	4.5
	Roping to Girder	0.5	1.0	1.2
	Guide & Position	1.0	1.5	1.8
	Untying	0.5	1.0	1.2
	Crane Return	1.0	2.0	2.3
	Rigging	0.8	1.0	1.5
Girder Bolting	Robot Move	0.2	0.3	0.4
	Anchoring	0.1	0.2	0.3
	Aligning Holes	0.9	2.0	4.0
	Bolting	1.0	2.0	5.0
	Move to overside	0.2	0.3	0.4
	Anchoring	0.1	0.2	0.3
	Nuts Insert	4.0	5.0	5.5
Plumbing	Plumbing	225.0	240.0	245.0
Column Fastening	Column Fastening	4.5	5.0	6.0
Girder Fastening	Robot Move	0.2	0.3	0.4
	Anchoring	0.1	0.2	0.3
	Fastening	7.0	9.5	12.0

Table 7 presents the total time of steel erection per floor as predicted by PERT in the pilot project. The time of the RCA system is much longer than that of the traditional process, and the bolting work time is the main reason for this. However, this table doesn't consider concurrent activities, it only indicates how much works is required in CF.

Table 7. Predicted total time per floor by PERT in steel fabrication work of the pilot project

Sector	Traditional Construction		Automatic Construction	
	Mean	Std.	Mean	Std.
Preparing	20.5	2.17	20.5	2.17
Column Connection	178.2	1.59	180.2	2.17
Girder Positioning	323.9	3.55	274.4	2.46
Girder Bolting	84.0	2.65	582.4	6.60
Plumbing	238.3	3.33	238.3	3.33
Column Fastening	61.0	0.87	61	0.87
Girder Fastening	194.1	1.50	560	6.25
Total	1100.0	6.40	1916.8	10.48

To determine the predicted time considering overlapping activities, the main works were plotted from Figure 5 above. Table 8 shows the total predicted time taking into consideration simultaneous activities.

Table 8. Total time predicted by PERT per floor in steel fabrication work of the pilot project considering concurrent activities

Sector	Traditional Construction		Automatic Construction	
	Mean	Std.	Mean	Std.
Preparing	20.5	2.17	20.5	2.17
Column Connection	178.2	1.59	180.2	2.17
Girder Positioning	323.9	3.55	**9.8**	0.47
Girder Bolting	84.0	2.65	582.4	6.60
Plumbing	238.3	3.33	238.3	3.33
Column Fastening	61.0	0.87	**0**	0.00
Girder Fastening	194.1	1.50	560	6.25
Total	**1100.0**	**6.40**	**1591.2**	**10.17**

The predicted total time per floor in the pilot building becomes 1591 min (25.5 h) by using the RCA system, and this can be compared with the 1100 min (18.3 h) predicted for the traditional process. The time gap is 491 min (8.1 h). The standard deviation of times in the RCA system is 10.17. It means that work of steel erection is expected to be completed between 1570.86 min (mean–2×Std.) and 1611.54 min (mean+2×Std.) with 95% confidence.

3.4. Discussion

The predicted traditional time is two days to complete the steel erection, whereas the automated system takes three days for the steel frame work per floor in the pilot project. As shown in Figure 6, the total time in the RCA system is expected to need one more day for steel erection for the application of the RCA system when comparing with the traditional method. Some of the information gained in the course of establishing the process and calculating the time of steel erection is presented below:

1. The speeds of lifting steel and bolting work by the robot are critical to deciding the working time. In particular, the bolting work by the robot accounts for 70% of the total time.
2. Although girder positioning by design for automation saves around 84% in positioning time, it doesn't affect the total time by much because of the overlapping work.
3. The automatic robot reduces the net work time by humans, however, the idle time of workers is increased, especially between the finish time of the girder positioning and the start time of plumbing. The dashed line in Figure 6 shows conflicts between human and robot work. It was moved as much as the solid arrow. Workers' idle time caused by the bolting robot is a problem that researchers have to resolve for productivity.
4. The traditional construction system operates in series and the construction automation process in parallel. This means that the automatic construction system has a lot of potential of reducing the total time by varying the combinations of equipment or construction process, whereas the traditional process has limits in further compressing the total time.

To sum up, the automatic construction system is slower than the conventional method; however, it has aspects that could be applicable to reduce total time and to resolve some problems caused by the lack of coordination between various parts of the work.

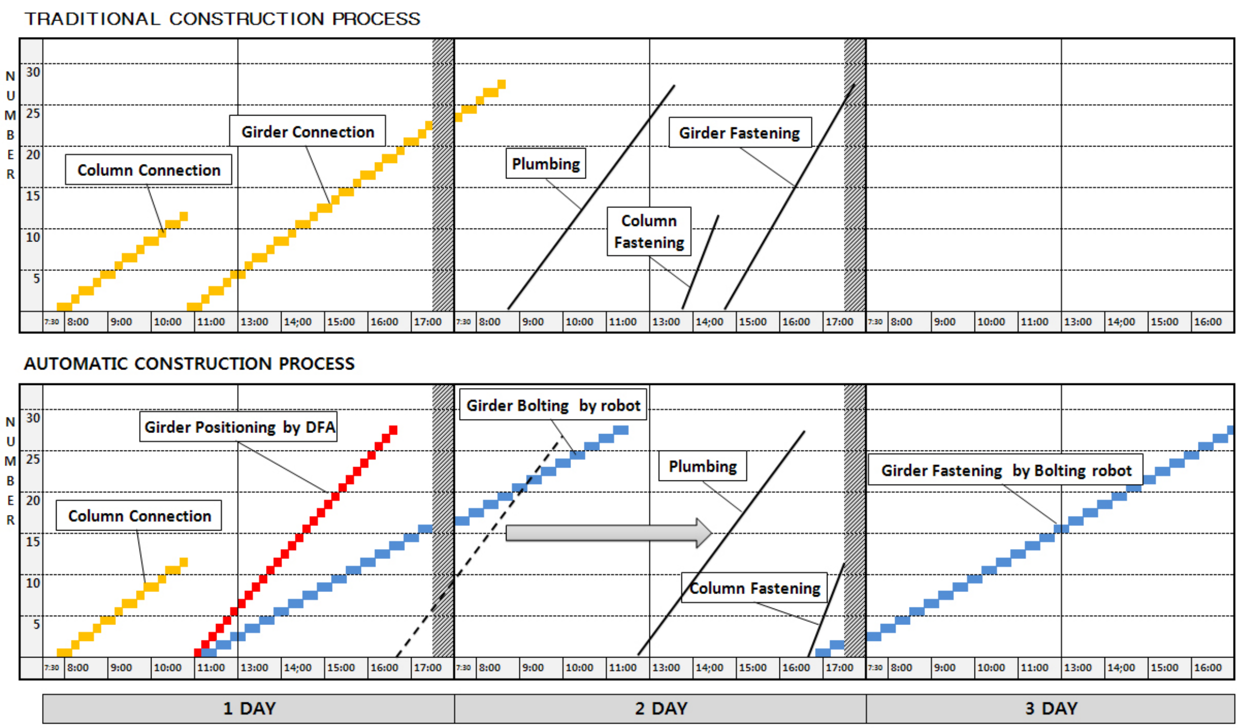

Figure 6. The line-of-balance (LOB) diagram for predicted time per floor of in pilot project steel erection

Table 9. Predicted time by using two bolting robots

Sector	Traditional Construction		Automatic Construction	
	Mean	Std.	Mean	Std.
Preparing	20.5	2.17	20.5	2.17
Column Connection	178.2	1.59	180.2	2.17
Girder Position	323.9	3.55	9.8	2.46
Girder Bolting	84.0	2.65	**291.2**	4.67
Plumbing	238.3	3.33	238.3	3.33
Column Fastening	61.0	0.87	0	0.87
Girder Fastening	194.1	1.50	**280.0**	4.42
Total	**1100.0**	**6.40**	**1020.0**	**7.88**

Table 9 represents reduced total time by using one more bolting robot. In this condition, the total time of the RCA system becomes 1020 min, which is much shorter than before and even shorter than the time of traditional steel erection method. Although using two robots in CF may cause other problems, such as safety or technical trouble at the research level, it is a proposal that should be considered for supporting the system in terms of time.

Until now, the robot-based construction automation system was analyzed from the viewpoint of the process. Based on the analysis, the total time of steel fabrication was calculated. However, there are some limitations to continue the study. First, economical considerations should be taken into account in the study for reality. Secondly, PERT has a slight limit to support decision-making, with some simulations providing a distribution which gives probabilistic data to help judge more correctly. Lastly, the new processes of construction need to be further studied to find optimal solutions.

4. CONCLUSIONS

The robot-based construction automation (RCA) system is considered as one of the solutions for the problems existing in Korean construction industry. It is expected to improve safety, quality, productivity, and lack of human resources. However, the RCA system has numerous unknown and complex operations. Therefore, there was a strong need to analyze the work process of the RCA for the development of an efficient system.

Through the analysis completed, we can find that the bolting robot causes the conflicts between human and robot due to the bolting speed. It makes workers remain idle. Moreover, the process we studied has a safety-related problem which leaves many positioned girders without any bolting for quite a long time.

As a result, we suggest two proposals: 1) application of two bolting robots or speeding up of the bolting robot performance, 2) finding out another construction process for safety and productivity.

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