Feasibility of beam erection with a motorized hook-block

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ARTICLE INFO

Article history:
Accepted 31 January 2014
Available online 22 February 2014

Keywords:
Construction automation
Construction safety
Economic feasibility
Rotation-controllable tower-crane hook-block (RTH)

ABSTRACT

On average, approximately 90 workers are injured or killed every year while lifting and installing steel beams in South Korea. Rotation-controllable tower-crane hook-blocks (RTH) remotely rotate beams horizontally to the target position, thus helping to prevent accidents related to steel beam installation. In this study, the expected safety improvements and economic effects of the RTH were analyzed. The real discount rate, and operation and maintenance costs in accordance with the general cash flow analysis practice as well as the CO2 offset price. The results of the analysis showed that when the effects of the RTH were at their maximum and average levels, the break-even points occurred in the first year and the second year, respectively. Although the RTH might not be profitable in the minimum case, this study demonstrated that using it would generally contribute to economic efficiency, and more importantly to worker safety.

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1. Introduction

Approximately 90 people are injured and die annually during the installation of steel beams at construction sites [1]. The accidents are mostly attributed to the current method of rotating and installing a beam on site. For example, after lifting a steel beam in order to rotate the beam to the target position, a worker who hangs from a column pulls the ropes that are tied to both ends of the steel beam. Depending on the position of the beam, sometimes the worker cannot reach the beam without help from other workers on the ground. This method results in accidents and increased work time. To solve this problem, a rotation-controllable tower-crane hook-block (RTH) is proposed to automate the horizontal rotations of a hook [2–6]. However, this hook-block has not been commercialized or deployed on actual construction sites, and has remained mostly a patented idea because actual construction sites require automated equipment that has been verified not only for safety but also for productivity and economic efficiency.

This paper qualitatively discusses the expected safety improvement and quantitatively analyzes the economic feasibility of the RTH by developing a working prototype. Given the fact that the economic loss due to accidents in the construction industry in Korea is USD every year [7], the findings of this study can contribute to the economic success of the construction industry by encouraging construction sites to utilize automated equipment. This paper is organized in the following manner.

First, the qualitative analysis of the expected safety improvements is composed of three steps. 1) The existing steel beam installation methods are explained. 2) The status and risk of industrial accidents that are closely associated with the horizontal rotations of steel beams are explained. 3) The major characteristics of the developed RTH are explained for improved safety during the installation of steel beams.

Second, the quantitative analysis of the economic feasibility is composed of three steps. 1) The measured efficiency of an RTH in terms of the work time is analyzed. 2) The costs incurred by developing and applying RTH and the obtainable benefits are analyzed. 3) The economic feasibility is analyzed based on the input and output variables explained in the section.

2. Literature review

Quite a few studies have been conducted regarding feasibility analyses of automated equipment [8–14]. Some of them have focused on the analysis method itself [8–10]. For example, Kangari and Gregory [8] analyzed a telerobotic and autonomous system based on socio-economic, technological, and operational factors. Slaughter [9] suggested an analysis method using automation and robotics based on adoption opportunity, perceived benefits, adoption complexity, and complementary changes. Hastak [10] suggested factors based on need-based, technological, economic, project-specific, and safety and risk criteria when automated equipment was substituted for the manual method. The other studies focused on feasibility analyses of automated operations or equipment [11–14] rather than on the analysis method itself. For example, Hastak and Skibniewski [11] evaluated the potential of automating pipe laying operations. They suggested hazards, productivity, quality, design standardization, repetitiveness, union resistance, and technological feasibility as the evaluation factors. However, the economic feasibility was not analyzed. Instead, the technical feasibility was analyzed based on a productivity analysis. Warszawski and Rosenfeld [12] developed the Technion autonomous multipurpose interior robot for an economic

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http://dx.doi.org/10.1016/j.autcon.2014.01.003
feasibility analysis in relation to painting, plastering, tiling, and masonry. Haas [13] analyzed the economic feasibility of a developed crack sealer from the perspectives of an introduction object, the design stage, and a market analysis. Song et al. [14] analyzed the technological feasibility of a radio frequency identifier (RFID) for pipe tracking. Their study did not quantitatively analyze the productivity and economic feasibility, but rather explained the effect of having accurate material information, information delay, and error reduction in terms of reducing the work time and work planning. Some previous studies, such as those of Warszawski and Rosenfeld [12] and Haas [13], analyzed the feasibility by comparing the economic effects of the manual and automated methods, considering only the labor costs and ignoring other operation costs.

Several previous studies of automation equipment analyzed the economic feasibility based on cost and benefit factors [15–17]. Rosenfeld and Shapira [15] developed a semi-automatic navigation system that is part of a crane, and analyzed its productivity and economic feasibility. Lee et al. [16] analyzed the productivity and economic feasibility of tele-operated pipe laying equipment that they developed. The labor costs, equipment rental costs, and labor productivity in that work were calculated without considering the discounted rate of cash flow. Kim et al. [17] analyzed the productivity and economic feasibility of a hume-concrete pipe manipulator that they developed.

This study takes a similar approach to previous studies. However, additional factors are considered to make the analysis result as acceptable as possible to potential users by following the standard practice in terms of the cash flow analysis and by considering the other maintenance cost factors and the CO₂ offset price. The next section discusses the additional variables that we consider in more detail.

3. Analysis method

Although this study generally follows the analysis framework used in previous studies, there are several differences. First, in addition to the labor cost, we consider the operation and maintenance cost factors such as the rental cost of the construction equipment, the electricity cost, and the fuel cost. The fuel cost is calculated based on the number of fuel replacements. This number also takes into account the CO₂ offset price, which has become one of the standard factors considered in a cost–benefit analysis these days.

Second, we adopt a standard practice used in the cash flow analysis and apply ‘real discount rates’ rather than nominal interest rates or the discount rate based on the minimum attractive rate of return used in previous studies [15,17]. In addition, the inflation rate is applied to various cost factors, and the analysis considers a consumer price inflation rate, a labor cost inflation rate, a rental cost inflation rate of construction equipment, an electricity cost inflation rate, and a CO₂ offset price inflation rate. When a tower crane is leased, the lease charge of the machine, including the machine’s depreciation costs and the labor cost of the operator, are included.

Third, the analysis is conducted based on Korean construction statistics because the first target market of the RTH is Korea. Rosenfeld and Shapira [15] applied 1800 h as the time for using a crane, while 2000 h are applied in this study, as suggested by the Korea Institute of Construction Technology [18]. In addition, we apply 5% of the purchasing costs for 5 years from the year of manufacture and 10% from 6 years to 10 years after the year of manufacture as the maintenance cost rates, following the Korean standard practice [19], whereas Rosenfeld and Shapira applied 9% [15].

Forth, as for productivity, while only the effect of the reduced number of workers resulting from the shortened work time was analyzed, this study also considers the effects of the reduced number of days of using tower cranes.

The factors of this study were divided into costs and benefits. Table 1 summarizes a list of the cost and benefit factors used in this study. The assumptions used for calculating the costs and benefits are also listed. The cost factors are the purchasing costs, annual maintenance costs, and fuel costs. The benefit factors from the shortened work time can be subdivided into reduced labor cost, tower-crane rental cost, energy consumption cost, and CO₂ offset price resulting from the reduced use time.

In the following sections, we first introduce any safety issues that may occur during the conventional beam installation process and RTH use, and qualitatively discuss the expected safety improvements. We then quantitatively analyze the economic feasibility of the RTH.

4. Expected safety improvement

4.1. Conventional installation method

In general, for horizontal steel beam installation methods, two workers adjust the horizontal location of a steel beam at both sides of the steel beam, as shown in Fig. 1. To adjust the location, the workers may hold onto the steel beam directly or may hold a rope that is hanging from the steel beam. The steps for this method, which are shown in Fig. 1, are as follows. First, one of the two workers standing on the ground holds the rope surrounding the steel beam to roughly adjust the horizontal location of the steel beam ((1), (2), and (3) of Fig. 1). Next, the worker goes up to the position for installing the steel beam ((4) and (5) of Fig. 1). Meanwhile, the other worker on the opposite side holds the steel beam to maintain the roughly determined horizontal location. Finally, both of the workers precisely adjust the horizontal location at the steel beam installation location ((6) of Fig. 1).

For cases in which the weight and/or size of the steel beam to be installed are large, and thus the horizontal adjustment work is difficult. In these cases, a worker may be additionally assigned to adjust the location of the steel beam from the ground by using a rope, or a worker may be added to either side of the steel beam installation location.

4.2. Status and risk of industrial accidents related to steel frame installation

Existing working methods require many movements and trips up and down in order to manipulate heavy steel beams in narrow and high positions, as shown in Fig. 1. The number of casualties per year related to steel beam installation is approximately 90 people [1]. The Korean Occupational Safety and Health Agency [20] conjectures that its statistics are assumed to be about 32 times lower than the actual number of accidents, because only accidents that are related to insurance compensation are reported. Table 2 shows a detailed classification of accidents by cause during steel construction. Among industrial accidents, falls occur most frequently. The mean of the number of casualties due to falls was approximately 51, which was at least five times higher than that of the other causes of casualties. The next highest rate of casualties was due to drops, which was followed in order by overturns, collision/contact, squeezing, and collapses. The definitions of the accident types are as follows:

• Fall: an accident in which a worker falls down while working in a high place.
• Overturn: an accident that occurs because a steel frame overturns during working.
• Collision/contact: an accident that occurs because of a collision between a steel beam and a worker.
• Drop: an accident that occurs as a steel beam is dropped down.
• Squeezing: an accident that occurs as a worker is caught between a steel beam and another structure or steel beam while the steel beam is being installed.
• Collapse: an accident that occurs as the place of the steel beam work collapses.

Fig. 2 shows the average recuperation period [1] of the injured parties in industrial accidents that occurred from 2004 through 2011.
The largest number of injured people (33,954 individuals) took 29 days to 90 days to fully recuperate.

Among the industrial accidents occurring in steel beam installation work, as shown in Table 2, falls, collision/contact, and squeezing are more closely associated with horizontal rotations of steel beams than other industrial accidents. This is due to the following reasons.

First, in the case of falls, as shown in Figs. 1 and 3-(1) workers have to continuously move between the steel beams and the ground in order to adjust the horizontal locations of the steel beams, with existing installation methods. In addition, as shown in Fig. 3-(2), the workers have to move frequently because they have to rotate heavy steel beams in unstable positions in high and narrow locations. The lack of stability and frequent movements increase the risk of falls.

Next, since the workers hold onto the steel beams directly while adjusting the steel beams’ locations, as shown in Fig. 3-(2), industrial accidents may occur not only because of falls, but also due to collision/contact with steel beams; a high level of difficulty is involved.

Finally, as shown in Fig. 3-(3), due to the swaying of steel beams in the process of installation and the workers’ inability to bear the weight of a steel beam, there are risks of squeezing accidents. Squeezing accidents entail either a worker being squeezed between a steel beam and a column or between an already installed steel beam and a new steel beam.

Therefore, if steel beams’ horizontal locations can be mechanically or simply adjusted, worker safety can be improved.

Automated equipment have been previously developed to move and install heavy construction material and to improve productivity and safety; these include the mighty hand from the Kajima Corporation [21], the mighty shackle from the Shimizu Corporation [22], the WASeda Construction Robot (WASCOR) project [23,24], and the automated crane motion from Bock [25,26]. However, these are not automated equipment for the installation of steel frames for buildings. This paper helps to improve the safety and economic feasibility by using the developed RTH, which is a type of automated equipment for horizontally rotating the steel beams of buildings.

4.3. Characteristics of RTH for safety improvement

An RTH is a motorized crane hook-block that can control the rotation angle of a lifted object from a distance using a remote controller. Fig. 4 shows the RTH designed and manufactured in this study based on the patent by Kim et al. [4]. The RTH is connected to the hook part of the tower crane, as shown in Fig. 4. The RTH is composed of a direct current generator, a gear module, a wireless control relay, a wireless control transmitter and receiver, and a swing controller. A direct current generator, a wireless control relay, and a receiver that can rotate in the forward and reverse directions are installed in the hook-block so that materials being lifted can be horizontally rotated to the target position. A swing controller and wireless control transmitter are installed to remotely control the direct current generator from the ground. A battery is used so that the power can be supplied even in high places.

Fig. 5 shows a diagram of a method used for a worker to rotate a steel beam without moving. The method involves the following steps: First, a worker who has a swing controller, or the tower crane operator, manipulates a steel beam in the desired direction of rotation. Second, the transmitter delivers the direction of rotation desired by the worker to the receiver installed in the hook-block. Third, the gear is driven by the DC generator to rotate in the required direction. Through these processes, the steel beam also rotates horizontally.

If the RTH developed in this study is used, the safety of workers will be improved because the workers’ movements for installing steel beams, as well as the related risks, will be reduced. Industrial accidents are rare when using the RTH, because the RTH is operated in combination with a tower crane. If accidents do occur, there are fewer than with the existing manual method. However, automated equipment is rarely utilized at construction sites because construction companies...
5. Economic feasibility analysis

The following sections explain the major benefits of adopting the RTH: the saved work time is measured first in this study, and then the cost and benefit factors used in the economic feasibility analysis are discussed.

5.1. Work time saved by the RTH

The time required to rotate a steel beam to the target position using the manual method and the time required by the RTH were measured in previous study [6], and this study utilizes that data. The following summarizes the test methods and results.

First, the rotation time using the manual method was measured at a construction site in Seoul, Korea. The installation of ten beams with various weights (205 kg to 966 kg) was observed. The average rotation time was 39.12 s, and the standard deviation was 26.58 s (Table 3). The large deviation was due to the weight differences between the beams. Because workers had to rotate the beams in very unstable positions, it took much longer to rotate the heavy beams when they manually rotated the beams. The average rotation time for a beam of 205–395 kg was 17.56 s with a standard deviation of 4.03 s.

Next, the rotation time of the RTH was measured. The experiment was conducted at a tower crane factory in Chonan, Korea. When a beam is rotated to adjust it for installation, the maximum rotation angle of the beam is generally 90°, because beams usually have a symmetrical shape. The average time to rotate a beam 90° and other angles was measured 10 times for each angle using the RTH. Beams with two different weights (169 kg and 350 kg) were used in the experiment. The average times to rotate a beam 90° were 16.29 s and 16.80 s for the 169 kg beam and the 350 kg beam, respectively (Table 4). The standard deviations were only about 2 s for both cases. There was no statistically significant difference between the rotation times of the beams with different weights according to the T-test \((p = 0.58)\), whereas the rotation time of the manual method showed a large deviation, depending on the weight of the beam.

This experiment showed that the RTH was approximately twice as fast as the manual method, on average. The automated hook-block could save at least 18.23 s (the difference between 28.34 s which is average time by manual method in Table 3 and 10.11 s which is average time by RTH in Table 4) per operation. Because the rotation time of the automated hook-block is not sensitive to the weight of a beam, whereas that of the manual method is weight-sensitive, if the weight of the beam increases, then the benefits of using the automated hook-block will increase. The shortened time when using the RTH was calculated as follows:

- Rotation time using the manual method: 28.34 s is applied as the time required when using the manual method, which is the average time

![Fig. 2. Average recuperation periods for injuries incurred in industrial accidents.](image-url)
required for rotating a heavy beam (39.12 s on average for 205–966 kg beams); the time required for rotating a light beam (17.56 s on average for 205–395 kg beams) is shown in Table 3.

- Rotation time using the RTH: 10.11 s is applied as the time required when using the RTH, which is the average time required for rotating beams weighing 169 kg (9.72 s) and 350 kg (10.49 s), as shown in Table 4.

- The shortened rotation time was calculated by subtracting the average rotation time of the RTH (10.11 s) from the average rotation time of the manual method (28.34 s). The shortened time was 18.23 s.

Next, to determine how much 18.23 s (the shortened time) is in terms of a percentage of the time required for one complete cycle of lifting, rotating, and installing a beam, the average one-cycle time to lift and install a steel beam was measured by monitoring the one-cycle times needed to install 1367 beams (including 924 girders, which are large beams) at a steel frame construction site in Korea that was completed in February 2009. Table 5 shows the average one-cycle times for all steel member types used in the steel frame construction project. The average one cycle time required to lift and install a beam was 8.5 min (510 s). Thus, approximately 3.58% (=18.23 s/510 s) of the beam installation time can be saved by adopting the RTH.

5.2. Costs and benefits of the RTH

The economic feasibility of the RTH is examined by analyzing both the costs incurred and the benefits of using the RTH.

5.2.1. Costs

The costs incurred were divided into the development costs, maintenance costs, and fuel costs, as shown in Table 1. The ownership costs, such as insurance and taxes, were not considered, because they are levied on tower cranes. Additionally, the depreciation of the RTH was not considered because the salvage value was not considered in this economic feasibility analysis for the minimum case.

5.2.1.1. Manufacturing cost. The development costs spent to manufacture the RTH used in this study are shown in Table 6. The labor costs are also included. The total cost to produce one unit is 13,422.82 USD.

5.2.1.2. Maintenance cost. The service life of construction equipment is generally regarded to be 10 years [18,19]. The service life of the RTH was therefore set to 10 years. In order to consider the worst-case scenario of economic feasibility, no salvage value was assumed. The maintenance costs were also determined using the values generally applied to other construction equipment in Korea [19]. The maintenance costs were calculated as 5% of the manufacturing costs during the first to the fifth years, and as 10% of the manufacturing costs during the sixth to the tenth years. The calculated maintenance costs were 671.14 USD for the first 5 years and 1342.28 USD for the second 5 years, for a total of 2013.42 USD over the equipment lifetime.

5.2.1.3. Fuel cost. The annual fuel costs were determined based on the service life of the batteries attached to the two sides of the RTH. This cost category may be reduced if a rechargeable battery is adopted. The service life of batteries varies depending on the amount of use and the work environment. Two years was applied in this study, which is the general service life of batteries used in production. The battery cost was 89.49 USD per unit or a total of 178.97 USD for the RTH equipment.

5.2.2. Benefits

The benefits that occurred were divided into the labor costs, tower-crane rental costs, electricity cost, and the CO2 offset price.

5.2.2.1. Labor cost. The number of workers required is generally five, including one tower crane driver, one flagman, two rotation adjusters, and one worker to connect the lifted structural members to the hook. Since the labor cost for the tower crane driver is included in the tower crane rental costs, this cost was excluded from the labor cost analysis. One of the two rotation adjusters is the driver for the RTH. Although one or two rotation adjusters may be added depending on the types of lifted structural members and the situations at different sites, we limited them to two for strict analyses of economic feasibility. Since the ratio of the shortened work time is 3.58%, as explained earlier, the reduction in the labor costs required for the lifting work was applied to economic feasibility analysis based on 250 working days per year [18,28]. The result indicates that the reduction in labor costs was 4518.15 USD.
Labor cost reduction = \((\text{flagman} + (\text{steel worker} \times 3)) \times 3.58\% \times 250 \text{ days} = (\text{USD } 90.27 + (\text{USD } 103.76 \times 3)) \times 3.58\% \times 250 = \text{USD } 4518.15\).

5.2.2.2. Tower crane rental cost. The annual use time of a tower crane is generally 2000 h [18]. If the work hours are considered to be 8 h a day, then an operation plan and cost plan for 250 days per year can be established. Since tower crane rental costs are paid until the tower crane-related work is completed, including the idle time, the latter was not reflected on the tower crane rental costs in this study. Therefore, the shortened crane use time and reduced rental costs for 250 days per year achieved by using the RTH can be estimated. The monthly rental cost of a tower crane in 2009 was 8253.63 USD [28], including the labor costs and loss costs. As explained earlier in the previous Section 5.1, the ratio of the time that can be shortened by using the RTH is 3.58% of the total work time. Therefore, 298.28 USD, or 3.58% of the monthly rental cost of a tower crane, can be saved per month.

5.2.2.3. Electricity cost and CO2 offset price. As the operating time decreases, the power consumption necessary for operating the tower crane and the resulting CO2 emissions also decrease. Surveys indicated that the average power consumption per day (8 h of operation) of 23 kinds of tower cranes used in Korea was 556.05 kWh, and the average per year (250 days of operation) was 139,012.50 kWh. As analyzed above, since the operating hours are shortened by 3.58%, the resultant reduction in the power used for one year is 4970.38 kWh. Based on the use charges, which varied with the seasons as shown in Table 7, the analysis indicated that the power use charges would be reduced by a total of 352.26 USD per year. The reduction in the CO2 emissions resulting from the reduction in the use of electricity was 2.21 (tCO2eq/kWh) per year, which was a total of 10.14 USD per year, based on the results of the analysis. (See Table 8.)

5.3. Economic feasibility analysis

In this section, the change effects of the economic impact factors on the economic feasibility were analyzed. The impact factors can be divided into the labor costs affected by the productivity, tower crane rental costs, tower crane electricity use charges, and CO2 offset prices. The number of working days, service life, maintenance rates, and fuel costs, which are the factors affecting the economic feasibility analysis in Table 1, are generalized values that are applied when using construction equipment in construction sites in Korea. Thus, their variability was not considered when the economic feasibility was analyzed. However, the impact factors described above can be applied differently, depending on the measurement methods and the situations of the construction sites.

The productivity gain was analyzed by applying the work times when the rotation angle was changed to 15°, 30°, 45°, and 90° also when the lifting material (steel beam) weight was changed to various weights as shown in Table 4. The average productivity gain of 3.58%
was obtained by dividing 18.23 s (which is the difference between the average time required to rotate an average weight steel beam using the RTH and that using the manual method) by 8.5 min (510 s), which is the one-cycle time. The average time required to rotate an average steel beam using the RTH is 10.11 s, as shown in Table 4, and the average time required to rotate an average weight steel beam using the manual method is 28.34 s, as shown in Table 3. The maximum productivity gain of 6.59% is the ratio obtained when the longest working time required to rotate a heavy steel beam using the manual working method is 39.12 s (Table 3), and the shortest time required to apply the RTH is 5.49 s (i.e., the time required to rotate a 169 kg steel beam by 15°; Table 4). The minimum productivity gain of 0.15% is the ratio obtained when the average working time required to rotate a lightweight steel beam using the manual working method is 17.56 s (Table 3), and the longest time required among cases in which the RTH is used is 16.80 s (i.e., the time required to rotate a 350 kg steel beam by 90°; Table 4), are applied.

The labor cost, tower crane rental and electricity costs, and the CO2 offset price changed in accordance with changes in productivity. The analysis showed that the largest labor cost reduction was 8330.35 USD, which was required when the productivity was the highest. Labor costs of 4516.92 USD were required when the productivity was average. Labor costs of 1882.66 USD were required when the productivity was the lowest. The analysis showed that the maximum tower crane rental reduction cost was 6599.43 USD, the average tower crane rental reduction cost was 3578.37 USD, and the minimum tower crane rental reduction cost was 149.14 USD. The analysis showed that the maximum electricity reduction cost charges and CO2 offset reduction price were 649.48 USD and 18.70 USD, respectively. The average reduction values were 1468.98 USD and 0.42 USD, respectively.

Fig. 6 shows the results of the economic feasibility analyses conducted using the maximum, mean, and minimum values of the impact factors, including the labor costs, tower crane rental costs, tower crane electricity use charges, and CO2 offset prices. The analysis results are the values obtained by deducting the costs spent when the values of the impact factors were the maximum, mean, and minimum from the costs required when using the manual method. The breakeven points were rounded up, because the profits were analyzed annually. When the impact factors are at the maximum, the breakeven point is the first year, and the economic profit in this case is 1208 USD. The economic profit after 10 years, which is the general lifetime of construction equipment, is 105,348 USD. When the impact factors are at the mean, the breakeven point is the second year, and the economic profit in this case is 1749 USD. The economic profit after 10 years is 46,774 USD. The analysis showed that when the impact factors were the minimum, the breakeven point could not be reached in 10 years.

Based on the results of the economic feasibility analysis relative to changes in the impact factors, the RTH demonstrated economic effects if the impact factors are at the maximum or mean, but has no economic effects if the impact factors are the minimum.

### 6. Conclusion

The RTH, a part of a robotic tower crane, is an automated device intended to horizontally rotate lifted materials, such as steel frame materials. In this study, the characteristics of RTH and the qualitative expected safety improvement were explained, and the economic feasibility was quantitatively analyzed considering the various cost and benefit factors.

First, the effects of the RTH in improving safety were discussed. When the existing steel beam installation working method is utilized, workers directly hold onto heavy steel beams to rotate them horizontally in high and narrow positions. When workers are rotating steel beams using the ropes installed on the steel beams, they have to continuously move between the ground and the steel beam installation locations. Consequently, industrial accidents may occur, and, in particular, falls, collision/contact, and squeezing are quite likely to occur. With the RTH, steel beams can be wirelessly rotated using swing controllers, and thus, workers' movements will decrease. Moreover, the amount of direct control of heavy steel beams by workers will decrease. Reduced movement in high and narrow positions will improve workers' psychological and physical safety and will eventually, reduce the risk of industrial accidents.

The economic feasibility of RTH was also analyzed when the productivity gain was at the maximum, mean, and minimum levels. With the maximum and average effects, the break-even points were achieved in the first year and the second year of using the RTH, respectively. However, when the impact factor values were set to the minimum, no economic benefit was expected until after the 10th year. Although the RTH may not be profitable in the minimum case of economic feasibility, this study demonstrated that using the RTH would generally be economically beneficial. In particular, if the construction period of the building is generally three years or less, the economic effect of the RTH can be anticipated.

The RTH developed in this study not only had economic benefits, but also improved workers' physical safety and psychological well-being, among other things. With the clear safety and economic benefits of the RTH shown in this report, we hope that the likelihood of automated
construction equipment units being introduced at construction sites becomes greater. The analysis method used in this study for the safety and economic feasibility included the operation and maintenance costs following the general cash flow analysis practice. We also hope that this method can be used as a reference method for future feasibility studies of automated equipment.

Acknowledgments

This work was supported mainly by the Korean Institute of Construction & Transportation Technology Evaluation and Planning (KICTEP) with the program number “06-Unified and Advanced Construction Technology Program-D01,” and also partially by the Ministry of Science, ICT & Future Planning (MSIP), South Korea, under the Convergence Information Technology Research Center (C-ITRC) support program (NIPA-2013-H0401-13-1003) supervised by the National IT Industry Promotion Agency (NIPA).

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