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Development and Application of Smart Construction Objects and Management System for an Efficient and Cost-Effective Safety Management

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Abstract: In this study, five Smart Construction Objects (SCOs) are developed and demonstrated. The usefulness and characteristics of the developed SCOs were evaluated using a tri-axial diagram analysis method. In addition, a smart construction management system associated with the developed SCOs is proposed. The efficacy of the management system is demonstrated by applying it to various types of construction site, including tunnel construction, railway construction, and underground water tank construction. The results of the tri-axial diagram analysis showed that the developed SCOs have improved awareness and autonomy compared to previously available ones. Multiple on-site applications of the developed smart construction management system resulted in a significant reduction in the time and cost required for construction by more than 40% and 70%, respectively, compared to conventional methods. This is attributable to the simplification of construction resource management procedures, JSA (Job Security Analysis), TBM (Tool Box Meeting), PTW (Permit to Work), and nonconformity management.

Keywords: smart construction; SCO; JSA; safety; productivity

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1. Introduction

Smart construction technology has received significant attention alongside the development of convergence technologies such as the Internet of things (IoT), big data, building information modeling (BIM), and wireless sensor networks (WSN) [1–3]. Smart construction aims to improve construction productivity and safety by digitalizing the entire construction process, automating construction equipment and site safety management. As of 2016, the size of the global smart construction market was estimated to be approximately USD 10 billion, and it was expected to grow at a compound annual growth rate (CAGR) of more than 12% [4,5]. In respond, countries have been promoting active investment and related policies to capture a share of the smart construction market. In the United States (US), smart construction technology is primarily being led by startups. For example, some private IT companies have formed a consortium for IoT standardization to enable the Internet to interact with construction objects. The UK government has introduced guidelines to expand the use of digital technology while emphasizing the smartization of the construction industry. Japan aims to increase the productivity of construction sites by 20% by 2025 to address anticipated workforce shortage in the future [6].

Academia also pays much attention to smart construction technology. Guzman-Acebedo et al. presented a technology that uses GPS, sensors, and smartphones for structural health monitoring (SHM) of bridges [7]. Sabet and Chong provided a systematic and comprehensive review of improved construction techniques to increase construction

productivity [8]. Stefanic and Stankovski reviewed technologies that utilize the IoT, AI, and cloud computing for construction monitoring, construction site management, safety, early disaster warning, and resource and asset management [9]. Liu et al. conducted a modeling study on how positively workers accepted a newly developed smart construction method using a user acceptance model [10]. Li et al. applied the smart product-service system (SPSS) and smart connected products (SCP) to prefabricated housing construction (PHC) and presented a smart construction model suitable for the COVID-19 era [11]. McCabe et al. introduced a system that manages automatic data capture, quality control, quantity check, and safety through the convergence of unmanned aerial vehicles (UAV) and IoT technology [12]. Xu et al. used 3D scanning, drones, BIM, Advanced Reality (AR), GPS, and WSN based on the IoT to supplement the missing information and efficiently collect vast amounts of information to manage construction projects and buildings [13]. Gbadamosi et al. proposed a method for using the IoT and cyber-physical modeling in smart construction [14]. Niu et al. described the 'third wave' of construction safety and health management brought about by smart construction [15]. In their work, the first wave of construction safety and health management was defined by the provision of personal protective equipment; the second wave by managerial approaches such as fostering a safety culture; and the third wave by the utilization of technologies related to the fourth industrial revolution, such as ICT, and AI. In the meantime, Stefanic and Stankovski [9] provided a comprehensive review of smart construction technologies, categorizing them into five groups: monitoring, process tracking, safety at work, disaster warning, and resource management.

Despite academic interest in and research on smart construction, its use on actual construction sites has been hindered by defensive national and corporate policies and practices, with construction workers or managers wanting to maintain the existing construction tasks [10]. Many researchers [4–6,9,10] have emphasized a need for easily applicable technologies in the construction industry, such as online safety-related paperwork, work permits, safety checks, payments, location identification, and opening management, in addition to monitoring the status of equipment and the workforce [16]. Managers find it difficult to track the location of workers and their daily working hours. Similarly, there is no feasible method for determining the amount of time for which construction equipment operates during the day. Consequently, it is often assumed that the equipment operates throughout the day, leading to a daily payment for rentals to dealers regardless of actual usage. As far as the authors are aware, there is no research that analyzes and provides solutions to the aforementioned practical challenges faced at construction sites, making our research critical.

Our study proposes a smart construction system that can prevent unnecessary wastage of time and the workforce at construction sites, increase safety, and optimize the use of resources including workforce and equipment. The smart construction system developed and presented in this study is shown to achieve improved awareness and autonomy compared to previously reported smart construction systems. The system interacts with the integrated control system through smart phones and NFC tags, significantly improving the construction time and costs associated with unnecessary paperwork. The developed system was successfully implemented at various construction sites, demonstrating its potential to significantly improve work safety while reducing the cost and time required for work.

2. Smart Construction Objects

Construction site safety managers (hereafter referred to as managers) are responsible for a multitude of tasks simultaneously, including documentation, communication with workers, emergency response procedures, list evaluations, worker training, personnel and site movements, and management of vulnerable areas. According to a report, construction site managers in Korea spend 4.9 h on average of 8 workday hours on administrative tasks in Korea [4]. This results in escalated construction costs and time constraints, as well as amplified hazard exposure owing to the lack of a dedicated safety officer at the construction site. Consequently, there is a pressing need for a construction management system capable

of streamlining administrative responsibilities, complying with ever-more-stringent workplace safety regulations, and effectively overseeing equipment and workforce operations. To fulfill this objective, we conducted an extensive analysis of the current state-of-the-art smart construction technologies [4,6,7,12–14,16–23], as outlined in Table 1.

Table 1. Statistical summary of previous studies on smart construction and its components (the number of prior studies available was obtained through Google Scholar using related keywords, and other indicators were qualitatively estimated based on our own experience and prior literature).

		No. of Studies (2010–2022)	Importance	Practicality	Need for Further Development
Construction Monitoring Technology	Equipment monitoring	46	High	Moderate	Low
	Road monitoring	4	Low	Low	Moderate
	BIM technology	2330	High	High	Low
	Smart construction system	64	High	High	High
Occupational Safety Technology	Health monitoring	98	High	Moderate	Moderate
	Hazardous area safety	51	High	High	High
	Equipment safety	22	High	Moderate	Moderate
	Worker position monitoring	51	High	High	High
Disaster Prevention Technology	Fire detection	13	High	High	High
	Equipment risk	21	High	Low	Low
	Earthquake monitoring	7	Low	Moderate	Low
Resource and site Management Technology	Worker position monitoring	82	High	High	High
	Waste treatment technology	237	High	Moderate	Moderate
	BIM/CAD/CAM	107	Moderate	Moderate	Low

Based on the results presented in this table, we identified key elemental technologies requiring further investigation to enhance both safety and efficiency of the work environment. These technologies encompass: fire detection, worker location monitoring, safety hook fastening detection, opening detection, and table lift laser guidance. Leveraging our extensive field experience and technological expertise, we successfully developed these five cutting-edge smart construction objects (SCOs, hereafter). A concise overview of these SCOs, along with their core features, is provided in Table 2.

2.1. Fire Detection

The fire detection system was developed to monitor fire-related conditions including flames and smoke within the construction site using video monitoring. Conventionally, CCTV or fire detection sensors are installed in areas where fire detection is required to detect fire. However, the analysis of the fire detection signals has encountered challenges such as inadequate noise reduction and frequent false positives, where non-fire incidents are mistakenly identified as fires. In this study, a method for the more accurate detection and notification of fire through improved image processing technology and an control supplement system is presented. Figure 1 shows the algorithm for the fire detection and notification technology developed in this study.

As shown in this figure, the algorithm consists of a video monitoring step that performs real-time video monitoring of the monitoring area; a fire detection step that detects fire signs based on the analysis of video data; a control step to support decision making; a control supplementation step to improve the accuracy of the decision making; a remote control supplementation step to supplement the decision making for the fire generating unit with remote support in situations where there is no response from the control person within the set time, and a fire notification step in which fire notification and warning are performed in the monitoring space and/or monitoring area in which the occurrence has been confirmed. The section enclosed by the dotted line represents the pivotal stage of the algorithm, namely the fire detection stage. Here, the presence of a fire is determined using the following equation:

$$F(x,y) = \begin{cases} 1, \text{ if } \left| C_r(x,y) - C_{r,ref} \right| \geq \tau \\ 0, \text{ others} \end{cases} \quad (1)$$

Table 2. Smart construction objects developed in the present study.

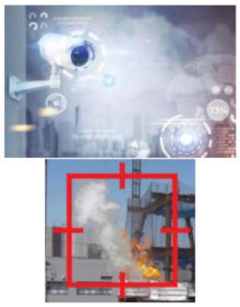
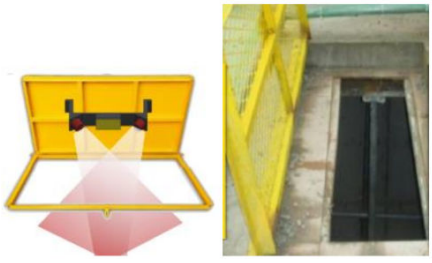
SCO	Description	Related image
Fire detection	Fire and smoke incidents are identified through advanced AI-powered real-time image processing of round-the-clock CCTV footage. Once a fire or smoke event is detected, prompt notification is relayed to the manager. This proactive approach not only mitigates potential harm to individuals and assets, but also enables cost savings by minimizing the need for human resource deployment.	
Worker location monitoring	This technology incorporates a location tag integrated into workers' helmets. By utilizing web and app platforms to identify the precise whereabouts of employees, several benefits are realized. Firstly, it enhances the efficiency of managers by providing real-time information on worker locations. Additionally, it enables effective control over access to hazardous areas and enables rapid response during emergencies through the utilization of location data. Furthermore, this system includes an SOS button that allows workers to immediately notify the manager in the event of an emergency. In cases where a worker is unable to press the SOS button due to incapacitation, the system automatically activates the SOS function by detecting any significant impact or shock. Moreover, the integration of LED lights ensures visibility in dark environments, further enhancing safety measures.	
Safety hook fastening detection	It is a system that determines whether or not a worker is engaged with a safety hook when working in high places, and provides notification through sound and platform. Through the web/app, an administrator can check whether the safety hook is fastened in real time. It does not require an independent safety hook, but only requires a dedicated piece of hardware applied to the existing safety hook.	
Opening detection	The system incorporates a Time of Flight (TOF) sensor, which is affixed to the opening cover. This sensor accurately calculates the distance by measuring the time it takes for emitted light to bounce back from an object, enabling precise spatial recognition. By establishing a data collection and alarm system through Bluetooth communication, the system assesses whether the opening is in an appropriate state and if it exceeds the designated threshold duration. The resulting data is then transmitted to the control system for further analysis.	

Table 2. *Cont.*

SCO	Description	Related image
Table lift laser guide	This hardware is installed on the table lift, projecting a virtual square laser line on the ceiling. This setup serves to verify the working position before ascending the table lift, thereby preventing repetitive and hazardous tasks resulting from positioning errors. Furthermore, it enables the system to anticipate potential collisions with pipes and other structures that may occur during the ascent, enhancing overall safety precautions.	

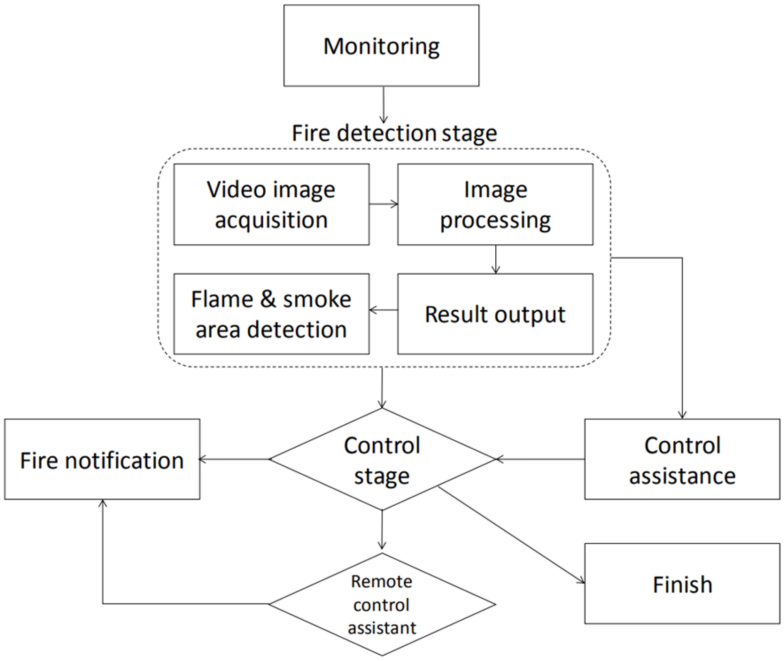


Figure 1. Fire detection and notification process.

In Equation (1), x and y are two-dimensional spatial coordinates, and F is an object function that determines whether or not there is a fire. C_r is a color difference signal at a given position, and $C_{r,ref}$ is the reference value for the color difference signal for determining whether there is an abnormality. In Equation (1), the flame candidate area is extracted through the F value, and by image processing the F value. By employing image processing techniques on the F value, a final determination is made regarding the occurrence of fire, in consideration of factors such as irregularities in the flame candidate area, flame texture, changes in flame area, and tertiary probability moment of the fire region. Upon confirming the presence of a fire, the signal proceeds through the control stage, where responsible personnel utilize an indicator as a decision-making tool. Subsequently, the signal passes through the control supplementation stage to enhance decision-making accuracy, as well as the remote-control supplementation stage to further improve the precision of fire detection. More details on the fire detection technology are provided in Appendix A, and Figure S1 of the Supplementary Materials.

2.2. Worker Location Monitoring

The worker location monitoring technology is associated with a location tag attached on the safety helmet, as shown in Figure 2. By identifying the location of workers through the web and an app, it is possible to increase manager work efficiency, control access to dangerous areas, and quickly respond using location information in case of an emergency. In addition, in the event of an emergency, the manager can be notified by pressing the SOS button, and even if the worker falls down without pressing the SOS button, the SOS function will be activated when the shock is detected. The safety helmet is equipped with an LED light with which vision in the dark can be assisted.



Figure 2. Worker wearable devices: the location tag and safety helmet.

Worker location monitoring can be effectively achieved by deploying beacons that can receive signals from the location tag at each part of the construction site so that the safety manager monitors the information of each beacon. This technology can be particularly useful for important tasks such as tunnel construction, where monitoring worker location poses significant challenges.

2.3. Safety Hook Fastening Detection

The safety hook fastening detection system is designed to ensure the secure engagement of workers with safety hooks when operating in elevated locations. This system utilizes sound and platform notifications to promptly alert users. Real-time monitoring of safety hook fastening can be conveniently performed by administrators through a web/app interface. Notably, this system does not necessitate the use of an independent safety hook, but rather relies on a specialized hardware component that can be seamlessly integrated with existing safety hooks, as depicted in Figure 3. Comprising a fastening detection unit and a warning unit, this system effectively detects the fastening status of the safety hook fastener and the worker-worn safety hook. The fastening detection unit employs a sensor module to accurately assess the fastening condition of the safety loop. A sensor control unit manages the sensor module, generating fastening detection information based on the assessment. Subsequently, the sensor communication unit transmits the fastening detection information to the alarm unit. In response to the received information, the warning unit generates audible alerts in accordance with the fastening status of the safety loop.

2.4. Opening Detection

The opening detection device presents an advanced solution to prevent slip and fall accidents resulting from operator negligence through detection and real-time monitoring of cover opening. The opening/closing detection device is depicted in Figure 4. As shown in this figure, it is composed of a detection sensor, a Bluetooth communication module, and a power supply. As shown in the middle of Figure 4, it is attached to the opening lid. The detection sensor employed is a Time of Flight (TOF) sensor, which accurately determines whether or not the opening is in an open or closed state. A TOF sensor works by measuring the round-trip time of a signal provided by a camera or beacon to calculate the distance between the camera or beacon and the subject for each point in the image. Information on several individual openings is coded as shown in the left figure of Figure 4,

and is monitored by the safety manager. If an opening that should not be opened is open or is open beyond the allowable time, an alarm sounds so that the operator and the safety manager immediately notice it.

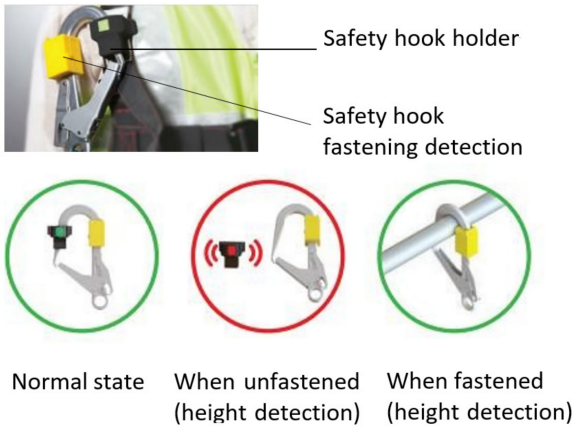


Figure 3. Schematic diagram of safety hook fastening detection technology.

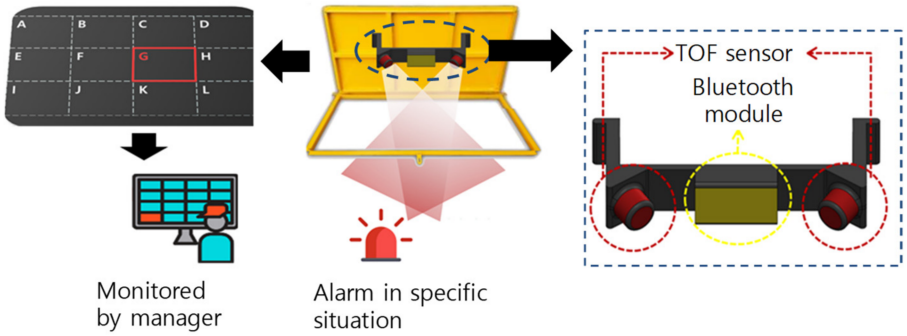


Figure 4. Working principle of opening detection technology.

2.5. Table Lift Laser Guide

The table lift laser guide is a safety device for a construction platform located in a high position, as shown in Figure 5.

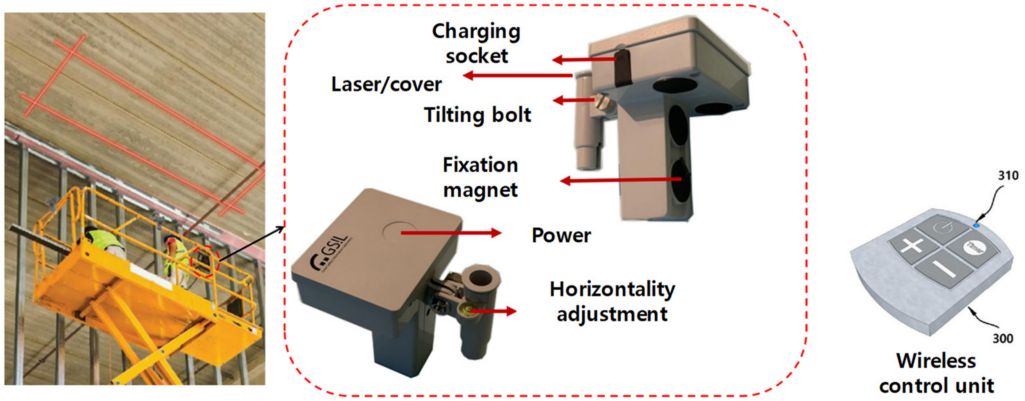


Figure 5. Use of table lift laser guide and its structure.

The system comprises a laser unit and a mounting unit designed to attach the safety device to the high-speed workbench. The laser unit is composed of a line laser that displays a work prediction area by projecting a line laser light to a work position predicted when the boarding part of the high-place work platform is raised, and a laser coupling unit to which the line laser is fixed. The mounting part is made of a magnet, and the line laser

projects the line laser light to a working position predicted when the boarding part of the high-place work platform is raised, and marks the job prediction area so that it can be confirmed with the naked eye. In addition, at the rear end of the line laser, there is a diaphragm for adjusting the length of the line laser light irradiated from the line laser by being coupled to be aligned with the line laser. The diaphragm incorporates an opening that regulates the length of the projected laser light by adjusting the distance between the opening and the line laser. The laser coupling unit is connected to the mounting unit and can rotate, providing adjustability through a screw mechanism. The system is additionally equipped with a wireless control device including remote on/off of the device, operation time adjustment of the safety device using a timer, and a driving confirmation unit of the high-place work vehicle, so that convenient use can be promoted. In Figure 5, the left-hand side shows how this system is applied to the actual work site. Through this system, as the line laser light is output toward the rising direction of the operator's board or chassis before ascent of the aerial platform, it is possible to visually identify the space in which the workers will be active, thereby preventing possible risks after starting work in advance. This proactive approach mitigates potential risks and helps prevent accidents before work commences.

3. Smart Construction Management System

3.1. Efficacy of Smart Construction Objects

In this study, the tri-axial diagram method proposed by Niu et al. [16] was used to evaluate the efficacy of the SCOs developed in this study. Niu et al. introduced a three-step breakthrough in the JSA methodology. The first stage refers to actions such as wearing a helmet and protective gear; the second stage is the preparation of safety guidelines and education regarding these; and the third, which has recently emerged, refers to SCO-based JSA technology utilizing sensors and wireless communication. In their work, it was pointed out that more study is needed in future regarding the third JSA, because the methodology has not yet been systematized or fully established, and there have not been many applied cases [15]. The tri-axial diagram analysis method is described in Figure 6. This method evaluates three essential factors for each SCO: awareness, communicativeness, and autonomy. The key factors are awareness, communicativeness, and autonomy, representing sensing ability, information exchange ability, and action-taking ability, respectively [16]. Each key factor, awareness, autonomy, and communicativeness, and their corresponding grades are illustrated in Figure 6.

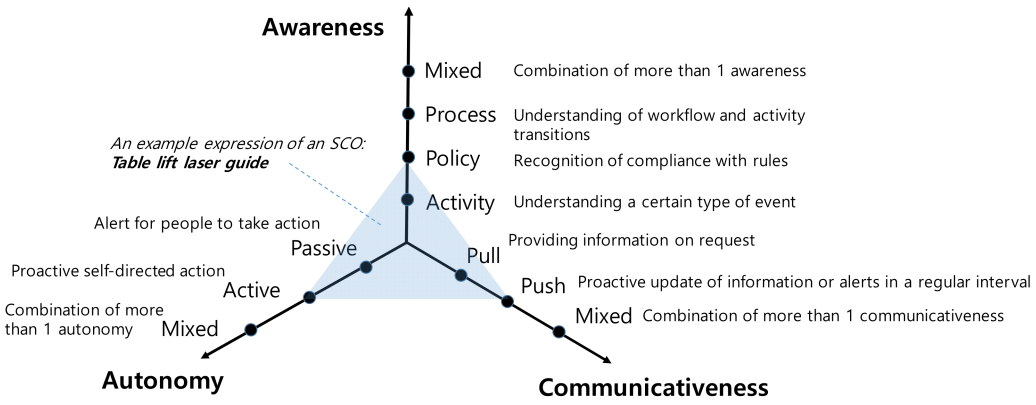


Figure 6. Three key parameters of SCO: a tri-axial diagram.

The tri-axial diagram presented in Figure 6 allows us to assess the suitability of the SCOs for Job Safety Analysis (JSA). The diagram evaluates the SCOs based on three dimensions: awareness, autonomy, and communicativeness. Awareness is classified as activity awareness, policy awareness, process awareness, and mixed awareness. Autonomy is classified as passive autonomy, active autonomy, and mixed autonomy. Communicativeness is

classified as pull communicativeness, push communicativeness, and mixed communicativeness. The grades assigned to each category represent their respective levels of advancement, with higher grades indicating more advanced capabilities and functionalities.

The tri-axial diagram presented in the figure allows the estimation of how well the SCOs can be utilized for JSA. The grades of each key factor for the SCOs developed in the present study are summarized in Table 3. Fire detection is performed by illuminance analysis, and acts as a criterion for the recognizing fire occurrence. The awareness of fire detection technology applied in this study is shown to correspond to policy awareness. In the case of communicativeness, it corresponds to a push, because it detects fire in real time and preemptively provides information and alerts. In the case of autonomy, since the SCO does not directly take an action, it falls under passive autonomy. Safety hook fastening detection technology exhibits mixed awareness, as it determines whether the hook is fastened and whether it is necessary simultaneously. The autonomy is mixed because preemptive responses and alarms to workers are made at the same time. The awareness of the opening detection technology corresponds to mixed awareness because, as in the case of safety hook fastening detection, both recognition and situation determination are performed at the same time. Communicativeness and autonomy are also in a similar vein, and are evaluated in the same way as the safety hook fastening detection technology. In the worker location management technology, the hazard area or the distance between the moving equipment and the worker (i.e., buffer distance) is the criterion for judging the level of risk. Therefore, awareness corresponds to policy awareness, as in the case of fire detection technology. The communicativeness is push, because it provides an alarm when the distance between the actual worker and the danger section is shorter than the buffer distance, and autonomy is passive because it only provides an alarm and does not take preemptive measures by itself. In the case of table lift laser guide technology, recognition and communication are the same as above, and autonomy can be interpreted as active autonomy because it predicts whether the laser line provided by the table lift will collide with pipes and other structures and enables a preemptive response. When referring to various studies [12–16], the indicators for recognition, communication, and autonomy of the SCO technologies introduced in this study are evaluated to be qualitatively superior to those of previous studies, suggesting that the SCOs listed in Table 2 are effective and useful in the construction site. The tri-axial diagram analysis method employed in this study can be utilized to evaluate and analyze future SCO development and implementation.

Table 3. Examples of events to be managed by developed SCOs.

Events to Manage	SCOs	Pre-Set Condition for Awareness	Dangerous Situations	Awareness	Communicativeness	Autonomy
Critical environmental situation	Fire detection	Threshold luminance	Threshold luminance $\leq$ luminance	Policy awareness	Information push	Passive autonomy
Failure to fasten the safety hook	Safety hook fastening detection	-	Hook unfastened when needed	Mixed awareness (activity and policy)	Information push	Mixed autonomy
Carelessness of the holes and openings in the floor	Opening detection	Criteria for how long a specific opening should be open	Hole/opening open without need	Mixed awareness (activity and policy)	Information push	Mixed autonomy
Failure to maintain safe distance from parts of machine/vehicle	Table lift laser guide	Distance detection between worker and moving parts	Distance $\leq$ buffer distance	Policy awareness	Information push	Active autonomy
Failure to maintain safe distance between on-foot worker and restricted area	Worker location monitoring	Distance detection between worker and restricted area	Distance $\leq$ buffer distance	Policy awareness	Information push	Passive autonomy

3.2. Management System for the Smart Construction Objects

The SCO technologies introduced earlier hold great potential for implementing smart construction practices and enhancing overall value. This section will outline the implementation method for these SCOs and discuss their resulting efficacy. Figure 7 shows the structural diagram of the SCO-based construction management technology developed in this study. As shown in this figure, the fire detection technology, worker location management technology, safety hook fastening detection technology, opening detection technology, and table lift laser guide technology generates advanced awareness, communicativeness, and autonomy. All of these are interconnected by electrical signals to the management platform handled by the construction manager. This management platform facilitates effective interaction with the SCOs, by acquiring and accumulating data from the SCO, or providing an alert when the pre-set condition shown in Table 3 is violated. This management platform can not only implement SCO, but also collect and analyze BIM (building information modeling) data. In addition, it can be used for monitoring the operation status of personnel and equipment, and can be effectively used for work documents, inspection, and regulatory response, which we will discuss in the next paragraph. As a result, the management system described in Figure 7 can bring about the effectiveness of work safety, quality, time, cost, and satisfaction. As emphasized by Raja and Niu et al. [5,15,16], the SCO-based JSA methodology presented in this study has a noticeable value and potential ripple effects in terms of work economics given the significant cost savings associated with improved safety measures.

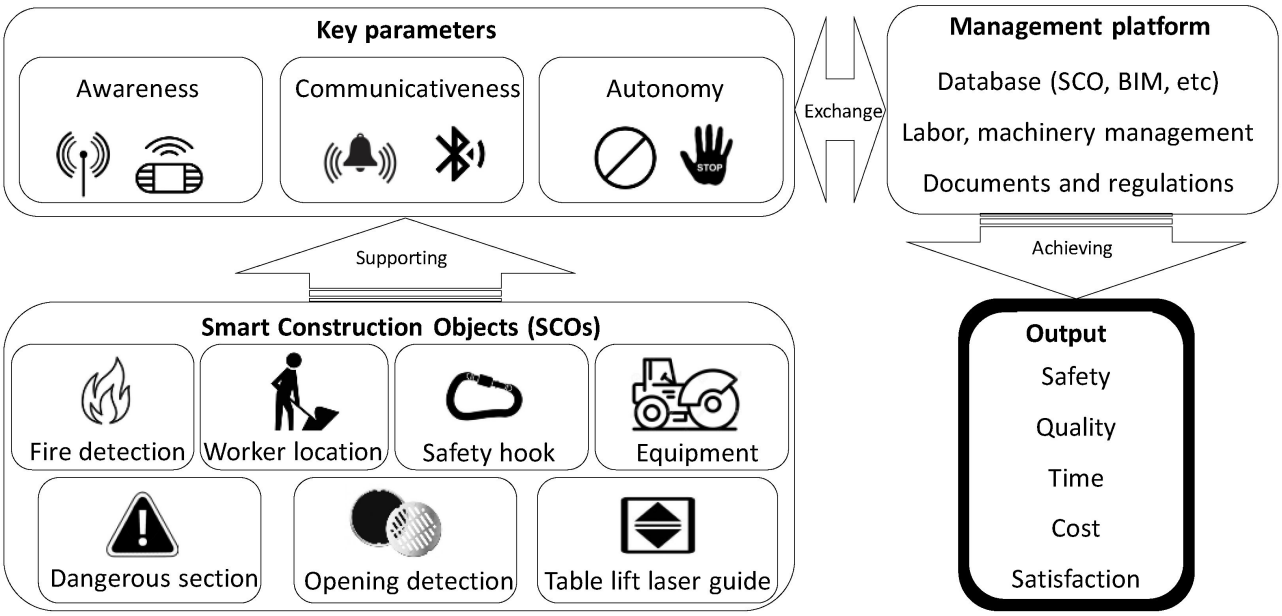


Figure 7. Architecture of the SCO-enabled management system.

3.3. Comparative Analysis with Previous Construction Work

Figure 8 illustrates the innovative smart construction management system (referred to as the smart construction system) developed in this study. In this figure, the integrated control system represents the management platform depicted in Figure 7, which maintains close communication with the safety manager and oversees all operations and resources at the construction site. Within the construction site, there are four key entities represented by rounded rectangles: the manager, the partner, and the workers and equipment provided by the partner.

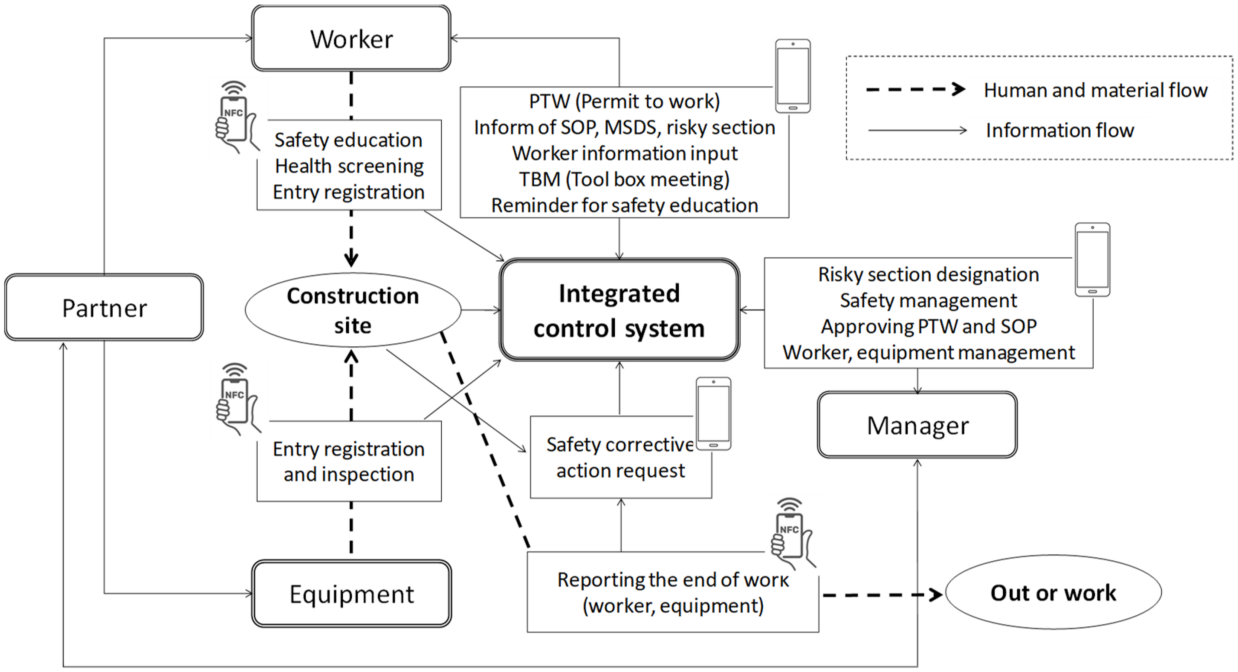


Figure 8. Generic smart construction management workflow.

In the conventional construction practices, significant manpower is allocated to construction sites, requiring new worker education and regular safety education, and must complete the paperwork related to completion in the education. In addition, the training history must be prepared and submitted, orally reported to the manager whenever every worker goes out, and a PTW (Permit to Work) must be obtained from the manager [24]. SOP (Standard operating procedure), MSDS (Material Safety Data Sheet), and hazard section verification are all in hand-writing, and a PCM (Pre-construction Meeting) as well as TBM (Tool Box Meeting) must be conducted for all-together before starting work [1,8]. TBM sessions often involve tasks such as exchanging greetings, inspecting attire, reviewing work instructions and contact information, discussing individual risk factors, and repeating safety measures for each worker. The manager writes the construction status board by hand during the work, puts it on the work site, and uses it for monitoring. Managers receive individual reports from workers, either verbally, or in writing. The manager establishes a nonconformity management plan (S-CAR, Safety Corrective Action Request) by synthesizing the worker's experience, discusses this with the partner who supplies manpower, and reflects the result in the TBM. Although it is obvious that the above-mentioned procedures must be performed in terms of the implementation of JSA, they have very time-consuming disadvantages. Furthermore, the reliance on written and face-to-face communication and approval processes does not align with the current trend of ICT technology advancements [2]. The consumption of time at the construction site also represents economic loss [5,15,16]. Another problem is that, despite such a time-consuming process, it is difficult to efficiently manage manpower through this process. First, it is difficult for managers to find out in real time which work section workers are in, so it is difficult to detect negligence and unsafe actions. The conservative nature of the construction industry, combined with opposition from unions and workers, makes it difficult to implement changes [10]. Inefficiencies in the management of construction resources exist not only in manpower but also in the use of equipment. Construction companies rent equipment from partners, the problem is that it is inconvenient to have to go through the registration and inspection process for importing this equipment every time they are put into the site. In addition, since there is no system to check the utilization rate of these equipment, even if the rented equipment is idle all day, there is also cost inefficiency in which the equipment rental fee is calculated on a daily basis and paid to the equipment maker.

In contrast to conventional construction practices, the smart construction system developed in this study offers significant alleviation of the aforementioned issues, as depicted in Figure 8. In this figure, the solid line represents the flow of people/materials, and the dotted line represents the flow of information. At the construction site, workers and equipment are supplied from partners to the construction site. The worker is wearing an NFC tag, and the details of completing safety education and receiving a health check are recorded in the system through the worker's smartphone, and can be put into the construction site through the NFC tag without a separate document procedure. If the safety training is incomplete or the period is imminent, a notification is automatically given through the NFC device. Equipment is also automatically brought in and registered/inspected through NFC tags, and how many hours it has operated during the day can also be monitored. The location of personnel and equipment is monitored in real time through NFC tags. The operator must obtain an SOP and a PTW from the manager before starting work, and must perform TBM, all of which are replaced by smartphone work. The manager distributes the SOP and PTW to the workers through the integrated control system and the work permit and standard work procedure. The S-CAR at the construction site can be issued, shared, and documented as an app through the integrated control system. Upon completion of work, workers and equipment provide job completion reports via NFC tags. Similarly, the smart construction management system, illustrated in Figure 9, consolidates various managerial tasks, including document management, emergency response, communication, equipment tracking, worker training, and supervision, into the integrated control system. This integration minimizes unnecessary time and cost expenditures while enhancing overall safety. Unlike traditional construction site networks that require hardware installations and maintenance of location scanners, access points (APs), and gateways, the present system relies on NFC technology and smartphones, resulting in time and cost savings and increased management efficiency.

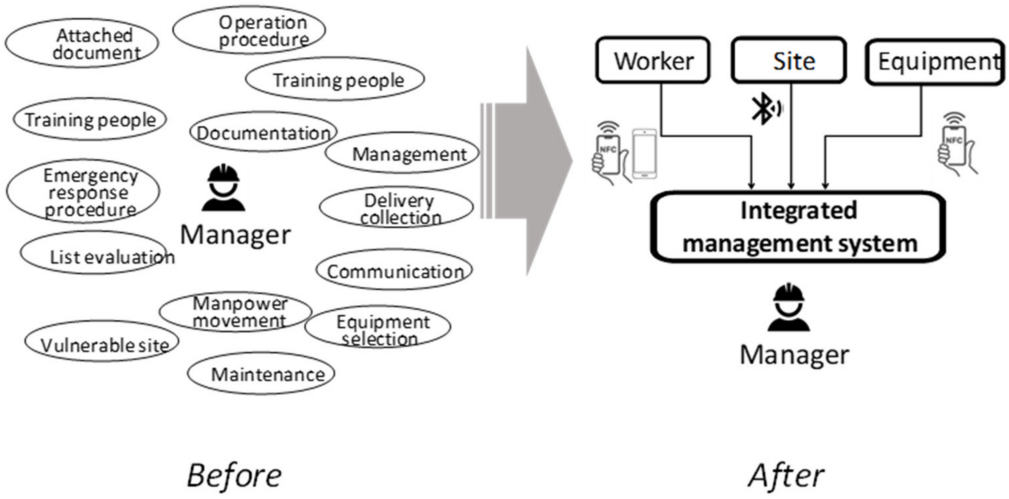


Figure 9. Comparison before/after application of the smart construction system.

4. Demonstration

4.1. Tunnel Construction

This section presents a demonstration of the smart construction management system, focusing on a tunnel construction project carried out by Doosan Heavy Industries & Construction in Korea in 2016 as part of the Janghang train line improvement initiative. Tunnel construction sites pose higher risks compared to general construction sites, as they involve performing various tasks such as excavation, blasting, lining formwork, rebar work, and concrete work, and the risk is higher than that of general construction sites. In tunnel construction, one of the major challenges is that the location of workers is difficult to monitor due to noise, lack of wireless communication, and the short reach of radios. In

this study, leveraging the smart construction objects and management system, efficient construction status identification, safety enhancement, real-time risk assessment, and environmental information analysis were achieved in the tunnel construction area. For the demonstration, Bluetooth-based positioning scanners were installed at intervals of 50 m, and the workers wore the wearable device introduced in Section 2.2, as shown in the left image of Figure 10, so that the location of the worker was transferred to the server in real time for smooth communication in all areas in the tunnel. The web-based screen displays the identified worker locations, accessible via any operating-system-compatible browser, allowing checking from the workers' lounge and the safety management room.



Figure 10. Application of location monitoring technology in tunnel construction.

The right image of Figure 10 illustrates that each scanner can simultaneously detect a maximum of 20 location tags. Considering the number of workers in each scanner interval does not exceed 9, it can be stated that one scanner can sense a sufficient number of workers simultaneously. The maximum communication distance between tag and scanner was estimated to be 100 m. The communication stability of the tag and scanner was also tested and demonstrated in accordance with BTS-16 standard. Further details on the BTS-16 standard are presented in Table S1 of the Supplementary Materials.

The user interface of the safety manager for the smart construction management system comprises 11 items, including monitoring, sensing and analysis, resource management, disaster management, reporting management, and organization and personnel management. Among them, sensing and analysis consists of three major items, including location identification, environmental sensor, and image analysis, and resource management consists of four major items, including worker management, equipment management, vulnerable point management, and nonconformity management. Each of these major/semi-major items is further divided into two to six sub-items, resulting in a total of 46 sub-items that can be managed by the system. Through the monitoring window, it is possible to inquire as to worker status, location information, equipment inspection status, vulnerable spot inspection status, non-conformity status, and necessary information for each site. In the environmental sensor window, it is possible to know the concentration of oxygen, carbon dioxide, carbon monoxide, temperature/humidity, hydrogen sulfide, and combustible gas and whether the standard value is exceeded, and fire can be detected from the image analysis window. The worker management window allows for efficient management and identification of departures, training, and related tasks, thereby reducing unnecessary paperwork. In the report management window, job start report and job completion report can be efficiently performed on the app. An example screenshot of the user interface handled by the administrator is shown in Figure 11. Details on the user interface are presented in Table S2 of the Supplementary Materials. In Table S3 of the Supplementary Materials, comparative data of implementable functions of user interface of present study and that of previous studies are presented.

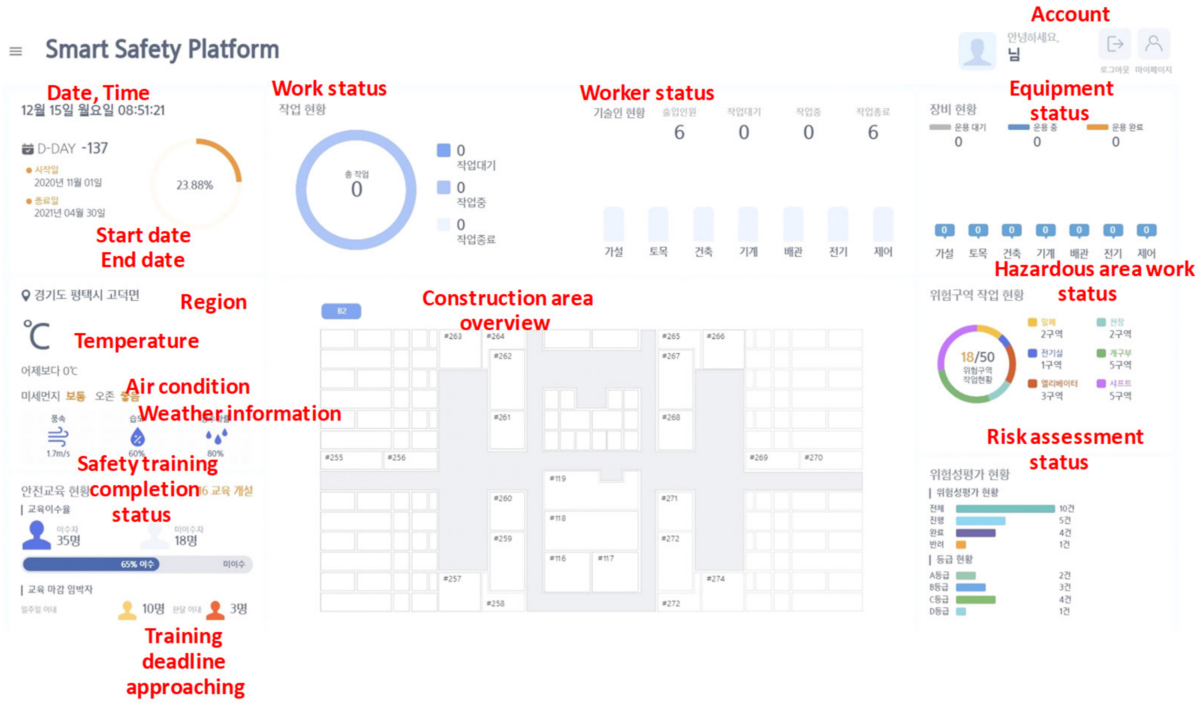


Figure 11. An example of the user interface of the present smart construction system (edited from a screenshot).

Table 4 presents a comparison between the construction cost using the technology developed in this study and the cost using existing technology. As shown in this table, the worker location monitoring technology developed in this study increases the material cost, but reduces the overall construction cost by 13% by greatly reducing the labor cost. Table 5 focuses on the maintenance cost of the tunnel constructed using the technology developed in this study. The table provides monthly and annual cost comparisons with the conventional approach. This reveals that the technology developed in this study enables substantial budget savings of approximately 38% on a monthly basis and about 77% on an annual basis.

Table 4. Construction and maintenance costs of the present and previous studies: construction cost (monthly based, unit: KRW).

Classification	Present	Previous
Material cost	28,617,480	14,782,812
Labor cost	7,598,358	27,434,236
Expenses	3,539,090	5,630,319
Pure construction cost	39,754,928	47,847,367
Total	44,168,634	56,108,518

Table 5. Construction and maintenance costs of the present and previous studies: overall cost taking into account the maintenance cost (unit: KRW).

Classification		Present Study	Conventional Construction
Construction cost		44,168,634	56,108,518
Maintenance cost	Inspection	408,769	-
	Maintenance	1,117,275	17,768,190
	Subtotal	1,526,044	17,768,190
Total (monthly)		44,168,634	73,876,708
Total (annually)		62,481,162	269,326,798

The underlying principle of how this system enhances work efficiency and economic benefits can be illustrated with an example. In the traditional tunnel construction blasting process, the safety manager visually verifies the presence of workers, and information is communicated through radios or walkie-talkies within the tunnel. Consequently, the pre- and post-blasting worker checks consume a substantial amount of time, as depicted in Figure 12. In contrast, the current management system facilitates real-time monitoring of workers through a network of tags and scanners, as depicted in Figure 12. This real-time monitoring capability translates into significant time and cost savings compared to the conventional approach.

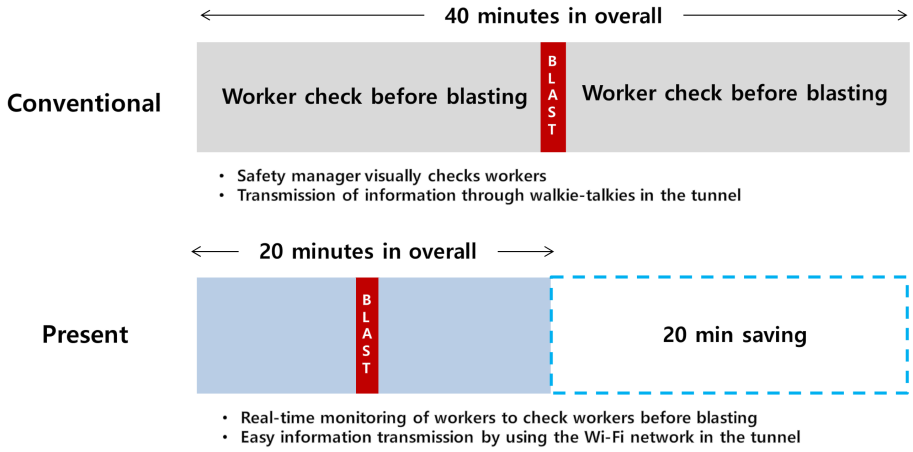


Figure 12. Principle of time saving using the worker location monitoring system of the present study: 20 min of time saving and worker safety enabled by excluding the visual- and walkie-talkie-based worker location monitoring process.

4.2. Discussion

Figure 13 showcases the successful application of the smart construction technology in various projects, affirming its effectiveness. Firstly, it was applied to the construction of Samsung Engineering's underground water tank in the second quarter of 2017 (Figure 13a). In addition, in the third quarter of 2017, the present smart construction system was also applied for the safety of 21 railway work sites at the KR (Korea Railroad Authority) Gangwon Headquarters, associated with the management of 1061 workers and 123 pieces of equipment (Figure 13b). Additionally, it was applied in the construction of the Baam subway in Korea (Figure 13c), and it was also applied as the construction management system for the Dangjin–Pyeongtaek undersea tunnel (Figure 13d). According to reports from the project manager, it was reported that the construction time was reduced by about half, and the productivity was also remarkably improved through the improvement of safety. However, it is worth noting that it is difficult to investigate the efficacy of the smart construction system quantitatively; therefore, this has not been performed yet, suggesting that additional research is needed. As previously discussed, prior studies have primarily focused on investigating individual technological components and their values within the context of smart construction. However, on real-world construction sites, a comprehensive evaluation should consider various factors, such as the integration of different technological elements, feasibility, economic viability, and the perspectives of managers and workers who are adopting new technologies. In this regard, this study holds significance, as it evaluates the practical applicability of existing smart construction technologies by extracting and merging field-friendly elements. The proposed smart construction management system enables seamless connectivity throughout all stages of construction, including planning, design, procurement, construction, and maintenance, facilitating effective collaboration among stakeholders involved in the construction process.

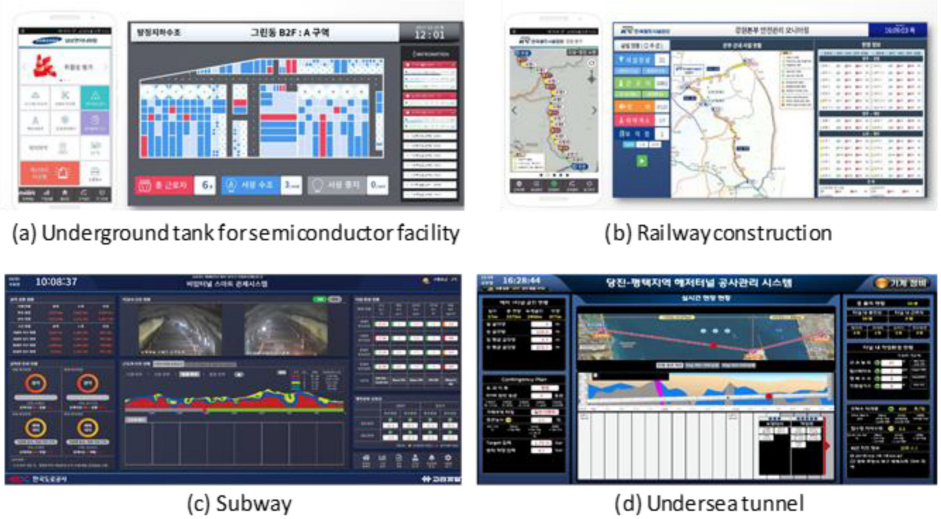


Figure 13. Examples of construction sites where the smart construction technology was applied.

The selection of the five specific SCOs was based on a comprehensive analysis of previous studies on smart construction technologies, as summarized in Table 1. Among numerous smart construction technologies, those exhibiting high importance, practicality, and potential for further development were chosen as the focal points of this study. However, it is important to acknowledge that this paper may not provide an exhaustive justification for the selection of these five SCOs among the wide array of available options, nor can the findings be readily generalized to broader contexts. Our research primarily emphasizes the practical applicability and academic contribution of the chosen SCOs, thereby consolidating the content within a single paper. It is crucial to note that these SCOs converge at a construction site to collectively enhance safety, while simultaneously streamlining time and cost requirements for construction projects.

The proposed smart construction management system presents various advantages in terms of enhancing efficiency, reducing costs, and improving construction processes. However, it is crucial to acknowledge and address the potential ethical concerns associated with its implementation. One notable concern is related to privacy and data security. The system relies on tracking the location and daily working hours of workers through mobile apps, which may raise privacy issues. To mitigate these concerns, appropriate measures should be implemented to ensure data protection, consent from workers, and compliance with relevant privacy regulations. Strict access controls, encryption techniques, and anonymization practices can be employed to safeguard sensitive information. Another ethical consideration is the potential impact on job displacement. As the smart construction management system incorporates automation and artificial intelligence, there is the possibility of reducing the reliance on human workers for certain tasks. To mitigate this concern, it is essential to prioritize responsible deployment and consider the system as a tool for augmenting human capabilities rather than replacing human workers entirely. This can be achieved by providing training and upskilling opportunities for workers to adapt to the changing job requirements and by ensuring transparency in the decision-making process regarding the implementation of automation technologies. Moreover, involving stakeholders, including workers and labor unions, in the development and implementation phases can help address ethical concerns and ensure that the system respects workers' rights and well-being. Regular dialogue, feedback mechanisms, and clear communication regarding the purpose, benefits, and limitations of the system can foster trust and facilitate a smoother transition.

5. Conclusions

In this study, a systematic smart construction system was developed to improve safety at construction sites, eliminate unnecessary waste of time and manpower, and implement

efficient operation of manpower and equipment, and demonstrated empirically. From the study, the following conclusions were derived:

1. Five SCOs were developed to enhance safety and efficiency at construction sites, including fire detection, operator position monitoring, safety hook fastening detection, opening detection, and table lift laser guidance. The efficacy and technical value of these SCOs were evaluated using the tri-axial diagram method. Three key factors, awareness, autonomy, and communicativeness, were empirically evaluated. Results showed improved awareness and autonomy compared to previous studies' smart construction objects, with effective information push and policy awareness.
2. A smart construction management system was developed based on the developed SCOs. The system interacts with the integrated control system through smartphones and NFC tags, significantly improving construction site safety and reducing time and cost associated with unnecessary paperwork.
3. Through multiple empirical applications of the SCO element technology and smart construction management system, construction time was reduced by over 40% and construction cost by over 70%. This was achieved through simplification of construction resource management procedures, such as Job Safety Analysis (JSA), Tool Box Meeting (TBM), Permit to Work (PTW), and nonconformity management.
4. This study comprehensively considered the pros and cons of existing smart construction-related research and the effectiveness of smart construction element technologies, and conducted a comprehensive study on a construction method that could dramatically increase safety and productivity while being site-friendly. However, establishing the quantitative relationship between the functions of the developed system and the cost/time reduction effects, still remains an unresolved issue, urging further studies.
5. This study also urges follow-up studies that attempt to build a better construction industry by introducing ICT convergence technology, which is rapidly developing along with the fourth industrial revolution for addressing potential concerns such as user satisfaction, cost-effectiveness, and ease of adoption.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13061383/s1, Figure S1: Image processing for the fire detection; Table S1: Structural stability test items and results; Table S2: Overview of user interface for the smart construction system; Table S3: Comparison of implemented functions of various smart safety platforms.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

With reference to Section 2.1, more details on the fire detection technology are described in Figure S1 of the Supplementary Materials. Figure S1a shows the flame candidate area extracted from an image. In Equation (1), τ is a constant and can be determined by ROC (Receiver Operating Characteristics) analysis. ROC is one of the analysis methods for hit probability that deals with signal detection theory, as shown in Figure S1b. In this graph,

the origin refers to a delimiter that is never said to be "in", which means that it does not cause a runout, but does not hit it either. Conversely, (1,1) always means 'yes', and the upper left (0,1) indicates a perfect distinction. In other words, it is more conservative towards the lower left, more adventurous towards the upper right, and more accurate towards the upper left. As shown in this figure, the fire detection system developed in this study has sensitivity and specificity of 0.8 and 0.1, respectively, showing superior performance compared to the existing fire detection technology. With reference to Section 4.1, details on the BTS-16 standard are presented in Table S1 of Supplementary Materials. Regarding the same section, details on the user interface are presented in Table S2 of the Supplementary Materials. In Table S3 of the Supplementary Materials, comparative data of implementable functions of user interface of present study and that of previous studies are presented.

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