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Development and Application of an Integrated Management System for Off-Site Construction Projects

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Abstract: The off-site construction (OSC) method has attracted the interest of experts to resolve productivity stagnation and lack of skilled workforce and to reduce greenhouse gas emissions in the construction industry. Due to the unique characteristics of OSC projects, wherein building elements are produced in a factory, transported, and installed in the field, a management approach that differs from the management techniques of previous construction projects is required. Accordingly, with this study, we examined the characteristics of OSC projects and derived key management items through literature review, case analysis, and expert meetings to develop an integrated management system for OSC projects (OSC-IMS). The proposed system, OSC-IMS, integrates the entire supply chain of the OSC project. It includes the following functions: drawing management, scheduling and planning, site installation planning, production planning, production monitoring, shipping and transportation, delivery and inspection, site installation monitoring, and progress payment management. To verify the applicability and effectiveness of OSC-IMS, it was implemented in four projects. The application of the system to the case studies demonstrated the improvements in work efficiency and accuracy and decreased waste time in every work step. The findings indicate that the system can enhance project performance. This study contributes to the identification of the features and key elements of OSC management such that these factors can be linked with managing system development. This work describes the overall effect of the proposed system on real projects.

Keywords: off-site construction; management system; supply chain management; integration; building information model

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1. Introduction

The construction industry is facing several challenges. Low labor productivity is a long-unsolved problem for the global construction industry. McKinsey & Company reported that the construction industry's productivity grew by only 1% over 20 years [1]. Furthermore, the lack of a skilled workforce exacerbates this phenomenon [2]. The United Nations Environment Program announced that the construction sector emitted 38% carbon dioxide, the highest among all sectors [3]. As interests and concerns about environmental issues continue to increase globally, solutions to reduce the environmental load generated from construction projects are vital [4].

Off-site construction (OSC) is drawing attention to solve these internal and external problems in the construction industry as a driving force for future development [5]. OSC is a construction method that completes buildings and facilities by producing elements and components of a construction project at different locations from where they will be permanently installed and then transporting and installing them on site [6]. OSC is also called prefabrication, industrialized construction, modern methods of construction, modular construction, or prebuilt construction, depending on the construction method and country. Although these terms differ subtly, they share a core meaning.

OSC is expected to address the limitations and disadvantages of the most common construction methods, where most work is performed sequentially on site [7]. OSC could improve project performance to complete the construction object with higher quality, less time, and lower cost in a safer and more comfortable environment [8]. Workers can safely work in well-equipped production facilities [9], and less on-site work can reduce wasted energy and materials [10]. Because the portion of construction field work constrained by limited working time, limited space, and bad weather is performed at off-site factories, project time and cost could be significantly reduced [11]. Furthermore, production in dedicated off-site factories and site installation could improve the quality of construction projects by producing high-quality elements [12].

The OSC method requires a new management approach because it differs from existing site-oriented production methods. For the OSC method to work effectively, integrated management must be conducted to improve the efficiency and productivity of each project process, including planning, design and engineering, production, transportation, and site installation [13]. The management of OSC projects should be approached from the perspective of supply chain management (SCM) so that the flow of elements and components, essential characteristics of OSC, can be understood and the entire process of production, transportation, and installation can be synchronized [14]. From this perspective, OSC projects require a management system that can deliver each phase organically. In particular, it is important to ensure that each process ultimately leads to efficiency and productivity improvement during project execution through integrated management [15].

The aim of this study is to develop an integrated management system for the efficient execution of OSC projects. The development of the integrated management system for OSC project follows the waterfall model, as many previous studies [16–19] considered in the next chapter. The waterfall model consists of five steps: requirements, design, implementation, verification, and maintenance [20–22]. However, this study has a more challenging goal of realizing the integrated management of OSC projects. To this end, we followed the three steps shown in Figure 1. First, the characteristics of OSC projects that differ from those of on-site constructions are identified. Moreover, the key factors for OSC project management are derived through literature review, expert interviews, and case studies. Then, an integrated management system is designed and implemented to achieve the derived key factors of OSC project management and apply the system to the field. Finally, a field application case analysis is conducted, and the effect of the integrated management system is presented.

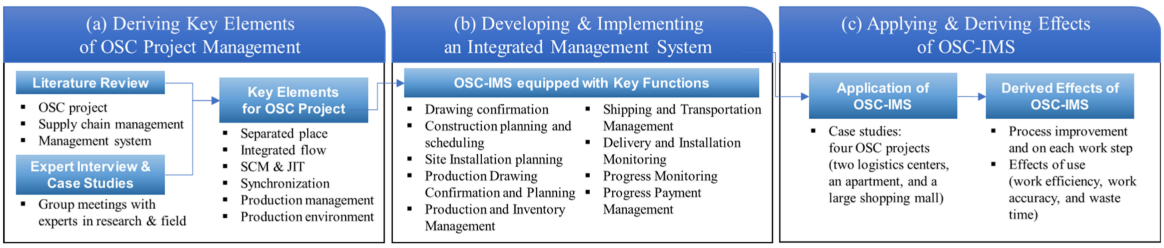

Figure 1. Research flow.

2. Literature Review

2.1. OSC Project Management

With OSC still being introduced or implemented by countries and for projects, project participants are unfamiliar with this new production system, and their knowledge is shallow [23]. Because the policies and guidelines for OSC have not yet been standardized, the more flexible the project, the higher the risk [24]. Such flexible conditions must be managed differently because OSC projects are fundamentally distinct from on-site construction projects. Zhang et al. [25] suggested a process-oriented framework to identify and improve the performance of OSC projects through value stream mapping. Although OSC overcomes the limitations of the conventional construction method, new risks arise. Zhai et al. [26]

proposed a new management plan for OSC projects that identifies, evaluates, and responds to risks that may occur in each stage.

Because each phase of OSC project execution—production, transportation, and installation—is critical for project success [27], the literature has suggested new managerial methods. Researchers have focused on optimization theory with respect to the production phase occurring at off-site factories that emulate the manufacturing environment. Arashpour et al. [28] derived a method for producing a concrete panel in the shortest time using optimization problems. Ma et al. [29] optimized two different production lines with genetic algorithms. Furthermore, Abdula and Usman [30] identified factors impeding the lean supply chain flow of all resources through the six-sigma method, and Ismail [31] applied ANN and a genetic algorithm to monitor and manage workflows. Several studies identified that integrated management is of paramount importance in OSC projects; each phase is closely linked like a chain [27], focusing on integrated management to fill and bridge the gaps between the project phases. Lee and Lee [18] proposed a digital twin framework for managing schedules during entire processes. Hussein et al. [32] conducted a holistic review of material management in OSC projects.

2.2. Supply Chain Management (SCM) in OSC Projects

SCM is the broad range of activities required to economically plan, control, and execute a product's flow from materials to production [33]. The importance of SCM for practical OSC projects has been emphasized. Hussein et al. [32] claimed that SCM—a vital connection between construction sites and off-site factories—is a crucial challenge in the successful delivery of OSC Projects. A poor supply chain causes multiple problems, such as early or late transportation, project delays, additional workforce input due to business setbacks, and increasing costs [34]. Therefore, SCM serves as the backbone of OSC to fully realize its benefits.

SCM could eliminate waste factors by seamlessly connecting all the processes from production to installation to move the correct elements within time. There have been two research directions for SCM. The first is the management of storage and inventory. Efficient stocking of produced components is a critical factor affecting time and cost. Accordingly, Ekanayake et al. [35] classified key indices in the view of flexibility, recovery, collaboration, and security of supply chain capabilities. Furthermore, Lee et al. [36] identified the logistical problem in OSC projects and proposed a stacking strategy considering inventory stability and reshuffling effort during the transportation phase. Furthermore, researchers have optimized the process during transportation for efficient management. Xu et al. [37] identified the adverse conditions during loading–transportation of house wall components, and Shayanfar et al. [38] categorized the types of component damage during transportation.

The second research direction for SCM is just-in-time (JIT) production and delivery. OSC projects with JIT reduce carbon emissions, as well as time and cost, thereby improving quality [12]. Because the type and shape of components produced for OSC projects vary widely, recognition and tracking of components are significant for JIT management. Several technologies to identify and record the flow of components using RFID and barcodes have been developed. Panahi et al. [39] presented an RFID method for locating materials and managing inventory. Yang et al. [40] identified and categorized five sources of uncertainties affecting off-site logistics and transportation: off-site logistics process, demand side, supply side, planning and control systems, and environment. Furthermore, Xu et al. [41] proposed a transportation strategy that can achieve remote management using a cloud-based real-time status of the OSC components.

Although most previous studies have sought to increase efficiency at one stage in OSC projects, any malfunction or mistake in a stage could propagate to an entire project supply chain [42]. Accordingly, close collaboration among project participants, including designers, manufacturers, suppliers, specialty contractors, and general contractors across the supply chain, is valuable [43]. However, few studies on SCM in OSC projects have investigated this from an integrated and holistic viewpoint. Moreover, sharing information collected in each stage of the supply chain among participants and using said information for decision making is essential for efficient project performance. Most existing studies [44–46] have focused on the data collection mechanism rather than suggesting how the collected information can increase supply chain efficiency.

2.3. OSC Project Management System

A management system for efficiently managing OSC projects has been developed alongside the increased use of the OSC method. Luo et al. [47] and Yazdani et al. [48] derived a framework for the overall management of OSC projects based on a combination of existing architectural project management systems and manufacturing. Furthermore, some management systems have been used for real-world projects [36,49,50]. Sutrisna and Goulding [51] and Yang et al. [16] focused on system development to enhance the use of building information modeling (BIM) from the design stage. They analyzed the model needs for prefabricated buildings following the general waterfall model and designed the systems by dividing it into four layers: analysis, interoperability, realization, and data acquisition. The implemented model was applied to a local project for verification. Several platform studies [17,52–54] have also optimized SCM from the JIT perspective after the design stage. Furthermore, Tan et al. [55] proposed a user-friendly system for the effective collaboration of participants. Many platform studies [18,19,56–60] have been combined with emerging high-tech technologies, such as RFID, BIM, the Internet of Things (IoT), and blockchain.

OSC project management systems have different features than existing construction project management systems due to the characteristics of OSC projects. The importance of SCM is emphasized in OSC projects, so several research projects have been conducted for production management and information management across the entire supply chain. Based on the importance of knowledge sharing and diffusion in the system for the OSC project's supply chain, Liu et al. [52] examined the mechanism of knowledge exchange networks. Especially during the off-site production and transportation processes, Salari et al. [53] noted that the project could not be conducted as planned or additional costs would be incurred because all the materials, quantity, and distance supplied to each factory were different. They defined this situation as a stochastic NP hard problem and solved it using the grasshopper optimization algorithm. In parallel, Niu et al. [17] presented a system for planning, optimizing, and visualizing off-site supply chains. They attempted to manage uncertain factors associated with logistics resources, workforce, and process management when delivering prefabricated components to solve a vehicle-routing problem. To enable immediate application of the system in the field, they selected an OSC project in Hong Kong, analyzed the requirements, designed the necessary functions, and realized each system element through programming. Jaskowski et al. [54] proposed a fuzzy logic-based mathematical model to determine the optimal economic order quantity and minimize the total production, inventory, and delivery costs.

Furthermore, studies have been conducted to improve the efficiency of production, transportation, and installation and to optimize the supply chain in OSC projects by adopting rapidly developing information and communication technologies, such as RFID and BIM. Wang et al. [56] developed an information exchange system through cloud-based BIM, extending one step beyond RFID. A multidimensional IoT-enabled BIM platform [19] followed the linear model, introducing the system architecture, analyzing and discussing considerations to implement, and realizing the platform technically. They verified that information exchange using BIM in OSC projects could improve the performance of SCM. In addition to BIM, Lee and Lee [18] developed a digital twin system for real-time project monitoring and simulation mediated by IoT and geographic information system (GIS) technologies. Tang et al. [57] integrated semantic web-based BIM and a relational database for IoT at a detailed level. In contrast, Li et al. [58] embedded the blockchain into an OSC management system and proposed a novel service-oriented architecture to address security issues within current systems, such as data manipulation and accuracy. Furthermore, Zhang et al. [59] expanded the usability of system-based data collection devices to track cost information, computing the severities of related variables. Zhao et al. [60] studied a management system (specializing in the installation phase) to enable structural health monitoring with a stress sensor.

3. Key Elements of OSC Project Management

An OSC project has characteristics that distinguish it from the on-site construction method. Accordingly, the on-site construction project management method has limitations to apply to OSC projects, and a management method suitable for OSC projects is necessary. In this section, we describe the key elements of project management required based on the characteristics of OSC projects. We identified the technical level and function of OSC project management techniques and management system development by conducting a comprehensive literature review (presented earlier) and analyzed several OSC project cases to specify the project execution process. Then, we interviewed experts from five construction sites who are conducting projects with the OSC method, as well as designers, production plant managers, and installers, to verify the results of the preliminary research. We derived the key elements to be included in the development of OSC project management system by integrating these research results.

First, because production, transportation, and installation are performed in different places in OSC projects, time, cost, quality, and safety management, which are essential to construction project management, should be conducted based on the characteristics of each place (Figure 2). Time, cost, and quality control of the final product are critical in the factory responsible for most of the production, whereas time is critical during the transportation stage. Furthermore, quality control of members to be installed and safety management are additional critical factors. Accordingly, the key elements of project management include:

- Production: schedule management, cost management, production management, quality management, inventory management, delivery management, safety management, and process management;
- Transportation: schedule management, transportation equipment, and loading planning;
- Installation: schedule management, progress monitoring, quality management, labor and equipment management, quality management, site management, payment management, and safety management.

Figure 2. Supply chain in OSC production method.

Second, as shown in Figure 2, design and engineering, factory production, transportation, and installation must be closely linked, and information generated in each phase must be integrated into an OSC project. First, DfMA is performed in the design and engineering phase (Figure 2a) based on the requirements and constraints of the factory production, inventory management, transportation, and site installation stages. Then, from factory production to the transportation stage (Figure 2b–d), managers continuously adjust the production method, production plan, and transportation schedule through communication with field personnel. Manufacturers and constructors participate in the design stage to provide consistent and accurate information; then, factory production and site installation work (Figure 2e) are performed. Because the participants of each stage work in separate places, they rely heavily on information to understand the project's overall situation and make decisions about their work. Therefore, integrated management of project-related information is crucial—to avoid errors, omissions, and delays—for linking each stage through comprehensive information sharing. Accordingly, the key elements of project management include:

- Linkage and integration of distributed and disparate project information;
- Supporting features for collaboration and communication for integrated design work (i.e., DfMA);
- Supporting features for information provision and performing tasks using 3D drawings and information visualization;
- Connecting individual systems of project participants;
- Supporting features for real-time communication and decision making between production factories, transportation, and construction sites.

Third, SCM from production plants to the site is vital for JIT production and installation in OSC projects. Production in each plant can lead to maximized productivity due to specialized equipment and trained labor, and products must be moved to the next place or final construction site when the production process in one place is completed. The efficiency of the transfer process is essential to determining project performance. Therefore, JIT inventory management is necessary to prevent over- or underproduction. If there is a shortage of products, the project cost may increase due to delays in delivery and unnecessary overhead costs. In contrast, excess inventory caused by premature production can lead to increased stock management costs and poor quality. Accordingly, the key elements of project management include:

- Real-time production-level monitoring;
- Lead-time management for each element and part;
- Quantity and location management of inventory in production plants and construction sites;
- Supporting features for establishing an optimal transportation plan and selecting optimal transportation equipment.

Fourth, it is necessary to synchronize the planning and execution of each stage of factory production, transportation, and on-site installation. The factory production plan is established consistent with the delivery schedule to avoid disruptions to the on-site installation process. If delays or omissions occur when examining the site installation plan and current status, they will disrupt the production plan and production process. Likewise, if the factory production plan and status are not adequately communicated to the field, problems arise in the installation process. Therefore, the production plant requires timely production based on the on-site installation plan and progress. In the field, it is necessary to synchronize planning and management to proceed with the work to meet the factory production status. Accordingly, the key elements of project management include:

- Supporting features for synchronizing factory production and on-site installation plans;
- Real-time production progress and transportation status monitoring;
- Real-time installation progress monitoring;
- Supporting features for synchronizing factory production control, inventory management, and on-site installation progress.

Fifth, the production process of OSC projects is performed predominantly in factories, increasing the importance of factory production management. It is necessary to thoroughly manage the production process, which affects the duration and cost of the entire project. Accordingly, the production period and cost should be optimized through the production plan linked to the work status of the site. It is necessary to increase productivity through line process monitoring of factories and constantly manage resources, facilities, and equipment. Furthermore, strict quality control is required for the entire production process due to the nature of the OSC project, where the final product of the factory is installed without additional processing on site. It is essential to monitor whether the specifications and performance conditions are satisfied based on the drawings and specifications.

In contrast, if a factory runs multiple projects simultaneously, it optimizes production time and cost by establishing an efficient resource management plan. Furthermore, it increases overall production efficiency through standardization, mass production, and cost reduction. Accordingly, the key elements of project management include:

- Supporting features for establishing and changing the production plan;
- Supporting features for decision making related to production planning;
- Production time and cost monitoring and management;
- Production quality monitoring and management;
- Safety and environment monitoring and management.

Sixth, the proper operation of facilities and equipment is critical to determining time, cost, and quality in factory production, transportation, and on-site installation. It is necessary to establish a comprehensive production and equipment operation plan during the factory production stage to avoid equipment failure, inappropriate planning, reproduction, and other factors that hinder the efficiency of the production process. Likewise, a well-established facility and equipment plan is required to install large and heavy components at the site. If facilities and equipment are not ready, the waiting time for the final product is increased, resulting in wasted time. Conversely, if unnecessary facilities or equipment are provided, the operation rate is reduced, resulting in wasted resources. Accordingly, the key elements of project management include:

- Establishing a production facility and equipment operation plan;
- Facilities and equipment operation simulation;
- Facility and equipment operation monitoring and inspection.

4. Integrated Management System: Development and Implementation

Ewha Womans University and Lotte E&C are jointly developing an integrated management system for OSC projects (OSC-IMS), which have recently been increasing. OSC-IMS is being developed based on the key elements of OSC project management described in the previous section and has been piloted and modified several times. The development scope of the system includes the frameworks and all finishing work. The development of the precast concrete construction management portion has been completed, and the development of the finishing work portion is in progress. In this paper, we present the implementation process and primary functions of the precast concrete construction portion of the system.

The system was developed by constructing basic systems and functions, implementing functions to support project management, and testing. The system was planned with two parts—user interface and database—and divided into four sections according to the management object: model management, drawing management, quantity management, and construction site management. Based on this plan, the development environment was established, and the general function to support OSC project management was implemented. The external functions were included as plug-in modules through the Open Application Program Interface. The system was developed based on object-based BIM and adopted Tekla Structures to generate industry foundation classes (IFC) formats to be used in the system. The script was programmed using Visual C# in the .NET framework, which is most compatible with Microsoft Windows for stable and efficient system implementation.

OSC-IMS covers the core processes of OSC project management: drawing confirmation, construction planning and scheduling, site installation planning, production drawing confirmation and planning, production and inventory management, shipping and transportation management, delivery, and installation monitoring. Furthermore, functions to monitor project performance in real time and calculate progress payments were implemented. User interface examples for each system function are presented in Figure 3, and detailed explanations follow.

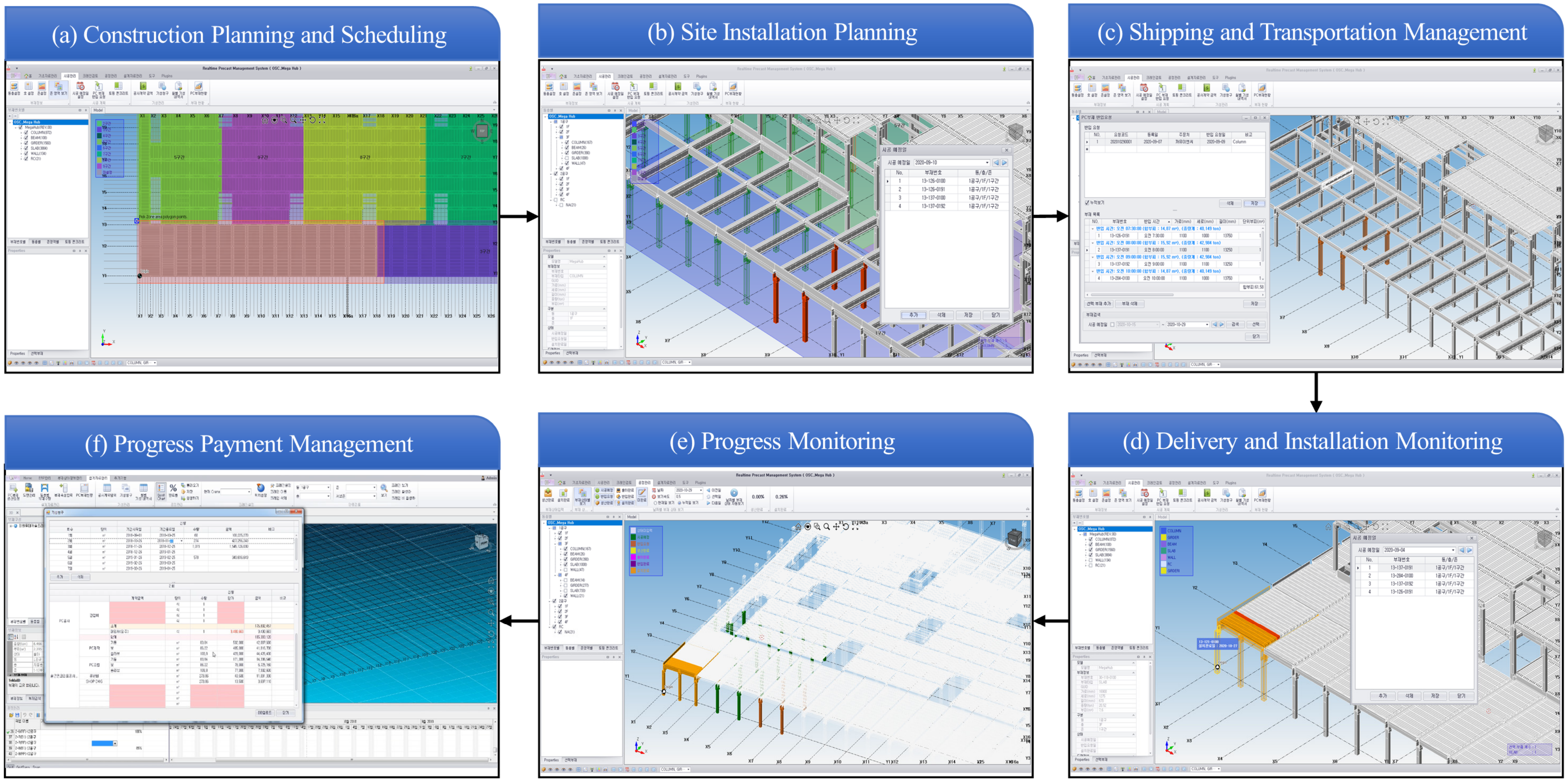

Figure 3. OSC-IMS user interface.

4.1. Drawing Confirmation

The system supports project participants in completing preparations for construction work by confirming structural drawings and construction drawings before the project begins. The construction drawing is converted from the structural drawing for project execution and includes a member assembly plane, an anchor drawing, an electric drawing, and other required components. The manager can upload the structural and construction drawings from the design data management menu in the system and check them without any additional software. Users can check the drawings and models in the system and write notes or chat on the necessary parts in real time. The determined drawings are linked with other information by storing them as object-oriented information in the database.

4.2. Construction Planning and Scheduling

OSC-IMS was implemented to synchronize all stages of project planning, production, transportation, and installation under the master schedule plan. The project manager uses the master planning function in the construction planning and scheduling menu to generate a blank schedule table containing basic information, such as the project name, period, type of work, and construction manager and inputs the detailed activity information to develop a master schedule. The completed master schedule is linked to the 3D model when establishing a work area plan in the system. The work area plan proceeds from the zone setting dividing the entire work area. The zone is defined by selecting objects in the 3D model view (Figure 3a). After zone setting is completed, a detailed work area plan is set up by building, floor, and unit. When a work area plan is established, the relevant information is stored in objects in the BIM model representing members to be installed. The master plan was developed to link functions, such as the production and installation plan, and minimize conflicts.

4.3. Site Installation Planning

OSC-IMS implemented an installation plan establishment function so that the member can be installed according to the master plan. The installation plan consists predominantly of a lifting equipment plan and installation scheduling. The manager first establishes a lifting equipment plan on site before setting up the detailed installation plan. In establishing a lifting equipment plan, the type, quantity, installation location, and period of the equipment are determined, and the movement path of the lifting equipment is set, considering the technical detail of the equipment and the installation sequence. The system designs the scheduled installation date for each member and installation completion date for each work area to be automatically calculated as the equipment movement plan is set up.

The system has a bidirectional function to select members in a 3D view and change their information. Conversely, it searches members based on information to select members in a 3D view, quickly checking and modifying the scheduled installation date for each member using the function. Furthermore, for the user's convenience, the conditional member selection function is implemented to select multiple members with the same properties and input/modify information, such as the scheduled installation date, simultaneously (Figure 3b).

The function of requesting and approving members was implemented to accurately bring them to and install them on site according to the established installation plan. The import request menu was activated only for members for which the installation scheduled date was set up among members. The user can easily make an import request by clicking among the activated members in the graphical user interface. Information (such as the import request code and request date) is automatically linked with the installation plan during the import request process, which the user can change if necessary. When the import request information about the corresponding installation date is completed, the request information is stored in the database and confirmed by the manager. Moreover, the system is easily compatible with the existing work process because the stored information can be converted into spreadsheets using import and export functions.

Figure 4 is a use-case diagram representing the decision-making process that occurs in establishing the system described above and used to design and develop the system. All data, such as schedule plans, components, drawings, and models, are integrated and linked to demonstrate the process of starting from the master plan, going through the detailed plan, and finally establishing the installation plan.

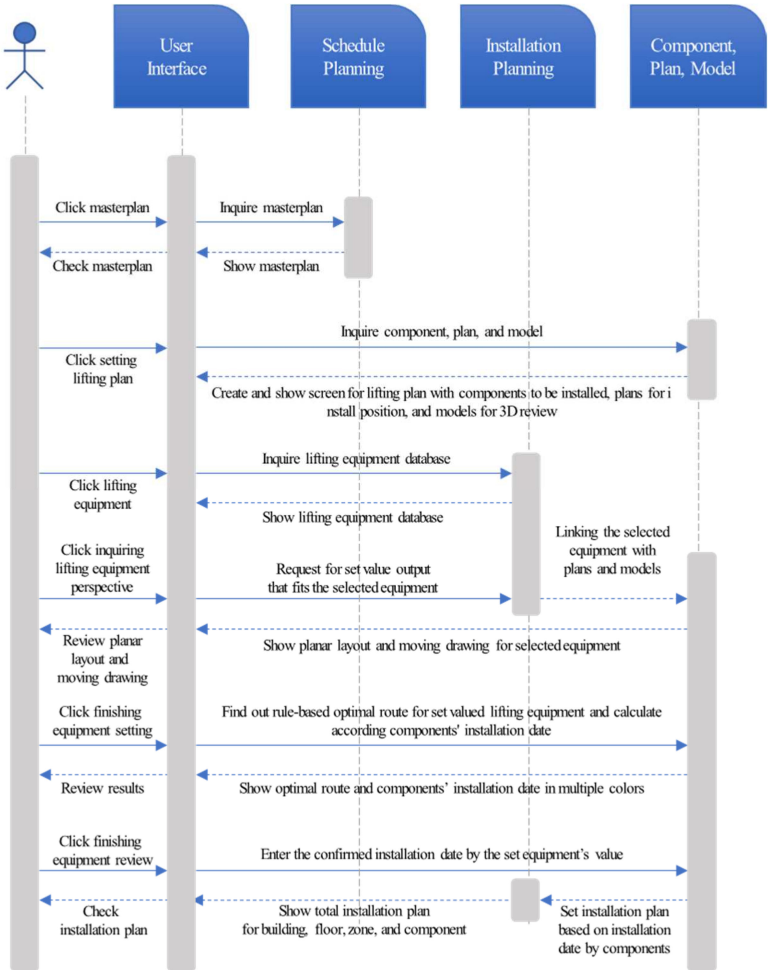

Figure 4. Use-case diagram for site installation planning process.

4.4. Production Drawing Confirmation and Planning

OSC-IMS has a function for designers and manufacturers to collaboratively review and confirm production drawings. This activity is available in the design data management menu and starts with uploading a draft production drawing with the details of the members. The system displays the feedback function for the loaded drawings and models to establish effective, real-time decision making between participants. The confirmed production drawings and model information are linked to the information of other databases in the system and are used to establish the production and installation plans. We devised an automatic production planning function—conforming to the project master plan, considering the member's type, standard, quantity, installation date, and import request date—and applied it to the system to simplify production planning. The system enables project participants to review the generated plans and adjust them according to the situation of the site and factories.

4.5. Production and Inventory Management

The system implemented a module that can reflect the current status of the manufactured members. A function to check changes in information related to the elements to be manufactured and production plan in real time was developed to cope with uncertainties, such as design changes, and schedule modifications during project execution. Furthermore, the production status can be automatically transmitted to the system based on an RFID tag embedded inside the elements. It was implemented to manage the quantity and location of the members temporarily stored in the yard using the system. The field manager transmits the location information to the system by recognizing the RFID of the member through the transportable reader.

4.6. Shipping and Transportation Management

OSC-IMS implemented a shipment and transportation menu so that the building elements can be transported to the site so that the site and the production plant are linked. The site manager can use the system to identify the current production status and request the shipment of building elements stacked in the yard according to the scheduled installation date. The basic information on the shipment request screen, including the name, weight, and volume of the element, can be verified. A shipment request can be made by inputting the element quantity, import date and time, and destination. The shipment request information can also be converted into a spreadsheet using the export function.

The shipping officer who received the shipment request confirms and approves the shipment requested in the system and requests transportation with preparation for shipping elements. The transportation request screen is implemented to appear when the transport request button in the list of shipping elements is selected. On the transportation request screen, information regarding shipping elements, total quantity and weight, destination, shipping date, and time is automatically inserted, and a proper vehicle is automatically allocated if a user designates the shipping time and detailed location. When the transportation officer confirms and approves the transportation request, the invoice is automatically generated, and the transportation process begins (Figure 3c).

4.7. Delivery and Installation Monitoring

The site installation manager can manage product delivery and installation status in the system. The system automatically records information, including element information and arrival time, using RFID tags embedded in the elements loaded on transportation vehicles recognized by an RFID reader attached to site gates. After the field manager completes inspection of the members brought into the site and selects the completion of the import button in the system (Figure 3d), the transportation process is completed. As field assembly and installation proceed, progress information about the completed elements is inputted into the system, and the field installation status is updated. The member that has been installed is implemented to be automatically included in the progress payment calculation.

4.8. Progress Monitoring

OSC-IMS implemented a monitoring function whereby participants can identify the project's progress in real time. It visualizes the project progress status by day and identifies the completion rate if the desired period is set. The system monitors the schedule and implements functions to monitor the state of each construction element. Each member successively stores information on its status based on the project progress, such as production and installation status, design change, and field location. Such monitoring by member status is possible by activating each member on the project view screen. The possibility of error and omission is prevented by providing a non-input button. Project participants can use the real-time monitoring function to minimize the difference between project planning and performance (Figure 3e).

4.9. Progress Payment Management

The system can automatically estimate the amount of progress payments throughout the entire process of production, transportation, and installation. The project manager can manage the contract amount, create new payment details, and inquire about progress payment history through the progress payment management menu in the system. The user can start to process a progress payment by setting the payment period in the progress payment management menu. The contract amount consists of three items: direct cost, indirect cost, and others. The direct cost is composed of the four subcategories of design, manufacturing, transportation, and installation based on the characteristics of the OSC project. The direct cost for element production and installation is automatically calculated in the system, and the item requiring user input is generated as a blank. For indirect and other expenses, all subitems other than administrative expenses and insurance premiums are implemented so that the manager can organize and input them according to the characteristics of the project. The system simplifies payment management by tracking changes in the contract amount during project execution. Users can convert the prepared progress payment information into several formats and check the cost execution rate compared with the project cost plan by implementing the inquiry function to examine the current status of the progress payment (Figure 3f).

5. Application and Effects of OSC-IMS

OSC-IMS has been tested and applied to several projects. The system's applicability and effectiveness were verified by collecting data for four representative projects among all the applied projects and used to improve the system. In this section, we present the applicability and effects of the integrated management system for precast concrete construction in four projects in Korea (Table 1): two logistics centers, an apartment building, and a large shopping mall. The system was applied for some of the total project duration, and the applicability and effect were analyzed based on the data and feedback provided by users. Consequently, work process improvement effects, such as increased work efficiency and accuracy and reduced wasted time, were observed for each project stage. The work process improvement compared with the previous process and the effects of system use are presented in Table 2.

Table 1. Project overview.

	Project A	Project B	Project C	Project D
Type	Logistics warehouse	Logistics warehouse	Residential building	Complex shopping mall
Location	Yangsan	Jincheon	Seoul	Uiwang
Project Period	July 2019–March 2021	June 2019–March 2021	November 2019–April 2020	March 2020–November 2020
PC Installation Area	Six storeys above ground level	Three storeys above ground level	Three storeys below ground level	Three storeys below ground level
Number of PC Elements	2600	6600	2400	2900

Table 2. Work process improvement and effects based on OSC-IMS use.

Step	Work Process Improvement		Effects of Use
	Without OSC-IMS	**With OSC-IMS**	
Construction drawing management	• Increased loading time due to large model size	• Reduced model loading time by applying filtering	• 90% file loading time reduction (◆) • Simple repetitive task reduction (◆)
	• Unnecessary time and human resources input due to repetitive document creation when changing part of the information	• Updating only necessary parts in the central digital model when information changes are required	
Scheduling and planning	• Incompatibility between plans; separately establishing the work area plan after reviewing the master plan	• Avoiding omissions and errors by linking the planning process by recycling the digital model	• Schedule conflict prevention (■) • Error prevention in planning process (■) • Simple repetitive task reduction (◆)
	• Possible errors in manually reviewing plan details	• Automatic generation of the initial schedule suggestion by the system	
	• Manual revision for all related data when changing planning information	• Automatic update for all linked data when changing a part in the digital model	
Site installation planning	• Manual installation planning and management on printed drawings or documents	• Automatic generation of the installation plan suggestion linked to the master schedule	• Planning accuracy improvement (■) • Simple repetitive task reduction (◆)
	• Difficulty in information storage and tracking with paper-based work process	• Information linkage, storage, and reuse using the digital model	
	• Manual revision for all related data and consultation via telephone and email with production plant when changing the plan	• Automatic update for all linked data and communication among project participants in the digital model when changing the plan	
Production planning	• Manual production planning in a spreadsheet format	• Automatic generation of production plan linked to the site installation plan	• Two-thirds data exchange time reduction in planning process (about 48 to 16 h) (■) • Error reduction in communication process (■)
	• Manual revision of all related data when changing the plan	• Automatic update for all linked data when changing the plan in the digital model	
Production monitoring	• Spreadsheet-based production log recording and sharing via email	• Automatic production log creation in a digital format using the RFID system	• Half data exchange time reduction in monitoring process (about 4 to 2 h) (■) • Simple repetitive task reduction due to RFID system use (◆) • Omission and error reduction inventory management due to RFID and GPS system use (■) • Integration of production status monitoring of all plants (●)
	• Manual monitoring of whether production status meets the plan	• Automatic monitoring production status based on data input by the RFID systems	
	• Inventory management with the naked eye or skipping	• Automatic record of the location information by RFID and GPS when stacking elements	

Table 2. *Cont.*

Step	Work Process Improvement		Effects of Use
	Without OSC-IMS	With OSC-IMS	
Shipment request	• After confirming the installation plan, creation of separate shipment requests	• Automatic creation of shipment requests in a digital format linked with the installation plan	• Error prevention through automatic shipment request (◆) • Simple repetitive task reduction (◆)
Shipping and transportation	• Difficulty locating elements to be shipped due to manual location management	• Immediate inquiry of elements to be shipped using GPS-based location management	• 90% element-seeking time reduction (0.5 to 0.05 h) (◆) • Simple repetitive task reduction (◆) • Communication error reduction (■)
	• Possible errors in manually searching elements to be shipped	• Error prevention in searching elements to be shipped using the RFID system	
Delivery and inspection	• Manual validation of elements and the invoice	• Automatic validation of elements and the invoice using RFID tags and a reader installed on site	• 40% element-inspection time reduction (5.5 to 3.25 h) (◆) • Rework prevention through automatic inspection (■)
Site installation monitoring	• Manual installation status monitoring using printed drawings or documents and entering them in a computer file	• Installation status data collection using the RFID system and searching it in various ways using sorting and filtering function	• 75% design-change response time reduction (2 to 0.25 h) (●) • Installation error reduction due to mass and standardized production (■) • Work at a personal computer due to increased computing efficiency (●)
	• Manual revision for all related data when changing planning information	• Automatic update for all linked data when changing a part in the digital model	
Progress payment management	• Manual quantity calculation for progress payment using installation completion data inputted to spreadsheets	• Automatic quantity calculation for progress payment linked to the installation completion data stored in the system	• Reduction in progress payment delay (◆) • Reduction in disputes in progress payment (■)
	• Manual calculation of monthly progress payment	• Automatic calculation of monthly progress payment and generation of progress payment document	

◆ Increase in work efficiency. ■ Increase in work accuracy. ● Decrease in wasted time.

5.1. Construction Drawing Management

The system improved the efficiency in the drawing management of the projects by providing a data exchange function to the participants. Data exchange for decision making in the construction stage inevitably entailed the process of the user checking the data and resharing it with the project participants and required approximately 48 h, on average (three business days). Furthermore, it required ample time to determine whether there was an error in the data when the data were distributed from the user to the project participants. However, the uploaded data were immediately available to all authorized participants through the system, requiring less than 16 h, on average, which is approximately three times less than the previous communication method. Furthermore, because the information is shared through a centralized digital model, the frequency of finding and correcting incorrect information increased by multiple participants accessing the data simultaneously.

When uploading and downloading the digital model in the system for use in the construction stage, the data processing time was reduced by 90% compared with before the system application. Timely and appropriate decisions are essential in construction projects where various tasks are conducted simultaneously. If users need to load a large model containing detailed project information on an ordinary personal computer to make decisions, the waiting time can become excessive. Furthermore, incomplete decisions that are not based on comprehensive and accurate information could result in rework, as well as wasted time and human resources. In the applied projects, the filtering function implemented in the system was used to create and use a digital model with only the information and elements required by the user. Consequently, the upload time of the model, requiring up to 72 h, could be drastically shortened to 0.25 h. Field use of a 3D model with the filtering function increased, demonstrating the accuracy of decision making and the reduction in simple, repetitive work.

5.2. Scheduling and Planning

In the system's project scheduling and planning process, the users could reduce simple, repetitive tasks and manual information processing that frequently occurred in the previous work process, minimizing errors. In the previous scheduling and planning process, the master plan was first prepared in a spreadsheet, and the work area and equipment operation plan were established in a separate document and 2D drawings. Subsequently, the manager had to manually identify necessary information from other plans to establish a monthly plan, and errors, such as information conflicts and omissions, often occurred when linking with other plans.

Moreover, the plans were integrated—if changes occurred in a portion of the plan, all relevant data needed to be modified. In contrast, as the master plan was established in the system, its contents were automatically linked to the detailed plans, so the efficiency of the planning process was significantly improved. If there were changes related to project execution, all relevant information was collectively updated through the system. Therefore, simple, repetitive tasks by the user were declined, and task accuracy improved by preventing information collision by automatic data linkage.

5.3. Site Installation Planning

OSC-IMS effectively establishes the installation plan by quickly supporting optimized decision making using a lifting-heavy-equipment simulation instead of manual review, as in the previous work process. Prior to system application, the installation manager had to repeatedly write the installation sequence and schedule for numerous components on printed 2D drawings. Such an information management method was inefficient in terms of both time and cost because of storage, linkage, and tracking limitations. The projects were able to overcome these problems by using the system. Users were able to easily add installation schedules in any view of project information related to components in the system (including a 2D/3D model and a table view). Furthermore, the updated installation schedules could be checked in the desired format by calling them from the centralized digital model. The improved work process resulted in simple, repetitive task reduction and increased efficiency and accuracy of site installation planning.

5.4. Production Planning

Project participants communicated effectively during the production phase by sharing information quickly and accurately through the system. In the past, project data were exchanged primarily via email or a cloud storage system; when new data were transmitted, a manager needed 48 h, on average, to check, share, and process the information within the organization. In contrast, when users exchanged data using the system, all authorized officials could simultaneously check the data. Therefore, the subsequent process occurred quickly—within an average of 16 h.

The system provided an automatically configured production schedule table in the production planning process, allowing users to review and confirm it and start production faster. Without the system, ample time was required to enter each schedule in the spreadsheet by referring to the scheduled date and production drawings. It was difficult and time-consuming to re-establish the entire schedule whenever one element was changed. Moreover, an average of 48 h was required to check and confirm the request for production by email. In the projects to which the system is applied, the production schedule table was automatically created to meet the planned date of installation of the elements and the production drawing. Whenever it was necessary to change a part in the production schedule, the remaining schedule was adjusted according to the changed contents, and the production request was made in real time through the system. Consequently, the production plan was confirmed within 16 h, on average, and the work accuracy increased in terms of communication.

5.5. Production Monitoring

The system improves the overall efficiency, accuracy, and speed of work compared with existing systems in terms of understanding the production status of projects, such as mold and product management. Planning and production were automatically linked to the scheduled date and production drawing in the system to immediately identify the lead time and status of import, delivery, and inventory. Previously, a disruption in production required additional time to understand. However, it was possible to immediately inquire about the current status of the elements that differ from the plan using the system to track the product-related information. The projects used RFID inserted into the elements to automatically store the location information in the system and conduct integrated management activities related to the production status by linking it with the production log and the stacking yard status.

5.6. Shipment Request

OSC-IMS also improves the shipping stage, which is an essential process of SCM. The installer could request shipment of the product at a time that conforms to both production status and installation plan. Before the application of the system, the installation manager was periodically informed of the status of factories and reviewed it with the installation plan. In the meantime, the installer identified the following targets by repetitively hand marking installation components on paper-based 2D drawings and 3D models. Moreover, considerable time was required to request shipment. Effective communication was difficult because each company had various shipment request forms, even via email. The system fundamentally eliminates the time required, owing to its ability to immediately inquire about the following product to be requested from the factory on the spot based on the stored installation plan and status. The system also automatically recognizes the form for each company and automatically generates documents, requiring minimal information. After the shipment request, the person in charge shares it in the system in real time, with no need for a separate acknowledgment by email. During the system application period, simple, repetitive tasks were reduced, reducing errors and increasing efficiency.

5.7. Shipping and Transportation

As a result of applying the system in the shipment and transportation of the construction elements, manual management was reduced, and sensor-based automatic management became possible, increasing the execution speed, efficiency, and accuracy of the work. In the system, 0.05 h were required to check product availability and location immediately after selecting a target component, which is only 10% compared with the previous 0.5 h required to check the status of one component. Furthermore, because the invoice was shared with all parties on the system, there was no time difference due to exchange, so the accuracy and efficiency of work could be improved without errors in communication.

5.8. Delivery and Inspection

In terms of receiving and inspecting components on site, the system improved previous work processes to increase work speed and accuracy. When component transport vehicles entered the construction site, an average of 5.5 h per day were required to check the status of the components and invoices and then conduct the inspection procedure. In the case where the system was used and the import and inspection procedure progressed, if transport vehicles passed through the gate of the field in which the RFID reader was attached, the components and vehicle information were automatically identified, requiring approximately 3.25 h each day. After automatic inspection using the system, the manager conducted a second review within a shorter time, significantly reducing the error rate.

5.9. Site Installation Monitoring

The managers quickly and accurately examined the construction status through real-time monitoring using the system. They improved the performance speed, accuracy, and efficiency of their work compared with the previous method. Because individual information was not linked, ample time was required to observe the critical indicators of the project, such as schedule and cost, and it was troublesome to repeat these tasks periodically. In the projects, the system was used to monitor the progress of the project immediately according to various conditions. Even if the project contents were changed, all the related data were automatically updated so that the changed status could be easily managed. Consequently, the data update rate, which required approximately two hours for one change, was reduced by eight times to 0.25 h.

5.10. Progress Payment Management

In the last stage of construction, users improved work speed and accuracy by calculating progress payments within the system. It is critical but time-consuming to accurately write the quantity and unit price information when calculating the progress payment. Before the system was used, managers checked with the naked eye and manually displayed on 2D drawings, 3D models, or spreadsheets. The project manager repeatedly calculated the quantity to improve accuracy based on the indicated contents, and this process was repeated every month until the project was completed. In the projects to which the system was applied, users could check the quantity information of installed components automatically collected through the sensors linked with the system. Furthermore, unit price information could aggregate progress payments quickly and accurately by linking the latest information based on contracts. This automated quantity and unit price calculation prevented disputes during the progress payment stage by significantly reducing delays and errors.

The effects of using OSC-IMS summarized in Table 2 have implications complementing previous studies in three aspects. First, the focus of this study was on the OSC project's nature. The present study fills the gap left by previous studies wherein management systems were developed without sufficiently considering what management requires based on the OSC characteristics [16,17,19,56,58]. In this study, we explicitly presented the characteristics of the OSC project before development of the management system. Second, the gap between research and practice was narrowed further. The management systems developed in previous studies were only a prototype and often did not reach practical levels [16,55,56]. OSC-IMS was applied to actual projects to verify its effectiveness. Finally, unlike previous studies, which focused only on one or two phases of the whole project [17,18,54,56], OSC-IMS was designed and developed to manage the entire supply chain of an OSC project in an integrated manner. The development of an integrated perspective enables OSC-IMS to demonstrate the flexible flow of all phases in the OSC project and its result.

6. Conclusions

In this study, we developed an integrated management system to effectively manage OSC projects, which are being used as alternatives to the on-site construction production method due to recent environmental changes in the construction industry. According to an extensive literature review on OSC research, previous research focused on one stage of production, transportation, or installation in the performance of OSC projects or improved existing construction project management systems. Furthermore, integrated digitalization across the supply chain using BIM and sensing technology is essential to perform OSC projects efficiently, although existing studies have reported limited practical effects.

With this study, we addressed this gap by thoroughly analyzing the OSC project process through case analysis, expert interviews, and focus group meetings. Then, the OSC production method was systematized into six categories: place and time of production, process, construction method, method, subject and facility of production, and environment. Based on these characteristics, we developed an integrated management system by specifying and reflecting key management items for processes and activities during the project. As a result of applying the proposed system to an OSC project in progress, work efficiency increased, accuracy increased, and wasted time decreased.

This study contributes to three aspects of project management. First, the characteristics of the OSC project and key management items were systematized. Although there have been cases of OSC project management system development, few studies have derived the characteristics and key management items of OSC projects and applied them to system development. In this study, we focused on the synchronized management of the entire process in OSC projects and systematically presented the unique characteristics and key management items. Second, the results of this study improve practicability by implementing OSC-IMS, which is a BIM-based system contingent on the key items of OSC project management. The systems proposed in previous research were developed by improving the general construction project management system without considering the unique characteristics of OSC. Consequently, they were inconsistent with the OSC project management process and unable to achieve practicability. In this study, the management system's practicability was significantly enhanced by formulating an OSC-IMS that can manage the main items throughout the OSC supply chain. The final contribution of this study is that it presents system effects more comprehensively based on practitioner experience and data. Most previous studies presented the effects of OSC project management system application in a fragmented manner. However, the results of this study shows how OSC-IMS can work in OSC projects by systematically presenting a series of processes, from design to development and application. Furthermore, the influence of system application is described based on the objective of system design and implementation and not simply program testing or reviews of use. The system presented in this study is the result of research and development, reflecting the unique characteristics of an OSC project. It is purposeful because it identifies the development direction and potentials of an OSC project management system. In future research, we will extend the function developed in this study to provide more details, focusing on the technical aspects of BIM and ICT. In addition, an advanced OSC-IMS will be developed to examine the entire flow, including the planning, design and engineering, and construction phases.

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