Article

Requirements Analysis for Development of Off-Site Construction Project Management System: Focusing on Precast Concrete Construction

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Abstract: There has been increasing interest in the off-site construction (OSC) method in response to issues such as stagnant labor productivity, shortage of skilled workers, challenging site management, heightened safety and health-related regulations, and the push for carbon neutrality. Although efficient performance of an OSC project requires development of management techniques, and application of a management system that reflects the characteristics of the OSC projects, related technologies remain in their infancy. In this study, targeting precast concrete (PC) construction, which is one of the representative construction types of the OSC method, we derive the characteristics of OSC project management in six aspects: production place and time, production process, production method of construction, production method, production entity and facilities, and production environment. Based on this result, we further derived the requirements for developing an OSC project management system. Furthermore, based on the derived requirements, we constructed a system development scenario for the establishment of an installation plan and shipment requests. The managerial characteristics and requirements of the OSC project, presented in this study, provide the theoretical basis for developing OSC project management techniques, as well as guidance for the development of the OSC project management system in the future.

Keywords: off-site construction; prefabrication; project management system; requirement engineering; construction management

1. Introduction

1.1. Background and Objectives of Research

The construction industry has recently undergone changes in various aspects due to shifting socio-economic conditions and technological development. The shortage of skilled workers will be the biggest risk of construction supply falling short of demand according to urban sprawl [1], and challenges for site management, strengthened safety and health-related regulations, and rising construction costs due to supply chain disruption will result in major changes in the construction industry [2]. Furthermore, countries must reduce carbon dioxide emissions through energy saving, high-efficiency facilities, resource recycling, and reduction of environmental pollution to achieve the carbon neutrality according to the Paris Agreement, which took effect in 2016 [3]. There have been efforts to enhance the stagnant labor productivity, as an ongoing issue in the construction industry [4], by actively introducing information and communication technologies (ICTs), including technology related to the rapidly developing Fourth Industrial Revolution over recent years. Building information modeling (BIM) technology, since its infancy, has been utilized for various purposes across the construction industry [5], and there have been further active attempts to extend this technology in connection with big data, artificial intelligence, the Internet of Things (IoT), sensing technology, drones, and robotics [6].

However, the construction industry, as a representative onsite focus industry, is struggling with low productivity, low certainty in delivery, skills shortage, and low data transparency due to the one-off, outdoor-located, and labor-intensive characteristics of the production process [7]. A construction project, by the nature of the onsite construction method, is affected by site conditions, weather, and region, resulting in the overall inefficiency of the production process. Moreover, the work by many layers of onsite trades and suppliers, which are in complex relationships, prevents information transparency, increasing the uncertainty in the project planning and execution stages due to the labor-intensive nature of field work.

There has been an increasing interest in the off-site construction (OSC) method in response to the changes in the construction industry, leading to development of related technologies and their active utilization [2]. OSC is a method for manufacturing all parts of the main structure, non-structural elements, mechanical/electrical/plumbing components, and facilities at places other than the target site, and transporting them to the site for installation and construction.

The aforementioned characteristics of the production process in the OSC method have many socio-economic and environmental effects. First, the application of the OSC method moves 80% of on-site work to off-site production facilities, and productivity increases because work is performed in production facilities with efficient working environments [1]. This new production process reduces construction duration and cost by 30–50%, and 20–25%, respectively, through standardized design, repeated mass production, automated production facilities, and consistent quality assurance [8,9]. The OSC method can bring positive effects in terms of sustainability. Some studies have revealed that the OSC method can achieve effects such as reduced waste, reduced energy-in-use, and reduced road traffic movements compared to the conventional onsite construction method [9,10]. Furthermore, the OSC method can produce various social effects, such as reduced occurrence of major injury and death [11], reduced road traffic movements, and enhanced job security of skilled workers through reduced on-site work and improved work environments [9,10].

The efficient execution of an OSC project requires a management technique that reflects the characteristics of OSC projects, and a management system to support it. Unlike the onsite construction method, in which most construction work was performed on the site, an OSC project requires integrated management connecting all stages, including factory production, transportation, and site installation [12]. Information is generated at the design stage in an integrated manner to satisfy the technical requirements of production, transport, and site installation processes and to increase management efficiency, and production and site installation work proceed based on this information. The master plan and member installation plan established through working conditions and technical analysis at the site become the basis for the establishment of production and transport plans after consultation with the production factory. When a project begins, the progress and quality status at the site are continuously monitored, and production is performed to improve the efficiency of the entire supply chain through just-in-time delivery.

The technical level of the OSC project management system is still in its infancy, lacking systematic establishment of these requirements and functions [13]. Identification of the requirements in the entire development process of the management system is a key process for the system efficiency and the performance of actual work in determining the procedures, functions, communication methods, and data processing methods using the management system. There have been some cases of developing OSC project management systems [14–16], while there is a lack of research investigating the main characteristics of OSC project management and elucidating its requirements. To develop the management techniques and systems suitable for the OSC project, there is a need for analysis on information flow, work process, and management process along the entire supply chain related to the project, as well as identification of the requirements of the system to support them. Thus, this study is aimed at analyzing the characteristics of the OSC project management process, and on that basis derive requirements for developing management systems.

1.2. Scope and Method of Research

The scope of this study is limited to precast concrete (PC) construction among the OSC methods. Although an OSC project can be present in various forms, depending on construction methods and materials, the production process and method encompassing factory production, transportation, andsite installation determine the common managerial characteristics of OSC projects. This study intends to identify the common development direction and derive the requirements for system development in the process of developing the OSC project management system for PC construction, which is one of the representative applications of the OSC method.

Requirement engineering performed in this study is an essential process in system development. The identification of the requirements is an important step in determining the development direction and performance of the system in the process of system development utilizing software engineering development methods, such as Waterfall methodology [17] and Agile methodology [18]. This study focused on deriving functional requirements of the OSC project management system, excluding non-function requirements for the performance aspect of the system.

The derivation of requirements consists of the following processes: feasibility study, requirements elicitation and analysis, requirement specification, and requirement validation [19]. In the feasibility study stage, a literature review is performed to analyze the research trends on OSC project management and management systems, and the direction of management system development is established by conducting case studies and interviews with managers. The literature review in this study comprised comprehensive search of research articles relevant to a topic being researched in the electronic databases Web of Science, Scopus, and Google Scholar, which were published between the years of 2002 and 2022. In the requirements elicitation and analysis process, requirements were derived through work process analysis and continuous interviews with managers. The scenario-based development method was co-applied to derive the results reflecting the usability from the user's side in the process of deriving the requirements. In the requirement specification stage, the requirements and scenarios previously derived were described utilizing unified modeling language (UML) and flow charts. In the requirement validation process, practitioners checked the results, and a prototype was developed and tested. The details of the research process are described in each section.

2. Literature Review

2.1. OSC Project Management

The construction methods and materials related to OSC projects have been continuously evolving. However, although relatively few studies have been conducted regarding management techniques for efficiently performing OSC projects, there has been an increasing interest in OSC methods over the recent years. The OSC method requires a management technique, which is different from the conventional construction method where most of the production occurs on the sites [20–23]. Chen et al. [20] indicated that previous studies had been focused on only one aspect of either off-site manufacture or on-site assembly, with a lack of investigation on schedule delays of OSC. They developed a dynamic model that can cope with schedule delays as well as a constrained optimization model to generate initial schedules based on minimum cost through collaborative scheduling of on-site and off-site operations. Salama [21] pointed out the limitations of the conventional execution process and planning method of OSC projects and developed a BIM-based integrated framework for modeling and planning OSC projects to overcome these limitations. That study proposed a model for finding the optimal member combination in the OSC project and developed a planning method that integrates Linear Scheduling Method (LSM), Critical Chain Project Management (CCPM), and Last Planner System (LPS). Alvanchi et al. [22] indicated that various constraints that occur at off-site fabrication shops and during site installation are detrimental to establishing an accurate plan for OSC projects, developing a simulation-based planning method to overcome these constraints. Their study proposed a

method of modeling the production process at off-site fabrication shops, and site installation process utilizing Discrete-Event Simulation (DES) technique. Zhang and Flood [23] pointed out that conventional planning methods for construction project, such as Critical Path Method (CPM), have limitations in application to OSC projects, proposing a Dependency Structure Matrix (DSM)-based planning method to resolve this issue. Their study utilized the DSM and Markov Chain method to show that the predictive performance regarding the construction duration of the OSC project.

The factory production in the OSC project occupies a large proportion of the overall production process, exerting a significant influence on the project performance. Thus, research on the planning and management of the factory production stage is being actively performed. In the early 2000s, there were many studies to optimize the factory production plan using genetic algorithm (GA). Leu and Hwang [24] indicated the limitations of resource utilization in conventional PC production factories and devised a production planning method to overcome the limitations. Conventional PC production factories mainly performed production for single packages in a sequence. Their study developed a flow-shop planning method, in which limited production resources based on GA were utilized to perform optimized production for multiple packages. The authors argued that simultaneous production planning for multiple projects is available using the research results, and efficiency can be increased compared to the existing method. Zhai et al. [25] pointed out that the work efficiency of the mold operator is a crucial factor in determining the efficiency of the PC production process, developing a simulation-GA based model that can optimize it. They devised a method to find the optimal alternative from various production plans by combining the simulation method that can describe the production process, and GA. Ko and Wang [26] pointed out that the conventional PC planning method is inefficient because it relies on the rule-of-thumb of managers, and developed the GA-Based Decision Support System (GA-DSS) that can assist in the establishment of production planning. The authors showed through a test project that a flow-shop sequencing model with GA-DSS can be utilized to establish a production plan with the minimum makespan. In recent years, many studies have been conducted regarding operational production management techniques by considering the fluctuations in production demand linked to the sites, and the uncertainty of the production process. Arashpour et al. [27] stated that, despite the advantages of resource sharing, multi-skilled labor, and multi-tasking, the efficiency in the production process of the OSC projects is significantly low due to frequent occurrence of changeover and preparation time during the production of multiple classes of products. They developed a model that can calculate the optimal production sequence in producing various types of products through mathematical modeling and validated it through application of data from the actual projects.

Recent studies related to factory production have strived to overcome the limitations of existing studies by applying various methods. Wang et al. [28] pointed out that the practical applicability of previous studies related to various OSC production planning is low due to their simplified assumptions, including infinite production resources, and fixed input values. To overcome the hurdles, the authors developed Two-Hierarchy Simulation-GA Hybrid Model for Precast Production (TGSH_PP) and modeled the uncertainty of the complex production process by utilizing simulation techniques under realistic conditions. In the verification of actual projects, a production plan according to the TGSH_PP demonstrated the concurrent results of on-time delivery and minimum production cost. Kim et al. [29] indicated that the production plan in the PC factory is affected by the fluctuations occurring during the related site installation process, proposing the Dynamic PC Production Scheduling Model (DPPSM), which can handle the fluctuations on the sites. The site installation plan may be subject to change due to poor weather, as well as worker and equipment conditions, and factory production that fails to respond in a timely manner to the changes of the site installation plan may result in inefficiency of the entire project. The authors modeled the PC flow-shop utilizing discrete-time simulation, which is advantageous for simulating a dynamic environment, reflecting the uncertainty of the site due dates due to

situational changes on the sites into the model. Similarly, Du et al. [30] developed a dynamic production scheduling model that reflects the fluctuations occurring during the site installation process into the factory production plan. This study modeled the production planning process through a mathematical method, and implemented it by applying GA to find the optimal production plan. Yazdani et al. [31] highlighted a lack of existing studies related to on-time production in connection to site installation, devising a production planning method considering the sequence-dependent due date, which is a characteristic of OSC projects. The authors defined a schedule with minimal earliness and tardiness in production compared to the site installation schedule as a sequence-dependent due date and developed a method to find it using a differential evolution-simulation approach. The recently expanded application of OSC projects has encouraged many studies regarding production planning methods for multiple projects [32,33] or multiple production lines [34], in addition to research on optimization of production work using multiskilled labor [35].

The OSC projects where most work is performed are in production factories, and products are transported and installed on the site, require integrated management combining necessary management for each stage, including factory production, transport, and site installation. Considering these characteristics, there have been studies on the entire supply chain management of the OSC project, connecting the factory production, transport, and site installation. Wang et al. [36] pointed out that there is a high level of interest in OSC due to the high degree of industrialization, environmental advantages, and expectations for sustainability improvement in the construction field, while there is a lack of research regarding the supply chain to improve the performance of OSC projects. The authors conducted a comprehensive literature review to identify the research gap in the OSC field, as well as future research directions. The study analyzed 103 related research articles published from 2007 to 2018, concluding that there is a research gap in the sub-fields of just-in-time delivery, transport route planning, and transport management in the field of OSC supply chain, and outlining gaps in the research for future work. Hussein et al. [37] further pointed out the need for a comprehensive analysis regarding OSC supply chain research, conducting a literature review on 309 related published articles. Based on the analysis results, the authors presented future research directions as follows: integration of knowledge among project participants, detailed production planning, establishment of optimized transport plans, establishment of on-site work plans, and supply chain management using IoTs and blockchain.

Many studies have sought to optimize supply chain management along the active application of OSC methods in recent years. Wang and Hu [12] developed a supply chain optimization method integrating the PC production process, specifying that the PC production process had been overlooked in PC-based project planning despite its decisive effect on project performance. The authors developed an optimization model encompassing all supply chain stages, such as mold fabrication, production, stocking, and transport by utilizing GA, and reported the validation result that this model enabled just-in-time delivery and reduction in construction cost.

Arashpour et al. [38] performed research on supply optimization at the production stage to improve the performance of the OSC supply chain. The authors showed that a mathematical method could be utilized in modeling and comparing various strategies related to purchasing in the production stage to derive an optimal purchase method at minimum cost. Zhang and Yu [39] developed a technique for optimizing transport route planning in the prefabricated component supply chain. They developed an optimized transport route planning technique for transporting the members produced in multiple factories to the sites using particle swarm optimization (PSO) method and validated it with a real project. Salari et al. [40] proposed a three-echelon supply chain management model to optimize the OSC supply chain. Their model reflects multiple suppliers, multiple types of materials, routing problems, and ordering systems, which had not been considered in the conventional OSC supply chain research, and they presented ways to optimize the supply

chain with examples. Zhai et al. [41] and Yang et al. [42] conducted a study to identify uncertainties present in the OSC supply chain and present ways to manage them.

Research related to the OSC supply chain is broadening its scope to the establishment of an information system for system development, and the utilization of various ICTs. Du and Sugumaran [43] stated that it is essential to combine the information that is distributed across the entire supply chain of design, production, transport, and on-site work, considering the characteristics of OSC projects. They developed an ontology- and multi-agent-based framework for decision support regarding the OSC supply chain, and validated the framework's applicability through an actual project. Xiong et al. [44] stated that development of an effective system and execution of tasks are challenging due to low interoperability of the information used in each stage, despite the importance of communication between organizations in charge of planning, design, production, transport, and site installation in OSC project. They developed an information exchange framework using process specification language (PSL) ontology to combine information within the OSC supply chain. Du et al. [45] emphasized the need for a data integration model utilizing ontology and semantics for information exchange in the distributed OSC supply chain, developing an ontology-based management support application. Recently, there have been attempts to apply rapidly developing ICTs, such as RFID sensing [46], IoTs [47], blockchain [48], and digital twin [49] to OSC supply chain management.

2.2. OSC Project Management System

The OSC project management system is the same as the conventional management system in that it stores information related to project execution and supports related decision-making. However, this system, due to the characteristics of the OSC project and the resulting difference in the implementation process, requires distinct requirements and functions from the conventional management system. Thus, there has been continuing research to develop a management system that reflects the characteristics of OSC projects. Previous studies related to OSC project management systems were often conducted by the stage or management function of the projects.

Arashpour et al. [50] and Nam et al. [51] developed a system for the management of the factory production stage. Arashpour et al. [50] indicated that inaccurate production tracking in the factory production stage results in schedule delays, and increased construction costs; they developed a system to predict a short-term shortage in production, and the likelihood of achieving long-term target production utilizing statistical techniques. Nam et al. [51] developed a system that can manage the factory production stage with its focus on projects using the modular method. They modeled the modular production stage in a computer system, and performed simulations by setting input values, such as labor, working hours, and materials. They derived a way to optimize the production process using the simulation results and applied it to production management.

Altaf et al. [52] and Altaf et al. [53] utilized RFID, data mining, and a simulation-based optimization technique to develop a technique for automatically optimizing production plans by analyzing real-time data from the production process; they proposed a cloud-based demand-dependent inventory management system for reducing excessive inventory costs or shortages in the factory production process.

There have been numerous studies regarding management measures to enhance the efficiency of the transport stage [39,54–58]. Niu et al. [58] developed an integrated OSC logistics planning and visualization platform based on BIM, geographic information system (GIS), and vehicle routing problem (VRP) algorithms to transport members in a timely manner. The authors stated that the platform could be utilized to establish an optimized logistics scenario and visualize it in a three-dimensional (3D) environment. Liu et al. [57] proposed an optimization method for transporting PC members based on real-time scheduling and tracking. They reported that an optimal transport plan could be established through a tracking system integrating with GPS and RFID technology, as well as a real-time BIM-based construction progress monitoring technique, resulting in 37%

reduction in transport time. Zhang and Yu [39] further developed a planning technique utilizing particle swarm optimization (PSO) algorithm to optimize the PC transport process.

Many studies have addressed scheduling [59], quantity take-off [60], lifting equipment [61–63], and collaboration [20,64,65], regarding the management of the site installation phase. Scheduling in the site installation stage was often performed by the person in charge by considering the installation sequence of members, and the efficiency of equipment utilization. Related studies were conducted to automatically perform site installation scheduling using the simulation technique [59] and the dynamic model [20]. Similarly, Zhao et al. [60] developed an automated system using BIM to enhance the efficiency and accuracy of the quantity take-off process, which mainly relies on the manual work of the person in charge. Careful planning of lifting equipment is important for swift and efficient site installation. The efficiency of the installation process can be raised by optimizing equipment location by considering the weight, volume, and work sequence of the target members [61,63]; in addition, the optimal lifting equipment can be selected through a preliminary review using 3D visualization [62]. Li et al. [54] indicated that delay and inaccuracy of information collection during the site installation stage prevents efficient work; to address this, they developed a site installation management platform integrating real-time information collected through IoTs, and BIM to resolve this issue.

Unlike the aforementioned research on the project stage and management function, other studies connect and manage all stages of the OSC project supply chain. Viana [15] and Dallasega et al. [16] applied the concept of lean construction to develop a project management technique suitable for engineer-to-order construction projects. Viana [15] utilized the Last Planner System (LPS) to develop a system for planning and controlling engineer-to-order prefabricated building projects, and Dallasega et al. [16] proposed a framework based on the concept of lean construction that can manage engineer-to-order construction projects in real-time. Chen et al. [14] developed a Physical Internet-enabled Building Information Modeling System (PI-BIMS), which manages the entire OSC project process using BIM and cloud computing technology. The PI-BIMS was able to increase the efficiency and accuracy of work by collecting and visualizing information throughout factory production, transport, and site installation in real time. Lee and Lee [49] and Li et al. [48] developed a system to manage the entire supply chain for modular projects. Lee and Lee [49] built a digital twin through real-time logistics simulation combining BIM, GIS, and IoT technologies, and applied it to the test project to prevent schedule delays of the entire project due to fluctuations in the supply chain logistics process. Li et al. [48] developed a blockchain-enabled IoT-BIM platform (BIBP) utilizing blockchain technology to ensure the security and reliability of IoT-BIM-based systems used in supply chain management.

The recent rapid development of ICTs has led to attempts to utilize various technologies for the OSC project management system, such as BIM, IoTs, GIS [58], computer simulation [66,67], RFID [68], digital twin [49], and block chain [48]. BIM is becoming the basis for generating information about the entire project, and for developing related systems in OSC projects, as in on-site construction projects that are widely applied [14,48,54,58,66,68,69]. The IoT performs the function of collecting and sharing real-time information on projects [14,70,71], and are applied in various fields, including project management systems for site installation [54], and supply chain management [48].

3. Analysis on Managerial Characteristics in OSC Projects

The present study analyzed the OSC project execution process and derived managerial characteristics prior to deriving the requirements for OSC project management system development. This corresponds to the feasibility study stage in the process of deriving the requirements for system development, which includes analysis of the current work process, derivation of problems and improvements, decision on system development, and establishment of development directions. For this purpose, this study identified the technical level and functions of OSC project management techniques and management system development through the literature analysis as presented in the previous section

and detailed the implementation process by analyzing OSC project cases. We visited five OSC project sites employing PC construction method, designers, PC production factories, and installation specialty contractors; through interviews with managers, we collected the content and materials related to project management, including the roles of each company, work processes, work tools, and document formats (Figure 1). Based on the results, this study modeled the work process of PC construction, and derived its managerial characteristics. We confirmed and verified the modeling results and managerial characteristics through several additional meetings. This chapter describes the modeling results from the analysis on the PC construction process, as well as the managerial characteristics of OSC projects.

| (a) Production factory | (b) Product list for production | (c) Installation plan | (d) OSC project site |
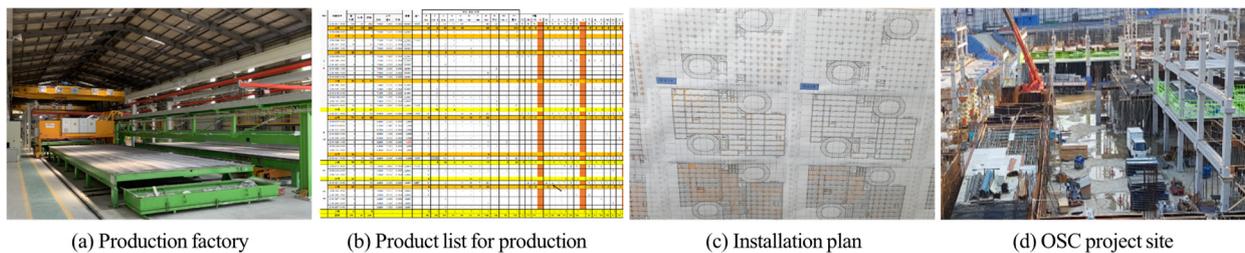
Figure 1. Site visit and data collection.

3.1. PC Construction Process Analysis

In PC construction, designers, manufacturers, installation specialty contractors, and general contractors are involved (Figure 2). A designer first prepares an installation drawing, anchor drawing, and mold drawing necessary for production based on structural drawings. When the installation drawing is completed, production drawing, electrical drawing, and bill of material are prepared and delivered to the general contractor and manufacturers, respectively. Prior to this step, the general contractor establishes the master plan for the overall project, plans the zones for installation work, and schedule the installation completion date for each zone. The scheduled installation completion date for each zone is shared with the manufacturers and installation specialty contractor, allowing the detail to be reflected in establishing the production plan and installation plan. When planning the zones, the general contractor selects a crane for the work, and decides the route at the same time.
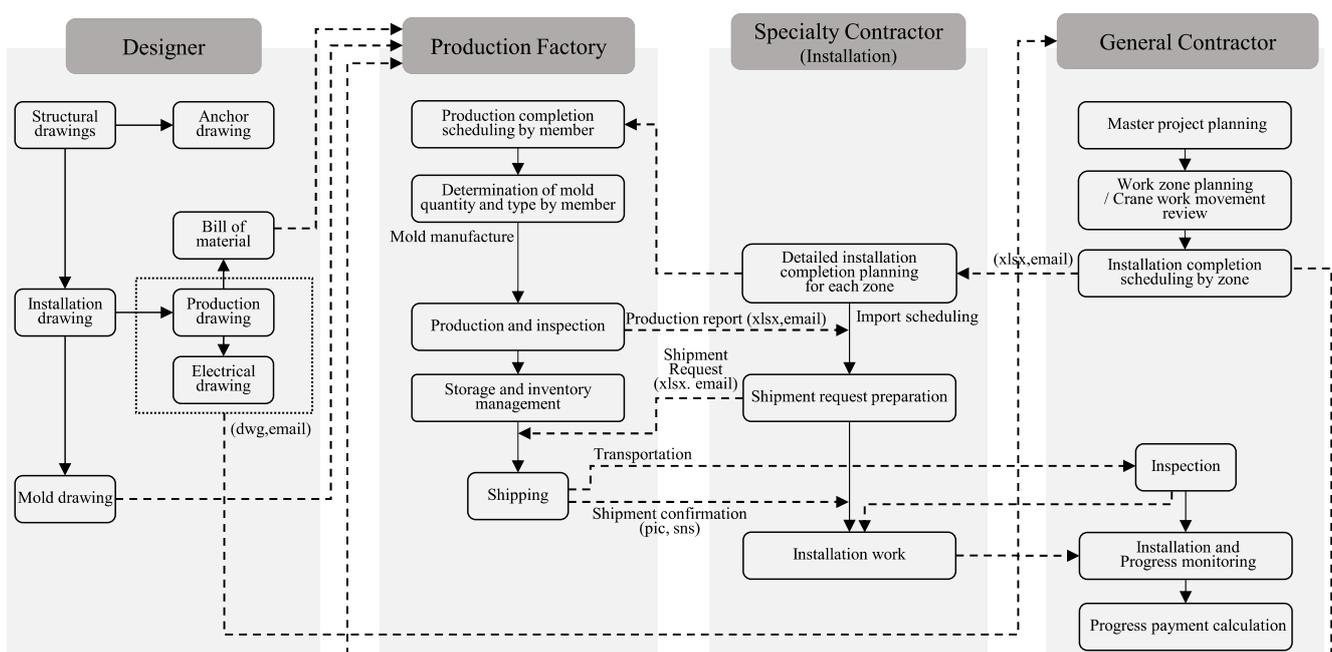
Figure 2. Precast concrete work process.

After receiving the information necessary for production, such as the bill of material, production and mold drawings, and the expected installation completion date, the manufacturers establish a production plan, including setting the production completion date for each part by considering the current work situation. Moreover, the manufacturers review the bill of material to determine the type and quantity of molds necessary for production and begin manufacturing the molds. PC production starts as the manufactured mold is installed on the production line. Finished products are stored in the yard after checking the quality through the inspection process.

The manufacturers share the inventory status information of the manufactured product with the installation specialty contractor, and the installation specialty contractor checks the information, and request shipment according to the scheduled installation date. When the manufacturers have transported the products to the site according to the shipment request date, the general constructor inspects the transported products, and the installation specialty contractor performs the site installation work. The installation rate is checked for the members whose installation has been completed, and the result of the installation rate is utilized as data for calculating the progress payment.

Communication and information exchange between participants during PC construction process are performed in a manner of exchanging drawings, documents, and Excel files via e-mail. The information is created in a manner that the person in charge directly fills out the information using the unique form used in each company.

3.2. Managerial Characteristics of OSC Projects

3.2.1. Production Place and Time

OSC projects proceed concurrently in multiple production factories, through multiple transport processes, and at dispersed locations of the site [33,59]. Unlike the conventional method, in which most of the production occurs on the site, the elements, parts, pre-assemblies, and modules in the OSC project are manufactured in the factory (Figure 3a). Each type of construction work performs production in consideration of its schedule and overall schedule, and then transport and installation continue through collaboration on a specific date. The conventional production method concerns the sequence and spare time management between work types, whereas comprehensive coordination of concurrent production, transport, and installation inside and outside the site is related to performance in the OSC method [12].

(a) Factory Production　　(b) Inventory Management　　(c) Production equipment　　(d) Transportation　　(e) Site Installation

Figure 3. Managerial characteristics of OSC projects.

Manufacturing taking place in a factory enables OSC projects to be free from the factors of weather, time, and constraints from the surroundings [9]. Furthermore, successive and additional work not possible in the onsite construction method can be done through the operation of facilities and equipment within the factory. In the installation stage, the working hours can be shortened through the one-time delivery of only the requested products for the completed production. Moreover, the working period is determined depending on the production status, which is subject to many restrictions in adjustment in the onsite construction method, whereas the working period in an OSC project can be accessibly shortened by increasing the pre-production through consultation with the production factory [29].

3.2.2. Production Process

An OSC project implements the connection and integration of the supply chain throughout the entire production process [12]. The design reflects the technical requirements, and performance goals of factory production, transport, and site installation from the design and engineering stages. Due to the nature of an OSC project, all technical matters required in the design, engineering, production, transport, and installation processes, as well as performance matters, such as cost, duration, and quality are determined in advance in close connection with the entire supply chain. Participants provide requirements and constraints in the design stage, and Design for Manufacture and Assembly (DfMA) is made by reflecting them [72].

In the production stage, a production plan is established in connection with the site installation schedule, and just-in-time delivery is performed accordingly [20,59]. The manufacturers establish an initial production plan in consultation with the site, and production proceeds accordingly. The production factory adjusts plans, facilities, and equipment by considering production plans for other projects, raw material status, inventory status, and lead time. Some of the finished products are transported to the site according to the shipment request, and the rest is managed as inventory. Excessively high or low levels of the inventory may result in issues such as cost increase, quality deterioration, and work interruption, requiring an appropriate level of buffer through just-in-time delivery [57] (Figure 3b).

In the site installation stage, work is performed in connection with the factory production process [20]. The shipment of products from the site to the factory is requested according to the installation plan in advance, and the received members are installed in a sequence. The progress is continuously monitored on the site, and the installation plan is revised as necessary. The revised installation plan is handed over to the manufacturers, allowing the revision to be reflected in the production plan and inventory management, and this cycle continues until installation completion. Optimal inventory management is performed in the case where the received products are stored in the yard and installed on-site.

3.2.3. Production Method of Construction

The production in the OSC project is performed by dedicated facilities, equipment, and labor available in the factory. Unlike the conventional fixed-position process, in which workers and equipment move directly to the production site to perform work, the OSC method manufactures products utilizing a line process, consisting of fixed facilities and equipment in the factory. This is efficient in repeated mass production of products due to the utilization of dedicated facilities, the learning effect of workers, and the ease of quality control [1] (Figure 3c).

In the production process of the OSC project, raw materials and intermediate products are converted into elements and parts as they are transported to the production facilities, and the final products are transported to the site for installation. In the onsite construction method, raw materials, intermediate products, and necessary equipment are transported to the location where one part is to be constructed for performing work, and they move to another location where the next part will be constructed. In contrast, in the OSC method, materials move along the fixed facilities and equipment at all stages to complete the final product, which is transported to the site for completing the final installation (Figure 3d).

3.2.4. Production Method

In the OSC approach, design and engineering proceed utilizing standardized elements and parts [72]. Unlike the one-off production method according to the design provided by the client in the conventional construction production method, the project in the OSC method proceeds in the manner of assembling products manufactured through the mass production. In the design stage, DfMA is performed based on standardized elements and parts that meet the technical requirements, as well as optimal cost, duration, and quality required in the factory production, transport, and site installation stages. The OSC design aims to enhance efficiency by reducing the types of elements and parts during the

production process, and to facilitate the transport process, as well as constructability and performance during the installation process.

In the production stage, repeated mass production of elements, parts, and modules is performed. One of the advantages in the OSC method is that it can enhance the efficiency of the production process through the mass production of standardized elements, parts, and modules [9]. The OSC production factory manufactures elements and parts necessary for each type of work, and further utilizes them to manufacture pre-assemblies and modules.

3.2.5. Production Entity and Facilities

Unlike in the conventional construction production method, factories manufacture heavy and bulky products in the OSC method, and the utilization of facilities and equipment increases in the entire process of transporting and installing them onto the site. For the factory production stage, manufacturing facilities are installed across the production line for mass production. Along the production line, workers perform production work utilizing production facilities and equipment and move elements through lifting equipment. The final product is transported to the site using transport equipment such as trucks and trailers. On-site installation is performed utilizing equipment suitable for each product. Typically, because OSC-type products are heavy and bulky, equipment planning is one of the crucial factors determining work efficiency [62,63] (Figure 3e).

3.2.6. Production Environment

The OSC system is less affected by climate and weather because the production is factory-based. The OSC factory is free from external influences, and a proper environment required for work can be created in terms of temperature, humidity, and lighting. Because continuous work can proceed in an environment that is blocked and controlled from the outside, time, quality, and safety can be secured, and efficiency can be maximized. When production is performed in a controlled environment, it is easy to process pollutants, such as waste and exhaust gases [9]. The OSC system can prevent the spread of harmful substances into the air by processing gas and fine dusts through indoor facilities, etc., reduce the amount of waste by reducing the loss rate through the combination and optimization of planning and production, and minimize the impact on the environment through the waste treatment process [73–75].

4. Derivation of Requirements for Development of OSC Management System

In this chapter, we derive the requirements for developing the management system based on the OSC project execution process and managerial characteristics previously analyzed. Requirement engineering is an essential process during the typical system development process, such as Waterfall methodology and Agile methodology, and system design and implementation occur accordingly [19]. This study, in developing a management system to enhance the efficiency of the OSC project, establishes functional requirements related to how the system should behave in particular situations and services, which the system should provide, rather than the non-function requirements that determine the properties and constraints of the system.

The requirements elicitation and analysis process were first performed to derive the requirements. For this purpose, interviews with the managers conducted in the previous feasibility study stage were resumed. The interview process with the managers embodied the requirements for the work procedure and practical tools to be included in the management system development through the process of discussing improvement ideas and opinions about the current work process and execution methods. Manager interviews were repeated according to the subsequent development stage for the management system, and the validation process was also repeated to ensure the efficiency and practical applicability of the system development by reflecting the opinions of the managers. The requirements derived through the requirements elicitation and analysis process are presented in Section 4.1.

In the requirements elicitation and analysis process, a scenario-based development method was co-applied along case analysis and interviews with managers. The scenario-based development method is one of the methods for developing a system, in which a specific scenario is set for requirements analysis, design, implementation, and modification [76]; in addition, the utilization of the system can be embodied at an early stage of development [77]. Scenarios serve as a detailed excursion into system use prior to design and implementation based on an understanding of the system development target. The advantage of the scenario-based development method is to reduce design errors and impeding factors to user convenience, in advance by identifying the optimal functions and interfaces for users in the process of setting up a scenario [78]. This advantage has enabled the scenario-based development method to be applied in various fields, such as open data platform [79], supply chain management [80], autonomous driving [81], and intelligent transportation systems [82].

In the requirement specification stage, this study represented the detailed scenarios of requirements derived from the requirements elicitation and analysis process through graphical notations, such as sequence diagrams and flow charts, as well as natural language specification. Because the previously derived requirements are enumerated by-item, it is necessary to define a detailed system execution procedure for actual implementation, by considering the business process, database configuration, system configuration, and user interface configuration. The case prepared in the requirement specification stage is presented in Section 4.2.

Finally, in the requirement validation process, we checked whether the requirements prepared in the requirement specification stage were consistent with the actual business process, which was performed through meetings with the managers. Moreover, to test whether the requirements were reflected, a prototype was realized prior to the full-scale system development. The detail on the requirements validation step is provided in Section 4.3.

4.1. System Development Requirements

4.1.1. Production Method Aspect

Time, cost, quality, and safety are among the key elements of construction project management. Production, transport, and site installation proceeds at different places in an OSC project, requiring management of these elements for each place. In particular, most of the production process in the OSC project is performed in the factory, resulting in a higher importance of production management there. Because the duration and cost of the production process in the production factory affect the overall project performance, there is a need for careful management accordingly. First, it is necessary to optimize the production duration and cost through the production plan connected with the current work status on the site. Monitoring of the line process at the factory enhances productivity, in addition to continuous management regarding inputted resources, facilities, and equipment. The OSC project, by the nature where the final product from the factory is installed at the site, requires quality control over the entire production process. In particular, it is essential to monitor whether the products meet the specifications and performance conditions based on drawings and specifications. The requirements and necessary functions derived from the production method aspect are presented in Table 1.

4.1.2. Aspect in Connection to Factory Production-Transport-Site Installation

The planning and execution of each stage, such as factory production, transport, and site installation, require management to synchronize them. The factory production plan is established based on the delivery schedule according to the site installation plan. When there is any issue on the delivery of this site installation plan, the factory undergoes difficulty in establishing and executing the production plan. Similarly, when the site fails to properly receive the factory production plan and its execution, any issue can occur in the process. Thus, it is necessary to synchronize the planning and management for each stage for just-in-time delivery according to the site installation plan and its execution status in

the production factory and site. The requirements and necessary functions derived from the aspect of the connection between the factory production, transport, and site installation are presented in Table 1.

Table 1. Requirements for the OSC project management system.

Aspect	Requirements	System Users
Production Method	- Perform work and manage process regarding schedule, cost, production, quality, inventory, shipping, and safety at the production stage - Establish and modify production plan - Support decision-making related to production plan - Monitor and manage production duration and cost - Monitor and manage production quality - Monitor and manage safety and environment in the production factory - Perform work and manage process regarding schedules, loading, and equipment at the transport stage - Perform work and manage process regarding schedule, progress, quality, manpower, equipment, installation, site, progress payment, and safety in the site installation stage	- Project manager - Factory production manager - Transport manager - Site installation manager
Connection to Factory Production-Transport-Site Installation	- Establish factory production plan synchronized with site installation plan - Monitor factory production and transport status in real-time - Monitor site installation status in real-time - Synchronize factory production with site installation progress, and manage inventory	- Project manager - Factory production manager
Supply Chain	- Monitor factory production level in real-time - Manage lead time for each production member and part - Monitor the quantity and location of the inventory in the production factory and site - Select optimal transport plan and equipment	- Project manager - Factory production manager
Equipment Plan and Management	- Establish management plan of production facilities and equipment - Plan and review facilities and equipment through simulation in advance - Inspect and adjust facilities and equipment management status through monitoring	- Factory production manager - Site installation manager
Information Integration	- Connect and integrate distributed heterogeneous information - Support collaboration and communication for integrated design - Provide information and support business based on 3D drawings and information visualization - Connect individual systems of project participants - Support real-time communication and decision-making between production factory, transport, and site	- Project manager

4.1.3. Supply Chain Aspect

In an OSC project, there is an increased importance of logistics management for the on-time delivery of products to the site. Although the production process in multiple factories proceeds with specialized facilities, equipment, and manpower, and maximizes productivity, the completion of the process at one place is followed by the movement to the next place. In this case, the efficiency of the mobile process is a key factor in determining the performance of the project. Thus, inventory management is required from the viewpoint of just-in-time delivery to prevent overproduction or underproduction. Insufficient inventory results in schedule delays and unnecessary overhead cost due to delay in shipment may induce the rise in cost of the project, whereas the excessive inventory due to earliness in production may result in the increase in inventory cost, and in reduction in quality. The requirements and necessary functions derived from supply chain management aspect are presented in Table 1.

4.1.4. Equipment Plan and Management Aspect

The OSC project tend to proceed with bulky and heavy members, depending greatly on facilities and equipment. Thus, the proper operation of the facility and equipment at each stage of factory production, transport, and site installation is a key factor in determining time, cost, and quality. The factory production stage requires the establishment of elaborate production and equipment operation plans to prevent failures of facilities and equipment that can disrupt the production process, re-production due to quality defects, or the inefficiency of repetitive mass production process. The failure to secure the level of equipment required in the site installation stage consumes unnecessary time by delaying the waiting time for installing the final product, while excessive deployment of facilities and equipment reduces the capacity utilization rate of equipment, causing unnecessary increase in cost. The requirements and necessary functions derived from the equipment planning and management aspect are presented in Table 1.

### 4.1.5. Information Integration Aspect

An OSC project requires integrated information management in addition to performing tasks, such design and engineering, factory production, transport, and installation. The OSC project proceeds with an integrated design considering both requirements and constraints at all stages of production, transportation, and site installation, from the design stage, and its production method and transport schedule are continuously adjusted through communication with the site. The manufacturers and the general contractor collaborate in generating consistent information from the design stage, and production and site installation proceed according to this information. Thus, because participants at each stage perform their work at different places, they rely heavily on information to identify the overall progress of the project and adjust the detail. This entails an urgent need for integrated management of information to perform the tasks. Thus, it is necessary to manage fruitful information exchange to prevent problems, such as errors, omissions, or delays. The requirements and necessary functions derived from information integration management aspect are presented in Table 1.

4.2. Requirement Specification

This study, based on the previously derived requirements, constructed a development scenario that can meet them. This development scenario is divided into construction execution processes and functions, including drawing management, process planning, installation plan, production plan, production and inventory management, shipment and transport, receipt and installation, progress monitoring, and completion level management. This scenario is detailed with sequence diagrams, flow charts, and natural language specification by considering the size of the system and the ease of communication. In this section, we will describe the cases of developing scenarios related to the representative installation plan and shipping request modules among the detail of this scenario.

4.2.1. Establishment of Installation Plan

The establishment of an installation plan follows the establishment of a master plan in the management system. In the master plan, spaces are allocated for the zone necessary for installation work, building, floors, and unit, and the sequence of these tasks is planned. The establishment of installation plan uses the following stages: (1) inquire masterplan, (2) inquire component, plan, and model, (3) inquire lifting equipment database, (4) find out rule-based optimal route, and (5) enter the confirmed installation date (Figure 4).
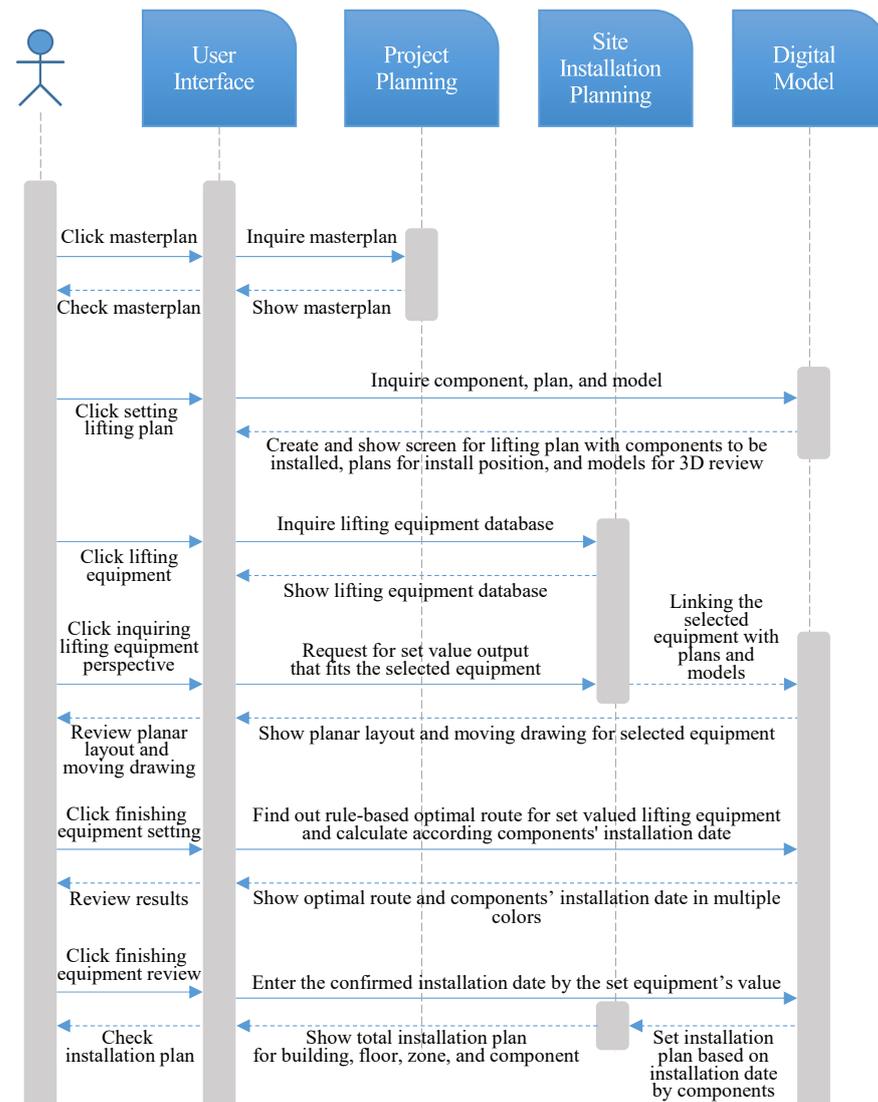
Figure 4. Sequence diagram for installation planning process.

(1)   Inquire Masterplan: When a user selects the "Master Plan" menu to call the master plan, which is the basis for the installation plan, the result of the master plan is requested through the project planning module, which is displayed through the user interface.

(2)   Inquire Component, Plan, and Model: When a user selects the "Setting Lifting Plan" menu, the drawing to identify the installation location of lifting equipment, and the digital model of the building to review the lifting equipment are used from the database of the management system, displaying a screen showing the components to be installed and lifting equipment plan on the user interface.

(3)   Inquire Lifting Equipment Database: When a user selects the "Select Lifting Equipment" menu, the information on lifting equipment stored in the database is requested

and outputted onto the user interface. When the user further selects one of the displayed information items on lifting equipment, and then the "Inquire and Select Specification of Lifting Equipment" menu, the specification data for the target equipment are presented, which are linked with the drawing and digital model called at the previous stage.

(4) Find Out Rule-based Optimal Route: When a user selects the "Completion of Lifting Equipment Setting" menu, the lifting equipment plan, and the corresponding route and installation schedule of the lifting equipment are automatically established, considering the type, number of units, installation location, and duration of the equipment selected in the previous stage.

(5) Enter the Confirmed Installation Date: When a user selects the "Completion of Lifting Equipment Review" menu, the installation plan for each component according to the lifting equipment plan set in the previous stage is updated to the digital model and site installation plan, and further displayed on the user interface. The user can select the component from the screen to adjust the schedule, or, conversely, request the date first to set the component. In this manner, this interactive function can be utilized to retrieve or modify the scheduled date of installation for each component.

4.2.2. Request for Transport

The shipment request is performed according to the site installation plan for the component whose production has been completed. On the site, that component is requested utilizing the management system and compared to the installation plan prior to shipment request. The shipment request proceeds with the following steps: (1) request an installation plan, (2) select components in 3d view and spreadsheet view, (3) check production status and verify installation is possible, (4) select components scheduled installation, (5) automatically determine a shipping order and transport vehicles, (6) create shipment requests, and (7) transportation requests (Figure 5).

(1) Request an Installation Plan: When a user in the construction site selects the "Installation Plan" menu, the existing installation plan is inquired in the database of the system, which is displayed on the user interface in the format of 3D model or spreadsheet.

(2) Select Components in 3D View and Spreadsheet View: The user selects the desired component from the inquiry results on the installation plan in a 3D model or spreadsheet format.

(3) Check Production Status and Verify Installation is Possible: The user checks when the scheduled installation date of the selected components, and whether their production has been completed to determine when their installation is available.

(4) Select Components Scheduled Installation: The user monitors the scheduled installation date of the selected components, and whether their production has been completed to finalize the selection of the components to be installed.

(5) Automatically Determine a Shipping Order and Transport Vehicles: When the user selects "Shipping Request" menu, the management system automatically determines the sequence of receipts regarding the selected components and assigns the transport vehicle by considering the characteristics of the transport vehicle, as well as the size of the components. Furthermore, the system determines the sequence of transport of the vehicles and stores it into itself.

(6) Create Shipment Requests: The management system automatically generates a transport request depending on the previously determined component, and the transport sequence of the vehicles, and stores the information in itself.

(7) Send Shipment Requests: When the user selects the "Send Shipment Requests" menu, a notification for confirmation of shipment requests is sent to the transport manager in the factory.
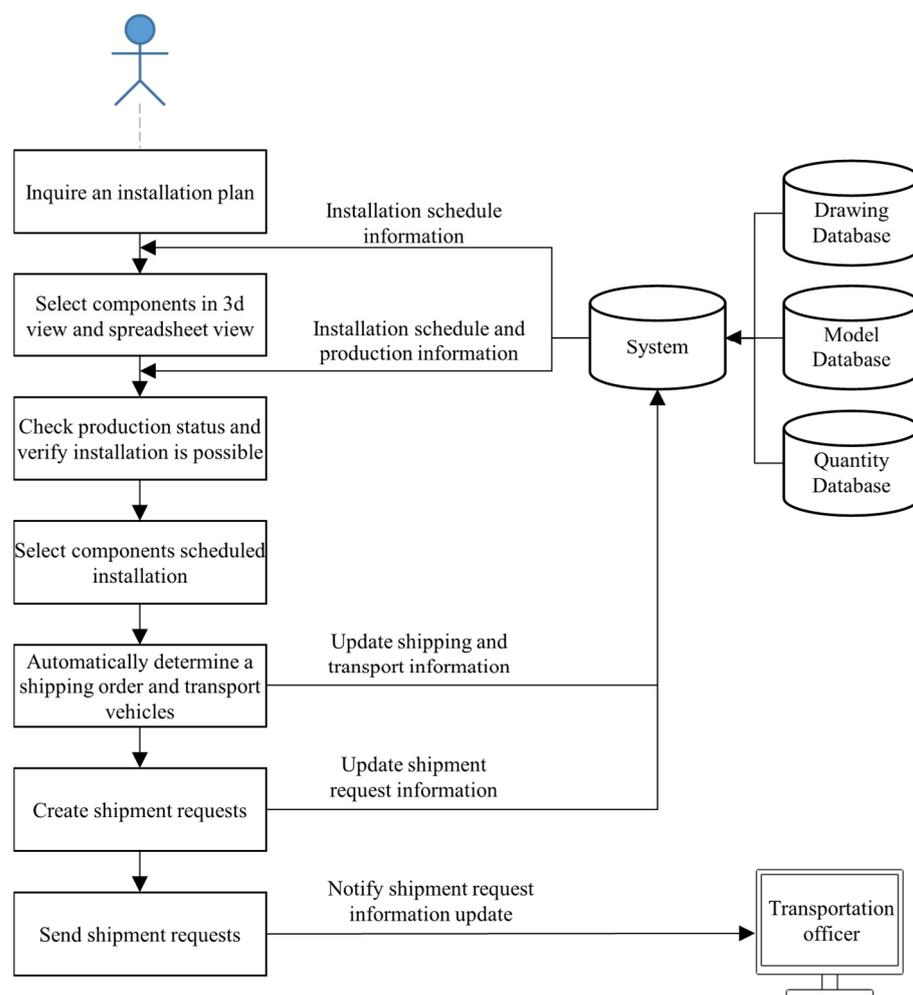
Figure 5. Flow chart for shipment request process.

4.3. Requirement Validation

In the requirement validation process, this study verified the requirements created in the previous stage with the actual work process and conducted a confirmation process through meetings with managers. We repeatedly performed requirement elicitation and analysis, specification, and validation to reflect the feedback generated during the requirement validation process. Furthermore, a prototype was created prior to a full-fledged system development to check whether and how the requirements were implemented. The prototype was applied by developing a part of the system to be implemented in advance to validate the requirements, which underwent modifications by collecting the opinions of the managers.

5. Conclusions

This study derived the requirements for the development of an OSC project management system. Although the OSC method has been frequently applied over recent years, OSC project management systems are still in its infancy. Identification of the requirements in the entire development process of a management system is a key process for system efficiency and the performance of actual work in determining the procedures, functions, communication methods, and data processing methods used in the management system. For this purpose, this study conducted a business process analysis for PC construction, which is one of the representative OSC construction types, and derived the characteristics of OSC project management on that basis. Based on these preliminary research results, the requirements for the development of the OSC project management system were derived and

presented in terms of production method, connection to factory production-transport-site installation, supply chain, equipment plan and management, and information integration.

This study makes the following novel contributions in the field of OSC project management system. First, this study presents the characteristics of OSC project management. The theories and techniques of OSC project management have not yet been systematized, and on-site construction management techniques remain prevalent. However, the OSC project requires integrated management connecting all stages, including the management of factory production, transport, and site installation stages. In this respect, this study summarized and presented the characteristics of OSC project management in six aspects (production place and time, production process, production method of construction, production method, production entity and facilities, and production environment) to provide a theoretical basis for developing OSC project management techniques.

In addition, this study outlines requirements that can guide the direction of development of OSC project management systems. There have been many cases of developing OSC project management systems in previous studies, limited to one level of the OSC supply chain, or development of element technology; however, no previous studies have derived system requirements for the management system encompassing OSC projects. In contrast, this study explicitly analyzed and presented the requirements to offer a direction to apply them to the development of OSC project management systems in the future.

Nevertheless, the results of this study are limited in that they cannot cover all the managerial characteristics of the OSC projects, nor all the requirements for system development. This study was conducted on PC construction, representative of the OSC method, but the OSC method varies depending on the method and materials. Furthermore, in addition to the frame construction, the finishing work, the electricity and equipment construction are conducted in the OSC method. Future research should develop project management theories and techniques for various OSC methods of construction.

References

1. Bertram, N.; Fuchs, S.; Mischke, J.; Palter, R.; Strube, G.; Woetzel, J. *Modular Construction from Projects to Products*; McKinsey & Company: Sydney, Australia, 2019.
2. Ribeirinho, M.J.; Mischke, J.; Strube, G.; Sjödin, E.; Blanco, J.L.; Palter, R.; Biörck, J.; Rockhill, D.; Andersson, T. *The Next Normal in Construction*; McKinsey and Company: Sydney, Australia, 2020.
3. Kim, S.; Lee, M.; Yu, I.; Son, J. Key initiatives for digital transformation, green new deal and recovery after COVID-19 within the construction industry in Korea. *Sustainability* **2022**, *14*, 8726. [CrossRef]
4. Barbosa, F.; Woetzel, J.; Mischke, J. *Reinventing Construction: A Route of Higher Productivity*; McKinsey Global Institute: Washington, DC, USA, 2017.
5. Jeong, W.; Chang, S.; Son, J.; Yi, J.-S. BIM-integrated construction operation simulation for just-in-time production management. *Sustainability* **2016**, *8*, 1106. [CrossRef]
6. Ottinger, E.; Minglani, H.; Gibson, M. *Technological Advancements Disrupting the Global Construction Industry*; Ernst & Young LLP: London, UK, 2020.

7. Southern, J. *Smart Construction: How Offsite Manufacturing can Transform Our Industry*; Technical Report CRT059791; KPMG: London, UK, 2016.

8. Bernstein, H.M.; Gudgel, J.E.; Laquidara-Carr, D. *Prefabrication and Modularization: Ncreasing Productivity in the Construction Industry*; McGraw Hill Construction: New York, NY, USA, 2011.

9. Oakley, M. *The Value of Off-Site Construction to UK Productivity and Growth*; WPI Economics: London, UK, 2017.

10. Krug, D. *Offsite Construction: Sustainability Characteristics*; Buildoffsite: London, UK, 2013.

11. Kim, S.; Hwang, S.; Son, J. Safety Management Guidelines for Precast Concrete Production Plants Using Importance-Performance Analysis. *J. Constr. Eng. Manag.* **2022**, *148*, 04022038. [CrossRef]

12. Wang, Z.; Hu, H. Improved Precast Production–Scheduling Model Considering the Whole Supply Chain. *J. Comput. Civ. Eng.* **2017**, *31*, 04017013. [CrossRef]

13. Jang, Y.; Lee, J.-M.; Son, J. Development and application of an integrated management system for off-site construction projects. *Buildings* **2022**, *12*, 1063. [CrossRef]

14. Chen, K.; Xu, G.; Xue, F.; Zhong, R.Y.; Liu, D.; Lu, W. A Physical Internet-enabled Building Information Modelling System for prefabricated construction. *Int. J. Comput. Integr. Manuf.* **2017**, *31*, 349–361. [CrossRef]

15. Viana, D.D. Integrated production planning and control model for engineer-to-order prefabricated building systems. Ph.D. Thesis, Federal University of Rio Grande do Sul, Rio Grande do Sul, Brazil, 2015.

16. Dallasega, P.; Rauch, E.; Frosolini, M. A lean approach for real-time planning and monitoring in engineer-to-order construction projects. *Buildings* **2018**, *8*, 38. [CrossRef]

17. Royce, W.W. Managing the development of large software systems: Concepts and techniques. In Proceedings of the 9th international conference on Software Engineering, Monterey, CA, USA, 30 March–2 April 1987; pp. 328–338.

18. Beck, K.; Beedle, M.; Van Bennekum, A.; Cockburn, A.; Cunningham, W.; Fowler, M.; Grenning, J.; Highsmith, J.; Hunt, A.; Jeffries, R. Manifesto for Agile Software Development. Available online: https://agilemanifesto.org (accessed on 1 August 2022).

19. Sommerville, I. *Software Engineering, 9/E*; Pearson Education India: Noida, India, 2011.

20. Chen, W.; Zhao, Y.; Yu, Y.; Chen, K.; Arashpour, M. Collaborative Scheduling of On-Site and Off-Site Operations in Prefabrication. *Sustainability* **2020**, *12*, 9266. [CrossRef]

21. Salama, T. Optimized Planning and Scheduling for Modular and Offsite Construction. Ph.D. Thesis, Concordia University, Montréal, QC, Canada, 2018.

22. Alvanchi, A.; Azimi, R.; Lee, S.; AbouRizk, S.M.; Zubick, P. Off-site construction planning using discrete event simulation. *J. Archit. Eng.* **2012**, *18*, 114–122. [CrossRef]

23. Zhang, Y.; Flood, I. Planning and scheduling prefabrication construction projects using dependency structure matrix (DSM). In Proceedings of the International Conference on Computing in Civil and Building Engineering, Orlando, FL, USA, 23–25 June 2014; pp. 1457–1464.

24. Leu, S.-S.; Hwang, S.-T. GA-based resource-constrained flow-shop scheduling model for mixed precast production. *Autom. Constr.* **2002**, *11*, 439–452. [CrossRef]

25. Zhai, X.; Tiong, R.L.; Bjornsson, H.C.; Chua, D.K. A simulation-GA based model for production planning in precast plant. In Proceedings of the 2006 Winter Simulation Conference, Monterey, CA, USA, 3–6 December 2006; pp. 1796–1803.

26. Ko, C.-H.; Wang, S.-F. GA-based decision support systems for precast production planning. *Autom. Constr.* **2010**, *19*, 907–916. [CrossRef]

27. Arashpour, M.; Wakefield, R.; Abbasi, B.; Lee, E.W.M.; Minas, J. Off-site construction optimization: Sequencing multiple job classes with time constraints. *Autom. Constr.* **2016**, *71*, 262–270. [CrossRef]

28. Wang, Z.; Hu, H.; Gong, J. Fraework for modeling operational uncertainty to optimize offsite production scheduling of precast components. *Autom. Constr.* **2018**, *86*, 69–80. [CrossRef]

29. Kim, T.; Kim, Y.-W.; Cho, H. Dynamic production scheduling model under due date uncertainty in precast concrete construction. *J. Clean. Prod.* **2020**, *257*, 120527. [CrossRef]

30. Du, J.; Dong, P.; Sugumaran, V. Dynamic production scheduling for prefabricated components considering the demand fluctuation. *Intell. Autom. Soft Comput.* **2020**, *26*, 715–723. [CrossRef]

31. Yazdani, M.; Kabirifar, K.; Fathollahi-Fard, A.M.; Mojtahedi, M. Production scheduling of off-site prefabricated construction components considering sequence dependent due dates. *Environ. Sci. Pollut. Res.* **2021**, 1–17. [CrossRef] [PubMed]

32. Jiang, W.; Wu, L.J.; Cao, Y.Z. Multiple precast component orders acceptance and scheduling. *Math. Probl. Eng.* **2020**, *2020*, 3849561. [CrossRef]

33. Liu, J.; Lu, M. Robust Dual-Level Optimization Framework for Resource-Constrained Multiproject Scheduling for a Prefabrication Facility in Construction. *J. Comput. Civ. Eng.* **2019**, *33*, 04018067. [CrossRef]

34. Ma, Z.; Yang, Z.; Liu, S.; Wu, S. Optimized rescheduling of multiple production lines for flowshop production of reinforced precast concrete components. *Autom. Constr.* **2018**, *95*, 86–97. [CrossRef]

35. Nasirian, A.; Arashpour, M.; Abbasi, B.; Akbarnezhad, A. Optimal work assignment to multiskilled resources in prefabricated construction. *J. Constr. Eng. Manag.* **2019**, *145*, 04019011. [CrossRef]

36. Wang, Z.; Hu, H.; Gong, J.; Ma, X.; Xiong, W. Precast supply chain management in off-site construction: A critical literature review. *J. Clean. Prod.* **2019**, *232*, 1204–1217. [CrossRef]

37. Hussein, M.; Eltoukhy, A.E.; Karam, A.; Shaban, I.A.; Zayed, T. Modelling in off-site construction supply chain management: A review and future directions for sustainable modular integrated construction. *J. Clean. Prod.* **2021**, *310*, 127503. [CrossRef]

38. Arashpour, M.; Bai, Y.; Aranda-mena, G.; Bab-Hadiashar, A.; Hosseini, R.; Kalutara, P. Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction. *Autom. Constr.* **2017**, *84*, 146–153. [CrossRef]

39. Zhang, H.; Yu, L. Dynamic transportation planning for prefabricated component supply chain. *Eng. Constr. Archit. Manag.* **2020**, *27*, 2553–2576. [CrossRef]

40. Salari, S.A.-S.; Mahmoudi, H.; Aghsami, A.; Jolai, F.; Jolai, S.; Yazdani, M. Off-site construction three-echelon supply chain management with stochastic constraints: A modelling approach. *Buildings* **2022**, *12*, 119. [CrossRef]

41. Zhai, Y.; Zhong, R.Y.; Huang, G.Q. Towards operational hedging for logistics uncertainty management in prefabrication construction. *IFAC-PapersOnLine* **2015**, *48*, 1128–1133. [CrossRef]

42. Yang, Y.; Pan, M.; Pan, W.; Zhang, Z. Sources of uncertainties in offsite logistics of modular construction for high-rise building projects. *J. Manag. Eng.* **2021**, *37*, 04021011. [CrossRef]

43. Du, J.; Sugumaran, V. Ontology-based information integration and decision making in prefabricated construction component supply chain. In Proceedings of the Americas Conference on Information Systems, Boston, MA, USA, 10–12 August 2017; pp. 1–10.

44. Xiong, W.; Yang, J.; Wang, Z.; Hu, H.; Xu, F.; Zhang, J. Improving supply chain communications for off-site construction using Process Specification Language. In Proceedings of the International Symposium on Automation and Robotics in Construction, Berlin, Germany, 20–25 July 2018; pp. 1–9.

45. Du, J.; Jing, H.; Choo, K.-K.R.; Sugumaran, V.; Castro-Lacouture, D. An ontology and multi-agent based decision support framework for prefabricated component supply chain. *Inf. Syst. Front.* **2019**, *22*, 1467–1485. [CrossRef]

46. Du, J.; Sugumaran, V.; Gao, B. RFID and multi-agent based architecture for information sharing in prefabricated component supply chain. *IEEE Access* **2017**, *5*, 4132–4139. [CrossRef]

47. Zhang, W.; Kang, K.; Zhong, R.Y. A cost evaluation model for IoT-enabled prefabricated construction supply chain management. *Ind. Manag. Data Syst.* **2021**, *121*, 2738–2759. [CrossRef]

48. Li, X.; Lu, W.; Xue, F.; Wu, L.; Zhao, R.; Lou, J.; Xu, J. Blockchain-enabled IoT-BIM platform for supply chain management in modular construction. *J. Constr. Eng. Manag.* **2022**, *148*, 04021195. [CrossRef]

49. Lee, D.; Lee, S. Digital twin for supply chain coordination in modular construction. *Appl. Sci.* **2021**, *11*, 5909. [CrossRef]

50. Arashpour, M.; Wakefield, R.; Blismas, N.; Maqsood, T. Autonomous production tracking for augmenting output in off-site construction. *Autom. Constr.* **2015**, *53*, 13–21. [CrossRef]

51. Nam, S.; Lee, D.; Cho, B.; Kim, K. Integrated management software for factory production of modular buildings. *Adv. Civ. Eng.* **2019**, *2019*, 1–10. [CrossRef]

52. Altaf, M.S.; Bouferguene, A.; Liu, H.; Al-Hussein, M.; Yu, H. Integrated production planning and control system for a panelized home prefabrication facility using simulation and RFID. *Autom. Constr.* **2018**, *85*, 369–383. [CrossRef]

53. Altaf, M.S.; Lei, Z.; Han, S.; Bouferguene, A.; Al-Hussein, M. Demand-dependent inventory management system for an offsite construction facility. In Proceedings of the Construction Research Congress 2020, Tempe, AZ, USA, 8–10 March 2020; pp. 29–37.

54. Li, C.Z.; Xue, F.; Li, X.; Hong, J.; Shen, G.Q. An internet of things-enabled BIM platform for on-site assembly services in prefabricated construction. *Autom. Constr.* **2018**, *89*, 146–161. [CrossRef]

55. Lee, G.; Kim, M.; Lee, C.; Koo, C.; Kim, T. Towards a transportation support system for off-site construction: Identifying key functions and diagramming functional blocks. *Korean J. Constr. Eng. Manag.* **2021**, *22*, 21–30. [CrossRef]

56. Si, T.; Li, H.X.; Lei, Z.; Liu, H.; Han, S. A dynamic just-in-time component delivery framework for off-site construction. *Adv. Civ. Eng.* **2021**, *2021*, 9953732. [CrossRef]

57. Liu, D.H.; Xin, L.; Chen, J.J.; Jin, R. Real-time optimization of precast concrete component transportation and storage. *Adv. Civ. Eng.* **2020**, *2020*, 5714910. [CrossRef]

58. Niu, S.; Yang, Y.; Pan, W. Logistics planning and visualization of modular integrated construction projects based on BIM-GIS integration and vehicle routing algorithm. In Proceedings of the Modular and Offsite Construction (MOC) Summit, Banff, AB, Canada, 21–24 May 2019; pp. 579–586.

59. Taghaddos, H.; Hermann, U.; AbouRizk, S.; Mohamed, Y. Simulation-based multiagent approach for scheduling modular construction. *J. Comput. Civ. Eng.* **2014**, *28*, 263–274. [CrossRef]

60. Zhao, H.; Liu, H.; Al-Hussein, M. Automation of quantity take-off for modular construction. In Proceedings of the Modular and Offsite Construction (MOC) Summit, Edmonton, AB, Canada, 19–21 May 2015; pp. 458–465.

61. Hyun, H.; Park, M.; Lee, D.; Lee, J. Tower crane location optimization for heavy unit lifting in high-rise modular construction. *Buildings* **2021**, *11*, 121. [CrossRef]

62. Han, S.H.; Hasan, S.; Bouferguène, A.; Al-Hussein, M.; Kosa, J. Utilization of 3D visualization of mobile crane operations for modular construction on-site assembly. *J. Manag. Eng.* **2015**, *31*, 04014080. [CrossRef]

63. Taghaddos, H.; Hermann, U.; Abbasi, A. Automated crane planning and optimization for modular construction. *Autom. Constr.* **2018**, *95*, 219–232. [CrossRef]

64. Ezzeddine, A.; de Soto, B.G. Connecting teams in modular construction projects using game engine technology. *Autom. Constr.* **2021**, *132*, 103887. [CrossRef]

65. Son, J.; Han, S.H.; Rojas, E.M. Embeddedness and collaborative venture networks among Korean construction firms for overseas construction projects. *J. Civ. Eng. Manag.* **2015**, *21*, 478–491. [CrossRef]

66. Wu, C.; Jiang, R.; Li, X. Integration of BIM and computer simulations in modular construction, A case study. In Proceedings of the Modular and Offsite Construction (MOC) Summit, Edmonton, AB, Canada, 29 September–1 October 2016.

67. Son, J.; Rojas, E.M.; Shin, S.-W. Application of agent-based modeling and simulation to understanding complex management problems in CEM research. *J. Civ. Eng. Manag.* **2015**, *21*, 998–1013. [CrossRef]

68. Li, C.Z.; Zhong, R.Y.; Xue, F.; Xu, G.; Chen, K.; Huang, G.G.; Shen, G.Q. Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction. *J. Clean. Prod.* **2017**, *165*, 1048–1062. [CrossRef]

69. Jeong, W.; Son, J. An algorithm to translate building topology in building information modeling into object-oriented physical modeling-based building energy modeling. *Energies* **2016**, *9*, 50. [CrossRef]

70. Zhong, R.Y.; Peng, Y.; Xue, F.; Fang, J.; Zou, W.; Luo, H.; Thomas Ng, S.; Lu, W.; Shen, G.Q.P.; Huang, G.Q. Prefabricated construction enabled by the Internet-of-Things. *Autom. Constr.* **2017**, *76*, 59–70. [CrossRef]

71. Zhao, L.; Liu, Z.; Mbachu, J. Development of intelligent prefabs using IoT technology to improve the performance of prefabricated construction projects. *Sensors* **2019**, *19*, 4131. [CrossRef]

72. Gao, S.; Jin, R.Y.; Lu, W.S. Design for manufacture and assembly in construction: A review. *Build. Res. Informat.* **2020**, *48*, 538–550. [CrossRef]

73. Ji, Y.; Li, K.; Liu, G.; Shrestha, A.; Jing, J. Comparing greenhouse gas emissions of precast in-situ and conventional construction methods. *J. Clean. Prod.* **2018**, *173*, 124–134. [CrossRef]

74. Mao, C.; Shen, Q.; Shen, L.; Tang, L. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. *Energy Build.* **2013**, *66*, 165–176. [CrossRef]

75. Sandanayake, M.; Luo, W.; Zhang, G. Direct and indirect impact assessment in off-site construction—A case study in China. *Sustain. Cities Soc.* **2019**, *48*, 101520. [CrossRef]

76. Rosson, M.B.; Carroll, J.M. *Usability Engineering: Scenario-Based Development of Human-Computer Interaction*; Morgan Kaufmann: Burlington, VT, USA, 2002.

77. Rosson, M.B.; Carroll, J.M. Scenario based design. In *Human-Computer Interaction*; CRC Press: Boca Raton, FL, USA, 2009; pp. 145–162.

78. Lim, J.; Cho, H.; Im, S.; Lee, Y.; Hyun, S. Ubiquitous computing application service development method using scenario-based development method. In Proceedings of the Conference of the Korean Society of Human Computer Interaction, Jeong-seon, Korea, 13–16 February 2006; pp. 188–196.

79. Ruijer, E.; Grimmelikhuijsen, S.; Hogan, M.; Enzerink, S.; Ojo, A.; Meijer, A. Connecting societal issues, users and data. Scenario-based design of open data platforms. *Gov. Inf. Q.* **2017**, *34*, 470–480. [CrossRef]

80. Pourmehdi, M.; Paydar, M.M.; Asadi-Gangraj, E. Scenario-based design of a steel sustainable closed-loop supply chain network considering production technology. *J. Clean. Prod.* **2020**, *277*, 123298. [CrossRef]

81. Li, X. A scenario-based development framework for autonomous driving. *arXiv* **2020**, arXiv:2011.01439.

82. Bäumler, I.; Kotzab, H. Scenario-based development of intelligent transportation systems for road freight transport in Germany. In *Urban Freight Transportation Systems*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 183–202.