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DEVELOPMENT OF A QUALITY MANAGEMENT SYSTEM FOR PRECAST CONCRETE FACTORIES

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Abstract. The precast concrete (PC) method involves manufacturing reinforced concrete building components in a factory that are then transported to and assembled on a construction site. Compared to conventional methods, PC is widely employed as an advantageous means of creating a sustainable environment and improving construction quality. However, due to time and cost increase, many modern PC factories inspect only randomly selected component samples, for which they write inspection reports using paper-based forms. The storage and management of these documents associated with inspections within factories are essential because any defects that occur during the manufacturing process adversely affect the subsequent delivery and assembly activities. In this study, a mobile application capable of automated documentation and the storage, and input of systematic data was developed to generate a system for comprehensive quality management and assurance within PC factories. The developed system was tested in a PC factory, achieving a 47% time-saving rate compared to the conventional inspection method. Inspection reports of the developed system contain considerably more information than those of the conventional method and fundamentally prevent the risk of document damage and loss as they are automatically archived on a server in digital format.

Keywords: quality inspection, inspection report, precast concrete, off-site construction, OSC, automation.

Introduction

The off-site construction (OSC) method involves manufacturing building components in a factory and then transporting them to be assembled on a construction site. OSC has recently gained interest as a means of improving efficiency, creating a sustainable environment, and enhancing the quality of construction (Jiang et al., 2018; Yu et al., 2019). OSC comprises diverse construction methods from prefabricated components to modular buildings, where the precast concrete (PC) method is a representative form of OSC. Components such as beams, columns, walls, and slabs are delivered to sites after being bulk manufactured in factories under optimal environments, in contrast to on-site manufacturing where components are exposed to weather effects. The delivered PC components are assembled on-site and connected through the grouting of connections. Compared to conventional cast-in-place construction, PC is more efficient as it allows for easier mechanization, systemization, and automation, and it reduces environmental pollution by decreasing the number of temporary supports and forms used. In addition, PC can lower the total cost by reducing temporary work and personnel and improving quality through factory manufacturing (Hong et al., 2018; Jaillon et al., 2009; Jaillon & Poon, 2009; Sacks et al., 2004; Yin et al., 2009).

The OSC method intimately links factories, transportation, and sites, where a chain of construction activities including manufacturing, delivery, and assembling are conducted at each stage. Consequently, defects within any activity will significantly affect subsequent activities (Kong et al., 2018; Ma et al., 2018; Wang et al., 2019; Yin et al., 2009). Typical defects associated with the OSC method are imperfections arising in manufacturing activities (Kim et al., 2016; Lee et al., 2020) and damage occurring during delivery and assembly activities (Jacobsen et al., 1998; Lee et al., 2020; Shayanfar et al., 2017). In particular, any defects that arise during earlier manufacturing activities adversely affect all subsequent processes; thus, monitoring and managing defects before factory release is an essential process in the OSC method (Lee et al., 2020). In this regard, previous studies found that 10% of fractures

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and fatigue in shield tunnel lining structures were due to defects that occurred during the manufacturing process (Chen & Mo, 2009). Quality management significantly impacts PC production costs since the repair or discarding of PC components incurs a cost burden on PC factories. Studies have previously reported that the processing cost of PCs with quality problems accounts for 60% of PC supply-chain costs (Wang et al., 2020). Therefore, proper quality management of PC manufacturing will improve the quality of PC construction as a whole while also reducing supply chain costs.

In addition to imperfections within PC components, damage such as cracks and fractures can occur during the manufacturing process from recurrent loading and transportation, excessive loading, negligence of management, and excessive vibration during transportation (Shayanfar et al., 2017). Such defects may exacerbate during delivery if they are undetected before factory release, and the boundaries of responsibilities between the factory, transportation, and worksite officials may become extremely obscure if damages are found during assembly on the construction site. In addition, if only a final inspection is performed preceding the factory release, the detection of defects may be delayed when the release time is postponed due to changes in the assembly schedule on the worksite, which may also lead to a loss of appropriate repair time. Therefore, a system is required for identifying the causes and tracking the history of defects found in the post-factory release by meticulously recording the quality inspection results and repair history, and gathering these into a database. Specifically, comprehensive and historical data management of quality inspections is an essential system in the PC manufacturing stage, particularly in current PC factories that mainly conduct quality inspections based on visual examinations.

The Korean Construction Specifications (KCS) for PC Member Manufacturing and Assembly (Korea Construction Standards Center, 2021) stipulates that concrete quality assurance reports be prepared in accordance with the inspection and test plan and construction plan. However, unlike the U.S. National Precast Concrete Association [NPCA] (2022) and Precast/Prestressed Concrete Institute [PCI] (1999) manuals that present a standardized report format and emphasize the management of results, Korean specifications lack a specific report format. In addition, most current PC factories write paper-based inspection reports without systematizing the information recording, archiving, and management process. Furthermore, previous studies have reported that such conventional paper-based inspection report methods consume an average of 7.5 minutes, with a range of 3.5–11.5 minutes; thus, requiring considerable time, effort, and manpower (Wang et al., 2020). Consequently, the NPCA (2022) and PCI recommend that PC quality inspections are frequently conducted during the manufacturing process and that a systematic method be applied to minimize the time and effort required for repetitive data recording and archiving tasks (PCI, 1999). However, most PC factories currently inspect only randomly selected component samples according to their production line or time without inspecting and reporting the quality of all manufactured components. In addition, they are yet to implement automatic or systematic manufacturing methods (Lee et al., 2020). Proper quality management in PC factories is considered an extremely critical process in the PC construction industry as it enables the early detection and repair of defects that may occur during the manufacturing process. However, the inspection of all manufactured components and the maintenance of personnel managing result documentation can incur significant economic burdens on PC factories (Shayanfar et al., 2017). Therefore, developing an automated reporting system for PC quality inspection that enables fast and efficient quality management of all PC components is crucial.

Factory manufacturing for PC components generally significantly impacts the overall schedule of PC construction projects. Accordingly, previous studies on PC manufacturing (Arashpour et al., 2015; Kong et al., 2018; Reichenbach & Kromoser, 2021; Wang et al., 2019, 2020, 2021; Yin et al., 2009) have primarily focused on supply chain management and production tracking during the production and transportation process of members. Compared to the conventional paper-based method, management systems with radio-frequency identification (RFID) for PC components manufacturing allow easier identification of components' manufacturing status and stock location. In addition, such systems enable monitoring throughout the manufacturing process, which can significantly improve factory production management efficiency (Yin et al., 2009). Arashpour et al. (2015) analyzed real-time variations in information about PC manufacturing processes and proposed an autonomous and customized production tracking method that can be applied to OSC projects to automatically track related parameters. Wang et al. (2020) developed a framework for supply-chain management using blockchains to track the on-time delivery of PC components and the cause of defects. Kong et al. (2018) defined optimal batch deliveries for the just-in-time management of PC projects and modeled them by applying a polynomial-time optimization algorithm. Recently, a method was proposed to analyze images taken at sites using computer vision, compare them with building information modeling (BIM) to monitor the assembly progress of PC components, and perform the on-time delivery to construction sites (Wang et al., 2021). Although many studies have been conducted to improve the productivity of PC factories as above, the rate of automation and systemization in current PC manufacturing remains relatively low and quality management in factories has also been rather neglected (Reichenbach & Kromoser, 2021).

Most previous studies on the quality management of PC components have focused on the methodology of inspecting and monitoring defects using sensors, laser scanners, or images. Hajdukiewicz et al. (2019) presented lifecycle performance monitoring, which covers manufacturing, delivery, assembly, and maintenance by embedding sensors into PC components. Kim et al. (2015) used a 3D laser scanner to develop precision measurements of PC components' dimensions and surface defects. This study was later expanded to methods that can automatically detect errors and defects by comparing BIM data with the dimensions of PC components obtained from the laser scanner (Kim et al., 2016). Wang et al. (2017) applied distance- and color difference-based filters to colored laser scanning data to develop an algorithm that can automatically estimate the reinforcing bars' positions in PC components. Lee et al. (2020) analyzed the surface images of PC components using Faster R-CNN – a deep learning model – and developed a mobile application that could automatically detect defects, and store and manage the results. However, as stipulated by the aforementioned specifications (Korea Construction Standards Center, 2021; NPCA, 2022; PCI, 1999), the quality management of PC components should be based on comprehensive data, including concrete properties, dimensions of molds, and cover concrete, dimensions, position of rebar, and surface defects.

Gan et al. (2017) conducted a survey of practitioners with experience participating in OSC projects or who possess related knowledge to analyze the essential factors regarding the implementation of OSC. The study identified a lack of quality criteria for component products as one of the most critical factors. Accordingly, this study aims to develop a mobile application that can input and store data and perform automated documentation to promote comprehensive quality management and assurance in PC factories. The developed tablet-based mobile application systematically records quality inspection results and automatically outputs reports. The reports include data such as general information, quality inspection, and repair history of components that can be instantly checked anywhere without further documentation work. The inspection checklists were investigated in depth to establish an information database related to the manufacture and inspection of PC components and for the practical use of automated documentation. Several visits were made to PC factories in addition to investigating the content described in the specifications. To inspect and access the data server within the PC factory without movement restrictions, a personal mobile device and cloud-based data management method were applied, following a previous study (Reichenbach & Kromoser, 2021). Using the developed system will help diverge from localized inspections that were restricted to the inspection of randomly sampled components and increase the number of components subject to quality inspections without additional manpower. Furthermore, defects that may be identified during post-factory release can be checked via the component's inspection report to determine their cause and track their history, as various information about any PC component can be examined at any time. Moreover, the continued use of the developed system can lead to the accumulation of PC quality-related data. An analysis of the association between the accumulated manufacture and inspection data can be used to define repair and discard frequencies and the causes of defects for a particular PC component. For example, Nicał and Anysz (2020) analyzed the correlation between accumulated inspection data and manufacturing processes and found that the simultaneous use of a particular company's cement and adhesive increased the number of defects in PC components. Such manufacturing management can serve as a means of quality assurance and analyzing the accumulated history can lead to a reduction of imperfect components, thereby securing the stock of PC factories and reducing misuse of raw materials.

1. Quality inspection for precast concrete components

Figure 1 shows the general inspection process conducted by PC factories. The green, blue, and red colors indicate the manufacturers, inspectors, and managers, respectively. Upon completing the manufacturing of PC components, the inspector inspects them and determines whether the manufactured components meet the member quality standards outlined by standard specifications. If the quality is subpar, the inspector determines whether they are repairable according to the reasons and measures for their substandard quality and request the manufacturer either repair or discard them. Conversely, if the components meet the quality inspection criteria, the inspector writes an inspection report that the manager reviews, and the components are then ready to be delivered. The storage and management of documents related to inspections conducted within the factory is an essential process of OSC projects as any defects that occur during manufacturing in the early stages of OSC projects will adversely affect all subsequent processes. Inspection reports should be written according to factory inspections, and any reasons and measures for substandard components should be recorded and archived. However, relevant documentation may be lost or information relating to particular components may be difficult to find in the future if the factory does not have its own manufacturing management system.

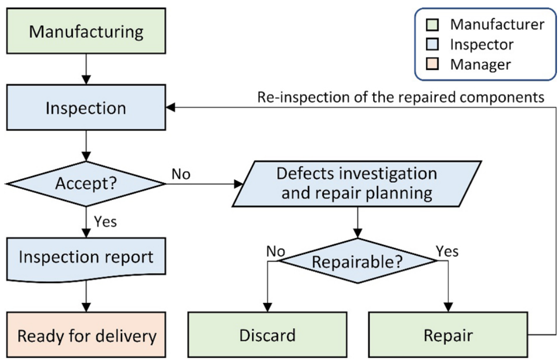


Figure 1. General inspection process conducted by PC factories

As shown in Table 1, PC component manufacture and corresponding processes are generally categorized as steps M1–9, including design review, shop drawing, mold assembly, rebar placing, embedded hardware placing, concrete casting, concrete curing, mold removal, and ready for delivery (Ballard et al., 2003; Ma et al., 2018; Wang et al., 2018). The approximate target dates for critical steps are typically D–120, D–90, D–60, and D–45 for steps M1–M4, respectively, and the last step, M9, must be completed before D–1. A PC quality inspection must be performed at all steps, excluding step M1, according to the standard specifications (Korea Construction Standards Center, 2021). Table 2 displays the inspection checklists for each corresponding manufacturing step in chronological order, based on the KCS (Korea Construction Standards Center, 2021) and PCI (1999) standard specifications. The inspection checklists consist of 19 items labeled I1–I19 that are conducted within the eight manufacturing steps M2–M9.

Inspections I1–I8 are conducted in the stage preceding the PC component's manufacture during the M2 manufacturing step. I1 identifies the PC component type and is used as a parameter to determine the concrete cover depth of I5 and the dimensional tolerance of I9 and I17. I2 determines whether the PC component is directly exposed to rain by checking its installation location using the drawing. I3 and I4 are parameters for identifying I5, and I5 is used as data to subsequently compare the I12 inspection results of the M4 manufacturing step. In general, concrete material information is received from the concrete plant in the M2 manufacturing step, and I6–I8 should be compared with the specification requirements.

Inspections I9 and I17, conducted in the M3 and M8 manufacturing steps, measure and inspect the dimensions of molds and components, respectively. Inspections I9–I11 refer to mold dimensions and defects on the beds and sides of molds, respectively, and are conducted in the

Table 1. General steps of PC components manufacture and corresponding processes

Manufacturing step	Process
M1. Design review (D–120)	Check PC methods, parts, and modification
M2. Shop drawing (D–90)	Check structural design, component detail, embedded plate, and mold use
M3. Mold assembly (D–60)	Clean molds, and apply form oil
M4. Rebar placing (D–45)	Assemble and place rebar and check the cover depth
M5. Embedded hardware placing	Place embedded anchor, plate, and other installations
M6. Concrete casting	Compact with vibrator
M7. Concrete curing	Steam cure and check temperature
M8. Mold removal	Check removal strength
M9. Ready for delivery (D–1)	Stock manufactured PC component

Table 2. General processes of PC quality inspection corresponding to the manufacturing steps

Manufacturing step	Inspection
M2. Shop drawing	I1. Component type
	I2. Direct exposure to rain
	I3. Rebar exposure to air or soil
	I4. Rebar diameter
	I5. Cover concrete depth
	I6. Maximum size of aggregate
	I7. Unit weight of cement
	I8. Water-to-cement ratio
M3. Mold assembly	I9. Mold dimensions
	I10. Defects on mold beds
	I11. Defects on mold sides
M4. Rebar placing	I12. Cover concrete depth
M5. Embedded hardware placing	I13. Embedded hardware location
M6. Concrete casting	I14. Concrete slump
M7. Concrete curing	I15. Compressive strength of concrete at 28 days
M8. Mold removal	I16. Removal strength of concrete
	I17. Component dimensions
	I18. Component defects
M9. Ready for delivery	I19. Defects on concrete surface

M3 manufacturing step. The dimensional tolerance for I9 should be within half that of I17. Inspecting the entirety of components is recommended for I17, but the number of inspections for components manufactured using the same mold can be reduced to one or more per 30 manufactured PC pieces after the initial inspection. However, the dimensions of relevant molds should be reinspected if the inspection results do not satisfy the tolerance criteria, and all manufactured components must be subsequently inspected. I12 inspects the cover concrete depth identified in I5 and is conducted during the M4 manufacturing step. Subsequently, the differences between the fixed and welded states, design location, and actual location of embedded hardware (connecting plate, lifting hook, electrical box, and others) are inspected in the M5 manufacturing step (I13).

Concrete inspections include concrete slump (I14) in the M6 manufacturing step and the compressive strength of concrete at 28 days (I15) in the M7 manufacturing step. I16–I18 are inspections of PC components during the M8 manufacturing step. The removal strength of concrete (I16) should be greater than 100 kg/m^3, and the concrete strength should be inspected using a non-destructive test if the concrete curing conditions before mold removal are poor. Component defects (I18) measure the bending and deflection of a component and involve visually inspecting irregularities, blistering, cracking, and damage on a concrete surface. When seeking to use cracked or damaged components after they have been repaired, the I18 inspection results and information about the repair area, method, material, and progress must be submitted to the inspector with photo data for approval. Inspection I19 is the last factory inspection before release and is conducted during the M9 manufacturing step. During this inspection, any defects on the surface of PC components (irregularities, blistering, cracks, and damage) are reinspected.

2. Development of an automated reporting system

Several PC factories investigated in this study conducted visual inspections using simple tools such as tape measures, squares, and line levels. Most of these factories wrote their reports manually, only recording the pass or fail status without including further data. Subsequently, the inspector carried out further documentation work at the office and prepared a quality inspection report. In particular, most factories did not archive photo data, where inspection results for defects on the surface of PC components should be collected with supporting evidence. To resolve this issue, this study developed a system that automatically records and archives quality inspection data and generates inspection reports for all types of PCs produced by factories. The system was developed based on a mobile device so that inspections could be conducted while moving around large factories and supporting evidence – including photos – could easily be stored. The mobile device was developed as a tablet-based mobile application considering the inconveniences that may arise when inputting inspection results if the size is too small. The specifications corresponding to all general processes of PC quality inspection (I1–I19) listed in Table 2 were embedded in the developed system. As such, the acceptability of input data can be evaluated in real-time in accordance with inspection requirements, allowing the quick performance of quality inspections and instant checking of inspection results. The system was developed such that the automatically generated inspection reports with repair histories could be viewed and outputted by simply searching for the component ID. Workers in several PC factories were interviewed to understand work procedures and identify the requirements for the system being developed, and therefore to develop efficient and practical quality management and inspection report system. In addition, the general manufacturing steps (Table 1) and inspection processes (Table 2) of PC components were investigated, and the inspection checklists and required information were analyzed by considering the diverse work environments within factories.

The mobile application was developed using Unity, where a Samsung Galaxy Tab S7 was the mobile device, and the database was built using Google Firebase cloud storage. The flowchart of the developed application was produced based on the interview results obtained from several PC factories and the typical processes of PC quality inspections (Figure 1), as illustrated in Figure 2. To systematize the PC manufacturing process, enhance responsibility depending on the tasks, and provide quick access to to-do lists, users were categorized into five authority levels: manufacturers (Lv. 1), inspectors (Lv. 2), managers (Lv. 3), administrators (Lv. 4), and clients (Lv. 0). The information for levels 1–4 was predefined and saved on the server. The application was designed to output a login graphical user interface (GUI) that receives IDs and passwords to search for predefined user information from the server upon initial access to the system. After login, the GUI automatically switches depending on the authority level. Users at each level could work with multiple tablets simultaneously, and the data was set to sync between the server and tablet every five seconds.

The manufacturer's (Lv. 1) main task involves checking the manufacture request list and requesting inspections after manufacture (blue arrows in Figure 2). Manufacturers must also repair components upon receiving repair requests from inspectors and request reinspections after entering information (black arrows). The developed system was designed to send push alarms to the user in charge when a request (manufacture, inspection, repair, approval, or report) is received, marked by green square boxes in Figure 2. In addition, processes performed outside the system are marked by grey square boxes (manufacture and repair), automated processes are marked in blue (inspection pass/fail and inspection report), and user inputs into the system are marked in white. Figure 3 shows the GUI displayed after a manufacturer log in, where the authority level is displayed in the upper right corner.

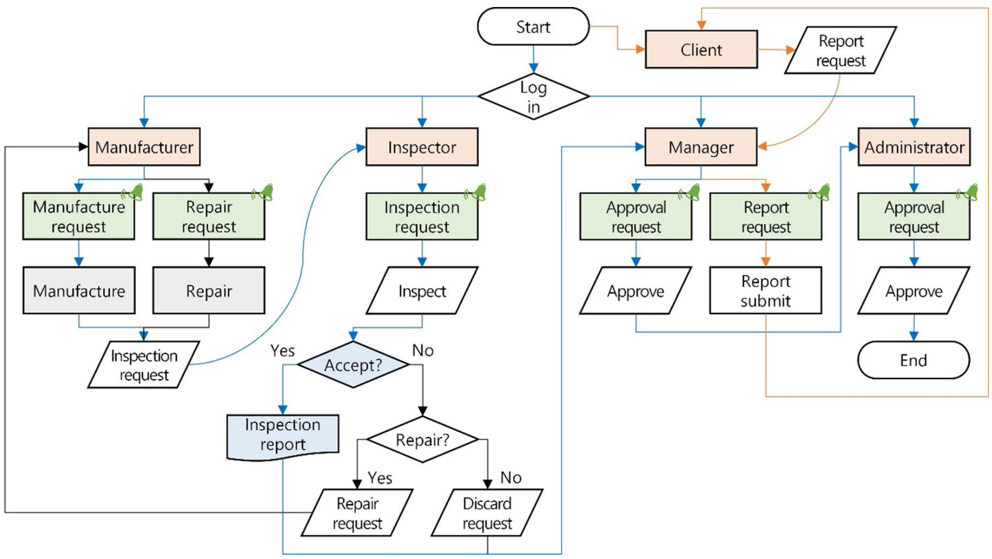


Figure 2. The flowchart of the developed application

After manufacturing is complete, the user selects the checkbox for the relevant component and taps the "request inspection" button below, which sends a push alarm to the inspector. An alarm rings when a repair request is made, and the manufacturer taps the "repair request list" button on the GUI in Figure 3 and can view the component in the table on the changed GUI, as in Figure 4. The GUI switches to register the repair information when the manufacturer selects a component in the repair request list, as in Figure 5. After checking the repair request details, the manufacturer attaches photos of before and after the repair, enters the repair details, and taps the "reinspection request" button, which sends a push alarm to the inspector.

When the inspector (Lv. 2) receives an inspection request from the manufacturer, an alarm is triggered, and the inspector proceeds with the inspection. The inspector generates an inspection report if all inspection data meet the specification requirements and subsequently sends an approval request to the manager, who is the next authority (blue arrows in Figure 2). Otherwise, the inspector determines whether a component should be repaired or discarded in accordance with specifications and sends either a repair request with descriptions to the manufacturer or a discard approval request to their manager (black arrows). Subsequently, the inspector receives an alarm when the manufacturer completes the repair process and then performs a reinspection in the same way. Figure 6 shows the GUI the inspector views after login, where the inspector's authority level is displayed in the upper right corner. The GUI changes when the inspector selects a component from the inspection request list, as in Figure 7, where the inspector can view a component's inspection status and enter the concrete compressive strength at 28 days. The inspector then taps the "build inspection report" button, automatically creating a report and sending an alarm to the manager for approval.

The developed system reflected the responses of interviewed workers, who noted that it would be good to conduct inspections in three phases depending on the time (Figure 7). From the general PC quality inspection processes (Table 2), the system was designed to perform I1–I8 (M2) in phase 1, I9–I13 (M3–M5) in phase 2, and I14 (M6) and I16–I19 (M8–M9) in phase 3. In accordance with the factory workers' requests, the compressive strength of concrete at 28 days (I15) was displayed on the GUI in Figure 7 so that it could be filled in at any time rather than including it in the three phases. Figures 8–10 show the GUIs for inspection phases 1–3, respectively.

The specifications were embedded in the developed system so that the acceptability of the input data could be evaluated in real-time in accordance with the inspection requirements, allowing the inspection results to be checked instantly. Items that fail to meet requirements are displayed in red (Figure 8), and the specification details can be viewed by tapping the "detailed criteria for decision" button on the bottom of the GUI for each inspection phase. The inspector can instantly check the acceptance status of input data and mark the relevant inspection phase as complete by tapping the "inspection complete", "repair request," and "discard request" buttons on the bottom of each GUI. Subsequently, the inspection results are reflected in the GUI of Figure 7, and a notification is sent to the manufacturer or manager. Reflecting the workers' requests, a preset dropdown menu was created for the phase 1 inspection GUI so that data can be promptly inputted when repeatedly producing the same components. Data can be manually input, or the preset can be modified if the desired input data set or preset list is unavailable. A function that can automatically import related data from a BIM will also be implemented in the future to save data input time further. Photos can be added to the phase 2 and 3 inspection GUIs (Figures 9 and 10, respectively) so inspection results can be visually checked later.

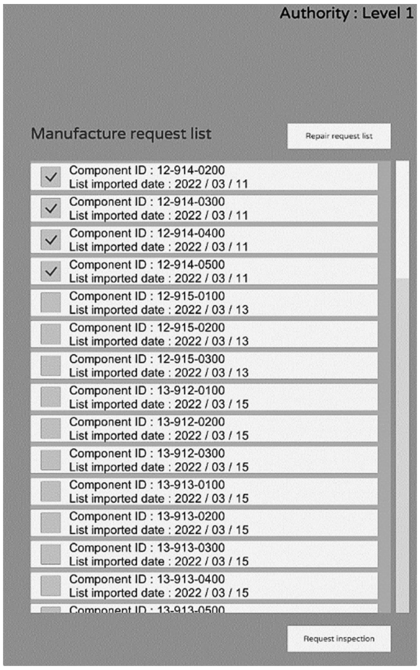


Figure 3. Manufacturer request list

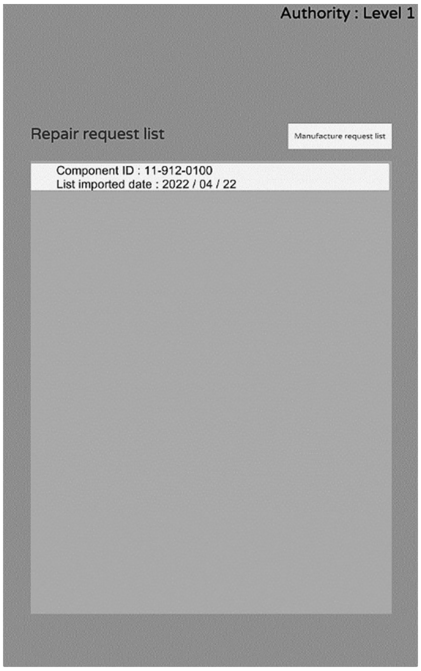


Figure 4. Repair request list

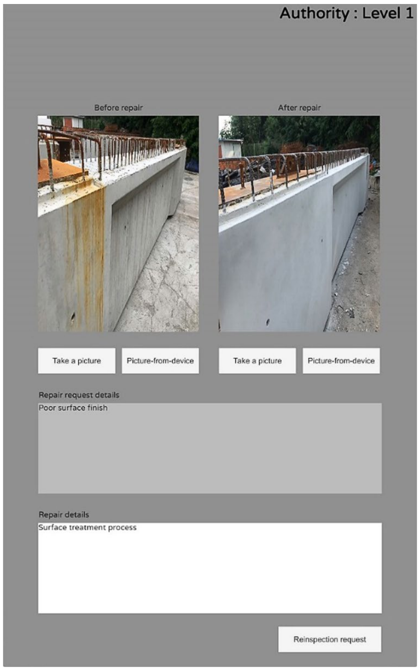


Figure 5. Selection of a component in the repair request list

Figure 6. Inspector request list

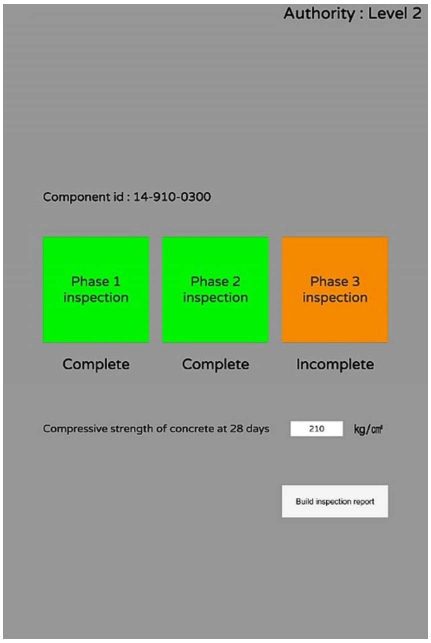


Figure 7. Component's inspection

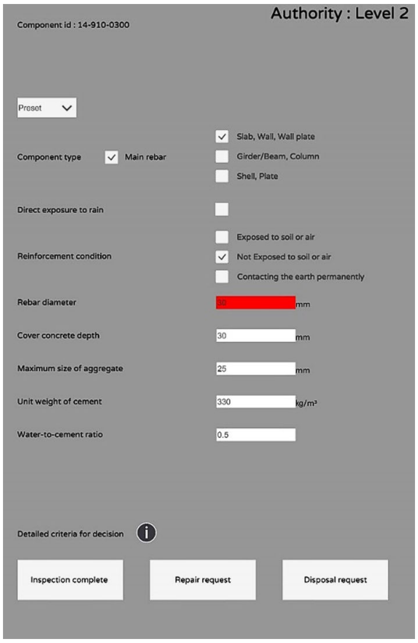


Figure 8. Items that fail to meet requirements (red)

The manager's (Lv. 3) tasks involve approving inspection reports and discarding requests, finding and presenting inspection reports from the server when requested, and registering component lists on the server. Most processes regarding PC component manufacture, inspection, and storing reports follow the blue arrows in the application flowchart (Figure 3), where repair and discards rarely occur. Over three months, two repair and discard cases were collected using the developed system in a PC factory. Figure 11 shows a repair case in which small holes on the side of a PC wall component were filled with mortar. Figure 12 shows another repair case in which chemical treatment was applied to repair discoloration on the PC beam surface stored in a storage yard due to the corrosion of exposed bars (Figure 5). Figure 13 shows a case in which map cracking occurred on the surface of a PC wall due to poor curing conditions. Although this case was not sufficiently serious to be categorized as grade 1 in accordance with the specifications, the component was discarded at the contractor's request. Figure 14 shows a

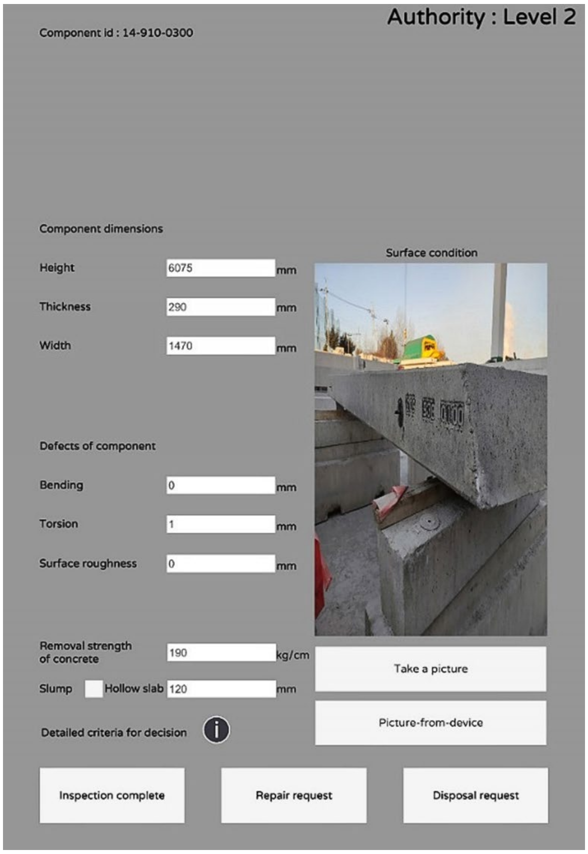


Figure 9. Phase 2 inspection GUI

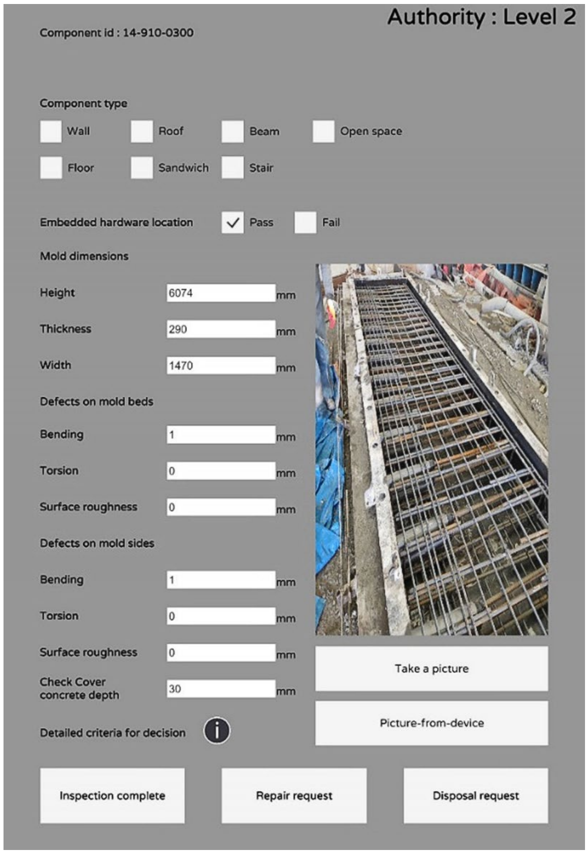


Figure 10. Phase 3 inspection GUI

Figure 11. Repair case: small holes on the side of a PC wall component filled with mortar

Figure 12. Repair case: chemical treatment was applied to repair discoloration on the PC beam surface stored in a storage yard due to the corrosion of exposed bars

Figure 13. Repair case: map cracking occurred on the surface of a PC wall due to poor curing conditions

Figure 14. Repair case: the edge of a PC wall severely damaged during transportation and storage within the factory

discarded case in which the edge of a PC wall was severely damaged during transportation and storage within the factory. The manager is responsible for finding the ID of relevant components in the server and submitting quality inspection reports when requested by clients (orange arrows in Figure 2). Figure 13 is a case in which the client checked an inspection report and requested that the component be discarded. The manager's task also involves bulk registering components lists on the server and notifying the manufacturer about the details of the components to be manufactured on the day in accordance with the manufacturing plan. The components list registered on the server is synchronized with the mobile system and added to the manufacture request list (Figure 3), and notifications are sent to the manufacturer. The inspector is currently required to input general information using the presets in the phase 1 inspection GUI (Figure 8); however, the system will be updated in the future to automatically input general information when the components list is registered on the server.

The quality inspection reports that are automatically completed with the data input by the inspector (Figures 7–10) are delivered to the administrator (Lv. 4) after the manager's approval, which is saved on the server after the administrator's final approval. The stored inspection report can be searched and viewed anytime and anywhere with an internet connection. Figure 15 presents an example of an inspection report that includes information on component ID, manufacturer, manufacture date, inspector at each phase, inspection requests and completion date, general information of components, inspection results, displays plots of errors and defects, and signatures. The attached photo data in inspection phases 2 and 3 (Figures 9 and 10, respectively) can be viewed by tapping the "photos" button. The "repair history" button is displayed in orange for components that have undergone repair; tapping it will show the repair details of Figure 5 and information on the inspection phases 1–3 for the corresponding components' before-repair states (Figures 8–10, respectively).

3. Validation of the developed application

The developed system was tested for approximately three months at a PC factory of 49,738 m^2 in Icheon, Gyeonggi, South Korea. The PC factory manufactures an average of 40 components per day and inspects the quality of randomly selected samples twice for components of the same specifications produced on the same line. Their initial inspection consists of inspection processes I1–I14 and is conducted during the M5–M7 manufacturing steps (Table 2); their second inspection consists of processes I15–I19 and is conducted during the M8–M9 steps. The factory writes reports by recording their visual inspection results on self-designed paper-based forms, a simple form requiring only a pass or fail status. Rarely, if a contractor requests specific report forms or inspection results, a report can be created in response, or an additional checklist can be used to conduct an inspection.

To validate the efficiency of the developed system during the testing period, the time required for the process was compared to the conventional paper-based inspection process in accordance with the Charrette test method (Clayton et al., 1998). Note that the inspection report used in the factory only included a pass/fail check; therefore, it differs from the developed application in input data level as the developed application requires input for all inspection data (Figures 7–10). Specifically, this study aims to separately measure the times required for inspection and documentation, as the developed system was designed to reduce the time for documenting inspection reports rather than the inspections themselves. However, accurately measuring the times required for the two tasks was impossible as a pass/fail check consumes considerably shorter time, and inspections and documentation activities were conducted repeatedly. Therefore, this study compared the efficiency of the developed system with that of the conventional method by measuring the times required for the two tasks without distinguishing inspections and documentation for report writing.

Table 3 shows the difference in the times required for the developed system and the conventional method used in the factory consisting of paper-based documentation with pass/fail checks. The inspections were conducted on PC wall components of uniform specifications, and the time for each method was measured for three workers familiar with the tasks, for which the average values were calculated. The average times required for the conventional method's first and second inspection processes were 17.3 and 20.0 minutes, respectively, totaling an average of 37.3 minutes. The average times required for the inspection phases 1–3 of the developed application were 2.4, 9.8, and 7.6 minutes, respectively, totaling 19.8 minutes.

Table 3. Working hours of PC quality inspection (min)

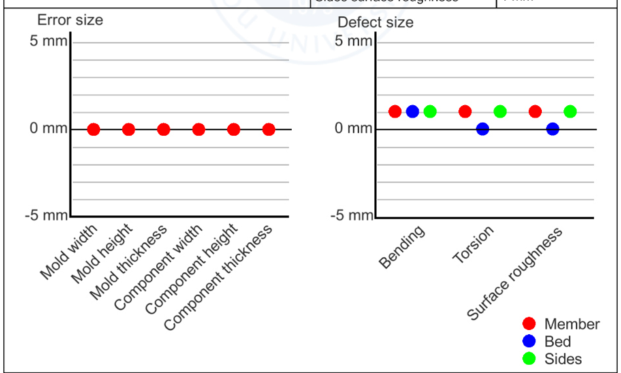
Method	Process	Test 1	Test 2	Test 3	AVG
Conventional	First	17.0	20.0	15.0	17.3
	Second	20.0	19.0	21.0	20.0
	Total	37.0	39.0	36.0	37.3
Developed system	Phase 1	2.5	2.0	2.6	2.4
	Phase 2	8.9	10.6	9.9	9.8
	Phase 3	8.7	7.4	6.8	7.6
	Total	20.1	20.0	19.3	19.8

The considerable time reduction in inspection phase 1 was due to the prompt input of general information using the presets (Figure 8). In addition, the test participants responded in the interviews that the function that evaluated the acceptability of the inspection results in real-time with only inputted data was beneficial when conducting quick inspections. While the conventional method requires that the inspector determine the pass or fail status after their inspection, the developed system can prevent judgment errors as it does not rely on human decisions.

The developed system saves approximately 17.5 minutes for inspecting and documenting one PC wall component compared to the conventional method, which accounts for 47% of the time saved on inspections. This result reflects the case of simple PC wall components without openings, and the differences in time will increase for components with openings or embedded hardware, requiring more complex inspections or those that have undergone repair. The KSC specifications (Korea Construction Standards Center, 2021) stipulate that error distributions in the dimensional measurements of concrete molds be recorded and archived for each component type for two weeks. Using the developed system can significantly reduce the work burden on managers compared to the conventional method, as it enables the easy analysis of error distributions during a specific period. In addition, while the conventional method only records the pass or fail status on inspection reports, the developed system contains more information in reports, including plots and input data (Figure 15). Furthermore, the developed system has dominant advantages over the paper-based method in archiving and managing inspection reports. Therefore, quality management undoubtedly requires less time using the developed system compared to the conventional method when considering the time consumed from finding to submitting relevant inspection reports when requested by clients.

Inspection report

General information					
Component ID	93-742-3105	Manufacturer	wsseo	Manufacture date	2022 / 04 / 20
Ph1. inspect	hmryu	Ph.2 inspect	hmryu	Ph.3 inspect	hmryu
Inspection request date		2022 / 04 / 20	Inspection complete date		2022 / 04 / 22
Component type		Beam	Rebar diameter		15 mm
Direct exposure to rain		Yes	Width		7,185 mm
Maximum size of aggregate		20 mm	Height		800 mm
Unit weight of cement		150 kg/m³	Thickness		1,000 mm
Water-to-cement ratio		0.3	Concrete strength at 28d		210 kg/㎠
Slump		80 mm			
Inspection results					
Mold width		7,185 mm	Removal strength		80 kg/㎠
Mold height		800 mm	Component bending		1 mm
Mold thickness		1,000 mm	Component torsion		1 mm
Bed bending		1 mm	Component surface roughness		1 mm
Bed torsion		0 mm	Sides bending		1 mm
Bed surface roughness		0 mm	Sides torsion		1 mm
			Sides surface roughness		1 mm



Manufacturer	wsseo	2022 / 04 / 22		Manager	wsseo	2022 / 04 / 22	
Inspector	hmryu	2022 / 04 / 22		Administrator	lovingjue	2022 / 04 / 22	

Photos Repair history

Figure 15. Inspection report

Theoretically, a worker must devote over 12 hours to performing quality inspections of 20 components using the conventional method, which is half the average daily production in a PC factory. This would exceed the eight hours of daily working time; thus, a single inspector cannot inspect even half the daily production amounts. However, using the developed system theoretically requires approximately six hours and 40 minutes per person under the same conditions. Therefore, using the developed system can increase the number of inspected PC components and improve the information in inspection reports while maintaining the existing personnel of the PC factory. PC components are generally released from the factory with their corresponding inspection reports. Reports may be damaged or lost during this process, which delays the verification of components received on the construction site. The developed system allows the easy archiving of reports as inspection reports are automatically stored on the server in digital format, fundamentally preventing their damage or loss. Accordingly, the developed system can improve the quality management process and ultimately reduce the economic burden on PC factories.

Conclusions

Currently, conducting quality inspections for all components is practically difficult due to limited personnel and time in most PC factories. Consequently, factories only inspect and record randomly selected component samples depending on the production lines and time period. In addition, they write reports by recording visual inspection results on self-designed paper-based forms that consist solely of simple pass/fail checks. Therefore, the exact causes of any defects found in delivery and assembly activities after factory release are difficult to track and the boundaries of responsibilities between the factory, transportation, and worksite officials may become obscure. As a solution, this study developed a system that allows the instant checking of general information, quality inspections, and repair history of components by automatically recording and archiving quality inspection data to generate inspection reports for PC factories.

A personal mobile device and cloud-based data management method was introduced to enable inspections and access to the data server without movement restrictions. In addition, specifications were embedded into the developed system to evaluate the acceptability of input data in real-time in accordance with inspection requirements, allowing the instant checking of inspection results and prompt performance of quality inspections. Automatically generated inspection reports with repair histories can be immediately checked and outputted by just searching for the component ID. In addition, a preset menu was created using the GUI to allow quick input for repeated data. The developed system was tested in a PC factory, which revealed time savings of 47% compared to the paper-based documentation with pass/fail checks. Since this result is based on simple PC wall components without openings, a greater difference can be expected for components with openings and embedded hardware that require more complex inspections or those that have undergone repairs. Therefore, using the developed system can increase the number of inspected PC components and improve information in inspection reports while maintaining the existing personnel of the PC factory, ultimately reducing their economic burden.

Unlike the conventional method that only records pass/fail statuses in inspection reports, the developed system reports contain considerably more information as they record input data while generating plots. Furthermore, the developed system has dominant advantages over the conventional paper-based method in terms of storage and management of the collected data. Such an exhaustive data-based quality management system can serve as a means of quality assistance for PC components. The system thoroughly manages information related to manufacturing and inspection until factory release, enabling the checking of inspection reports for components and tracking their history in the event that defects are discovered during delivery or assembly. Consequently, factories can be exempt from responsibility for such defects. Furthermore, using the developed system continuously enables the accumulation of data related to PC quality and association analyses between the accumulated manufacturing and inspection data. This can be used to define repair and discard frequencies and the causes of defects for specific PC components. The analysis of the causes of defects, repairs, and discards based on accumulated history will reduce the number of imperfect components, thus securing the stock for PC factories and reducing the misuse of raw materials.

The purpose of this study was to automate the recording and documentation process of inspection data based on visual examinations and excludes the automation of inspection methods. The tests at the PC factory showed that while the developed system could save time performing quality inspections, a single inspector was still not enough to inspect all the components produced in the factory. The developed system can be improved by integrating technologies such as dimension measurements, defect detection, and rebar position estimation using a laser scanner, or those that detect defects by analyzing surface images with deep learning tools. Furthermore, the system may be further developed to automatically determine whether PC components require repairing or discarding after scanning. In fact, the research team is currently working on applying automated inspection methods and aims to implement pass/fail check automation based on the photos of defective components collected by the developed system. When the developed system is combined with automated inspection methods, additional time savings are expected to be realized, thus enabling inspecting and reporting the quality of all manufactured components in PC factories. In addition, the continuous automation of PC manufacturing and inspection processes enables the integration of smart factories into OSC projects. This is expected to bring significant changes in OSC methods that have recently been increasingly emphasized for their importance and size.

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