Postprint of a Subway Segment Production Management System Based on QR Code Technology

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Date: 2017-11-06T00:00:00+00:00

Abstract

Currently, segment production is carried out in workshops. Factory management and quality monitoring information, such as production quantities, inventory levels, material amounts, and quality control data, is typically recorded in notebooks; this data is not entered into computers for process control purposes, but is only transcribed from paper records after returning to the office. Furthermore, issues related to information acquisition, data re-entry, segment tracking, delivery delays, and errors during the production, stacking, and transportation processes result in wastage of labor and raw material costs. QR code technology is a promising solution that can be effectively utilized for the collection and retrieval of segment stacking and transportation data. Although RFID technology has produced numerous research outcomes, it faces many practical application challenges and cannot be widely promoted in segment production. Therefore, this paper proposes a segment production management system based on QR code technology through experimental research.

Full Text

Vol. 8, No. 1, February 2016

Subway Segment Production Management System Based on QR Code Technology

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Abstract: Currently, segment production in workshops typically relies on notebooks to record factory management and quality monitoring information, such as production quantities, inventory levels, material quantities, and quality control data. This information is not entered into computers for process control purposes until staff return to the office and manually transfer the paper records to digital systems. Additionally, problems related to information acquisition, data re-entry, segment tracking, and delivery delays or errors during production, storage, and transportation result in wasted labor and raw material costs. QR code technology is a promising solution that can be effectively utilized for data collection and visualization during segment stacking and transportation. Although RFID technology has yielded numerous research achievements, it faces many practical application challenges that prevent large-scale promotion in segment production. This paper proposes a segment production management system based on QR code technology, validated through experimental research.

Keywords: Segment; QR Code; Production Management; System

CLC Number: F273
Document Code: A
Article ID: 1674-7461(2016)01-0022-07
DOI: 10.16670/j.cnki.cn11-5823/tu.2016.01.04

Tunnel lining rings are assembled from multiple segments, which constitute the primary structural lining in shield tunneling construction and play a critical role in the overall quality and service life of the tunnel. Currently, reinforced concrete segments are the most widely used type in China. However, several problems persist in the production, storage, and transportation of these segments:

(1) Segments are large in volume and produced in large quantities, requiring substantial production floor space. Particularly, the storage area occupied by numerous segments is extensive, making it time-consuming to locate specific segments among the vast inventory in storage yards.

(2) Segments for the same project are often manufactured by multiple factories, making production planning difficult to coordinate and failing to adequately meet the demands of actual construction schedules.

(3) Although data collection during segment production, transportation, and construction employs computer recording methods, information is first recorded on paper and then transferred to computers, resulting in redundant data entry. No effective solutions have been found for production progress management or segment identification and tracking.

With the development of information technology, RFID technology has been increasingly explored and applied in construction projects. Many organizations and enterprises have studied its implementation in building construction, achieving positive results and demonstrating that RFID can improve identification and positioning efficiency. Nevertheless, RFID technology faces significant challenges in practical application and large-scale promotion, primarily:

(1) **Insufficient technical maturity**: RFID electronic tags exhibit backscattering characteristics, and some frequency bands have weak penetration capabilities, causing significant interference in environments with metal, liquid, dust, and other substances that severely affect scanning and reading performance. Since segments are made of reinforced concrete containing large amounts of steel rebar, and undergo steam curing and water curing after demolding to achieve required strength, the inevitable dust at production sites seriously impacts RFID effectiveness.

(2) **High costs**: RFID tags are considerably more expensive than conventional barcode labels. Combined with the cost of RFID transmitters, readers, and encoders, and given the large production volume of segments, overall costs increase substantially, reducing enterprise adoption enthusiasm.

(3) **Lack of unified technical standards and inadequate security**: RFID technology has not yet formed unified standards, with multiple standards coexisting in the market, causing incompatibility between RFID tags from different manufacturers and leading to application confusion. Additionally, tag information is vulnerable to unauthorized reading and malicious tampering.

In contrast to RFID, QR codes offer significant cost advantages and provide better application prospects for user experience and interactivity when combined with portable mobile devices such as smartphones and tablets. With the popularization of smartphones and tablets under 3G/4G mobile network environments, QR code applications are no longer limited by time, space, or hardware devices. They can encode and bundle various digital information including product attributes, images, audio, text, and fingerprints, making them suitable for product quality and safety traceability, logistics and warehousing, product sales, and identification of materials and documents. Therefore, this paper proposes a QR code-based segment information management system for segment production information collection, identification, query, and tracking, providing a platform for information sharing among staff.

2 Related Research

Tan Yongquan, Yang Dingyi, et al. [3] introduced segment production technologies and quality standards in China, describing specific content related to segment production processes and technical regulations in conjunction with production process control for lining segments. Benjaoran and Dawood [4] proposed a production planning system for precast concrete management and its optimal utilization of factory resources. Informatization enables rapid information transmission, allowing production managers to promptly check precast progress and status through the system platform via the internet, improving work efficiency, promoting management integration, and reducing unnecessary expenses. Developing and implementing an informatized management system for concrete enterprises can achieve production management informatization, representing an effective method to strengthen enterprise management, ensure product quality, and protect economic benefits, which aligns with current development needs in the construction industry [5].

Many studies in construction engineering have demonstrated the potential of QR codes for improving data entry efficiency, labor management, productivity, cost savings, equipment and material tracking, and document management. Numerous studies have focused on integrating QR codes with other technologies. Bell and Williams [7] combined QR codes with GIS technology for statewide road sign management. Navon and Berkovich [8] integrated QR codes with RFID for automated data collection in raw material management and control. Shehab and Moselhi [9] developed an automated system for engineering deliverables such as drawings, reports, and specifications using QR code technology.

3 QR Code Application Analysis in Segment Production

3.1 QR Code Label Selection and Design

When selecting QR code labels, we simulated the natural environment of label adhesion on segments, considering primary influencing factors such as corrosion resistance, high temperature resistance, wear resistance, waterproof performance, and adhesive strength, while omitting minor and complex conditions such as air humidity, oxidation, and sun exposure. We conducted comparative tests on label samples provided by various manufacturers by adhering them to concrete test block surfaces and subjecting them to high-temperature steam curing, soaking, water immersion and air drying, and adhesion strength tests. Based on comprehensive evaluation of all test indicators, we selected a label with excellent performance, practicality, and high cost-effectiveness. The test results for five label groups (A, B, C, D, E) are shown in Table 1 (with star ratings indicating performance levels).

After experimental verification, the selected QR code labels remained intact during the one-month testing period, ensuring usability after the 28-day curing cycle. Considering segment dimensions, storage methods, transportation approaches, label placement on segments, label size, surface smoothness, and actual scanning conditions, we designed the QR code label size to avoid inadequate adhesion and potential damage, improve scanning success rates, and facilitate staff operations in label application and scanning, as shown in Figure 1 [Figure 1: see original paper].

3.2 QR Code Application Workflow

Addressing the current state of segment production, quality inspectors typically need to record checks at each process stage. The proposed QR code-based system workflow is illustrated in Figure 2 [Figure 2: see original paper].

Each segment is assigned a unique ID, and QR code labels are affixed to every segment after manufacturing for use during water curing, stacking, factory operations, and construction. Staff can scan segment QR code labels using tablets or smartphones to utilize the system and transmit segment information to the database, as shown in Figure 3 [Figure 3: see original paper].

When water-cured segments meet the 7-day curing standard, the system automatically sends age reminders to promptly lift segments out and displays their locations in the system, ensuring smooth production flow. In outbound segment management, staff can precisely locate segments in the storage yard through QR code information in the system, which retrieves segments that have reached curing standards from the database, thereby accelerating outbound efficiency.

Due to QR code technology' s rapid identification capability and quick access to segment information, relevant personnel can scan QR codes on segments using tablets or smartphones to view specific segment details. Consequently, at production or construction sites, QR code labels can eliminate information scarcity issues, facilitate segment quality traceability, and reduce search difficulty.

Segment QR codes contain extensive information, including manufacturing unit, segment type, raw material information, production details (embedded part layout, curing time, strength and other key indicators, repair records with photos), responsible personnel, quality acceptance certificates, production date, outbound date, transportation unit, delivery location and date, forming a comprehensive segment information profile.

4 System Architecture Based on QR Code Technology

4.1 Segment Production and Transportation Process Analysis

Segment production involves numerous processes, including: steel processing, steel cage fabrication, mold inspection and assembly, steel mold inspection, release agent spraying, steel cage and embedded part installation, concrete pouring, steam curing, demolding and marking, segment lifting, secondary water curing, segment inspection, three-ring pre-assembly, storage yard warehousing, and segment outbound. The segment production flow is shown in Figure 4 [Figure 4: see original paper].

From a workplace perspective, segment production is completed across four different work areas: steel cage binding workshop, segment production workshop, water curing pool, and storage yard, requiring multiple location transfers. Meanwhile, segments accumulate in large quantities during water curing and yard stacking. Considering the mobility of segment locations, tablet devices are used for information entry at production sites, QR code labels are affixed after demolding, and tablets scan the QR codes for information collection and transmission. Through a centralized database, construction and operation parties can also share this segment information data. Segment manufacturers can manage and optimize segment quality and production progress through analysis of relevant data, while construction and operation parties can use this data to guide tunnel construction and later operation and maintenance, achieving full lifecycle tunnel management.

4.2 System Basic Architecture

Therefore, this system adopts a B/S architecture model. Developed based on JAVA platform technology, the system uses Visual Studio 2013 integrated development environment for platform design. The server database employs SQL Server for data management. The B/S three-tier architecture model assigns distinct responsibilities to each layer: presentation layer, logic layer, and data layer.

(1) **Presentation Layer (Client)**: Defines web interfaces for management and end users, containing various programs that can interact with browsers. Users request data access to segment information from the web server through browsers installed on the client side. This layer primarily implements online plan publishing and real-time production process feedback functions. Users can formulate, select, and view relevant plans in the browser, and authorized users can directly feedback segment production status information on the page, with the backend automatically saving feedback information and updating page displays as needed.

(2) **Logic Layer (Service Layer)**: Primarily focuses on business rule formulation, business process implementation, and other system designs related to business requirements. It can also be understood as business logic processing of data or operations on the data layer. This layer defines main modules of various application systems, providing functions such as plan management, material management, production management, storage yard management, and system management.

(3) **Data Layer**: Its function is to store all relevant segment information data within the system and handle database access. Using SQL Server database to centrally store enterprise data documents, detailed data and progress records are saved in a relational database. Simply put, it performs operations such as Select (query), Insert (insert), Update (update), and Delete (delete) on data tables, providing data services for the business logic layer, making the system structure clearer and data storage and retrieval between the system and database fast and effective. The architecture is shown in Figure 5 [Figure 5: see original paper].

The segment production management system consists of three main components: tablet computers or smartphones, QR code labels, and the system website. Obviously, the mobile devices and QR code label components are on the client side, while the system website is on the server side. Relevant inspection information records entered by segment quality inspectors are stored in the central system database, and all staff can access required information through a central portal based on their access permissions.

According to user requirements, we divided the system into web and tablet versions. The web version is configured for desktop or laptop computers, accessed by system administrators and authorized users. The tablet version is configured for tablet computers, allowing quality inspectors and relevant responsible persons to carry mobile devices to production workshops for data entry, thereby replacing original paper report filling. Consequently, the tablet system module content is completely consistent with the paper inspection reports that previously needed to be filled out.

The system structure exhibits good scalability and modularity, employing a multi-layer component structure design for flexible system module assembly. This excellent scalability effectively addresses current and future environmental changes.

5 Engineering Application

A certain metro tunnel project comprises nearly 10,000 rings, with each ring consisting of six segments: one cap block, two adjacent blocks, two standard blocks, and one bottom arch block, totaling an enormous quantity of segments. In this project, we successfully applied the system (the web interface is shown in Figure 6 [Figure 6: see original paper]).

In the system, we created two models for a sample production supply chain of 300 segments (50 rings × 6 segments): a "basic model" time statistics without the system and a "QR code model" time statistics with the QR code system, to analyze and compare differences between the two scenarios and the changes brought by system adoption. The activity processes included in the model cover all aspects of segment production, curing, stacking, transportation, and construction. Based on field observation and recording at production sites, relevant results were obtained.

Table 2 shows the cumulative time for various activities (unit: h).

From Table 2, we can conclude that for all activities related to segment identification, processing, and positioning, the "QR code model" achieved significant time reductions compared to the "basic model," except for the label information writing process, which required longer time in the "QR code model." However, when QR codes are used for storage yard management at production sites, the time spent decreased from 5 hours to negligible.

The reason is that at production sites, the QR code-based segment production management system can automatically assign available storage areas to staff based on segment storage locations and conditions. Furthermore, after information collection, the probability of re-selecting storage areas due to errors is greatly reduced through automatic program analysis. Staff can immediately select storage zones according to plans without additional time spent determining the correct storage location for each segment. In the "basic model," although segment location information is displayed on planned paper layout drawings, the delivery dates for segments in each grid require manual checking and verification to ensure layout planning accuracy, which is time-consuming and inevitably leads to errors in manual data recording.

Another significantly reduced activity time is the duration of expanded search scope (i.e., from 55 hours to 1 hour), achieving time savings of up to 99%. This reduction occurs because segments are clearly positioned from the initial search, eliminating the need for expanded search scope. Additionally, during the expanded search phase, the system' s automatic positioning capability and accuracy substantially improve compared to dispatching personnel for on-site searches, resulting in considerable time savings. Time consumption in segment identification, scanning, transportation to construction site scanning, and inspection processes also decreased to varying degrees, with reduction rates basically exceeding 70%.

Table 3 shows the probability of various events for the "basic model" and "QR code model" (unit: %).

The results in Table 3 demonstrate that the "QR code model" significantly reduced the probability of incorrect shipping and identification. The probability of correctly positioning segments in initial searches at the storage yard increased from 65% to 99.5%, while the probability of missing segments during outbound shipment decreased from 0.5% to 0.1%. The probability of potential segment shipping errors also substantially decreased from 2.5% to 0.2%. Segments shipped to construction sites that do not meet current shield tunneling requirements or cannot be correctly assembled are unusable and must be stored at the already congested construction site or possibly discarded. Additionally, time costs for construction stoppages due to incorrect identification and shipping, as well as wasted additional transportation costs, are eliminated through QR code usage.

Based on practical engineering application results, the QR code-based segment production management system offers the following advantages:

(1) Standardizes segment manufacturing processes, improves production, outbound, and transportation methods, and provides clear visibility into age reminders, inventory status, and material conditions.

(2) Facilitates factory management by reducing segment search time while enabling segment traceability, obtaining timely information and complete logistics data throughout the supply chain, implementing time-based segment inventory management, and enabling more accurate demand forecasting.

(3) Reduces manual operation errors, saves labor and time costs, and conserves financial resources.

(4) Provides integrated, manageable, updatable, maintainable, and rapidly retrievable, transferable, and analyzable data information for segment production enterprises, enabling information transfer and sharing based on BIM standards across tunnel project phases from investment planning, survey and design, construction, to operation and maintenance, satisfying quality control and project schedule/investment management requirements at different construction stages. Additionally, it enables management and optimization of segment production progress, manpower, materials, equipment, quality, safety, and site layout, facilitates rapid project cost planning, enables efficient and accurate cost prediction and analysis, effectively improves cost control capabilities, enhances coordination between segment production and shield tunneling construction, and advances construction industrialization.

Currently, QR codes are only used during segment production and transportation phases. Since paper QR code labels have very short service life and cannot be applied throughout the tunnel' s full lifecycle during construction and operation/maintenance phases, developing durable, embeddable QR code labels for long-term use on each segment would enable integration of enterprise management systems with tunnel BIM technology applications, achieving full lifecycle tunnel construction.

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Design based on 2D Barcode Technology

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Abstract: Currently, in segment production plants, management and quality monitoring information is usually recorded with notebooks in the workshop, including production numbers, inventory stock numbers, material quantities, and quality monitoring information. Data are not typed into the computer until staff return to the office. Furthermore, during production, storage, and transportation, there are problems like information access, data re-entry, tracking, delivery delays, and errors, resulting in waste of labor and raw material costs. 2D barcode is a promising technology that can be effectively used for data collection and viewing during stacking and transportation. Currently, RFID technology has achieved many research results, but has encountered many problems in practical applications, and as a result, cannot achieve large-scale promotion in segment production. This paper studies and tests two-dimensional code and proposes a segment production management system based on two-dimensional code technology.

Key Words: Segment; 2D Barcode; Production Management; System

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