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

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Abstract

At present, segment production is carried out in workshops where factory management and quality monitoring information is typically recorded using notebooks—for instance, production volumes, inventory quantities, material amounts, and quality control data; this information is not entered into computers for process control needs, but is only transcribed from paper records into digital systems after returning to the office. Moreover, during the production, stacking, and transportation of segments, issues such as information acquisition, data re-entry, segment tracking, delivery delays, or errors lead to wastage of labor and raw material costs. Two-dimensional codes constitute a promising technology that can be effectively employed for the collection and viewing of data related to segment stacking and transportation. Currently, RFID technology has generated numerous research achievements; however, it encounters many problems in practical applications and cannot be widely promoted in segment production. To this end, this paper, through experimental research on two-dimensional codes, proposes a segment production management system based on two-dimensional code technology.

Full Text

Segment Production Management System for Metro Tunnels Based on QR Code Technology

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Abstract: Currently, in segment production workshops, factory management and quality monitoring information is typically recorded in notebooks, including production quantities, inventory levels, material quantities, and quality monitoring data. This data is not entered into computers for process control in real-time, but 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 production, stacking, and transportation result in wasted labor and 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. Therefore, this paper, through experimental research on QR codes, proposes a segment production management system based on QR code technology.

Keywords: Segments; QR Code; Production Management; System

A tunnel lining ring is assembled from several segments, which constitute the main structural element of tunnel linings in shield tunneling construction and play a critical role in the quality and service life of the entire tunnel. Currently, reinforced concrete segments are the most widely used type in China. However, several problems persist during segment production, stacking, and transportation:

(1) Segments are large in volume, produced in large quantities, and require substantial production floor area. Particularly, the stacking area occupied by numerous segments is extensive, making it time-consuming to locate required 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 actual construction schedule requirements.

(3) Although computers are used for data recording during segment production, transportation, and construction, information is first recorded on paper and then transcribed, creating redundant data entry issues. Moreover, 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 the application of RFID technology in construction, achieving positive results [2] and demonstrating that RFID can improve identification and location efficiency. However, RFID technology has encountered significant obstacles in practical application and large-scale promotion. The main issues are as follows:

(1) **Insufficient Technical Maturity:** Due to the backscatter characteristics of RFID tags and the weak penetration of certain frequency bands, significant interference occurs in the presence of metal, liquid, and dust, severely affecting scanning and reading performance. Since segments are reinforced concrete products containing large amounts of steel reinforcement, and undergo steam curing and water curing after demolding, the production site inevitably contains substantial dust, which seriously impacts RFID effectiveness.

(2) **High Cost:** RFID tags are considerably more expensive than ordinary barcode labels. Coupled with RFID transmitters, readers, encoders, and other equipment, the large production volume of segments leads to increased costs, significantly reducing enterprise enthusiasm for adoption.

(3) **Lack of Unified Technical Standards and Insufficient 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 resulting in application confusion. Additionally, tag information is vulnerable to unauthorized reading and malicious tampering.

In construction projects, numerous studies have demonstrated the potential of QR codes for improving data entry efficiency, labor management, productivity, cost savings, equipment and material tracking, and document management. Many studies focus 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 automatic data collection in 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. Application Analysis of QR Codes 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 key influencing factors such as corrosion resistance, high temperature resistance, wear resistance, waterproof performance, and adhesive strength, while omitting minor complex conditions like air humidity, oxidation, and sun exposure. Label samples from various manufacturers were tested and compared by adhering them to concrete test block surfaces and subjecting them to high-temperature steam curing, immersion, water immersion and air drying, and adhesion strength tests. Based on comprehensive evaluation of all test indicators, a label with excellent performance, practicality, and high cost-effectiveness was selected. The test results for five label groups (A, B, C, D, E) are shown in (with star ratings indicating performance levels).

After experimental verification, the selected QR code labels remained intact during the one-month test period, ensuring usability after the 28-day segment curing cycle. Considering segment dimensions, stacking methods, and transportation modes, the label size and placement position on the segment surface were designed based on actual scanning conditions and surface smoothness. This prevents label detachment or damage, improves scanning success rates, and facilitates application and scanning by workers, as shown in [Figure 1: see original paper].

3.2 QR Code Application Workflow

The proposed QR code-based system workflow for segment identification and positioning is illustrated in [Figure 2: see original paper]. Typically, quality inspectors must check and record each process 环节. After segment manufacturing, a QR code label with a unique ID is affixed to each segment for use during water curing, stacking, factory operations, and construction. Using tablets or mobile phones, workers can scan the segment QR code labels, utilize the system, and transmit segment information to the database, as shown in [Figure 3: see original paper].

When water-cured segments meet the 7-day curing standard, the system automatically sends age reminders to promptly lift the segments and displays their locations in the system, ensuring smooth production flow. For outgoing segment management, workers use QR code information in the system to precisely locate segments in the storage yard. The system retrieves segments that have reached curing standards from the database, thereby accelerating segment dispatch efficiency.

Due to the rapid identification capability of QR code technology and its function for quick access to segment information, relevant personnel can scan QR codes on segments using tablets or mobile phones to view segment information. Therefore, at production or construction sites, QR code labels can eliminate information deficiency, facilitate segment quality traceability, and reduce search difficulty. The QR code contains extensive segment information, including manufacturer, segment type, raw material information, production data (embedded part layout, curing time, strength and other key indicators, repair records with photos), responsible personnel, quality acceptance certificates, production date, dispatch date, transportation unit, delivery location and date, forming a comprehensive segment information profile.

4. System Architecture for QR Code-Based Segment Production Management

4.1 Analysis of Segment Production and Transportation Process

Segment production involves numerous processes: steel bar 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 dispatch. The production flow is shown in [Figure 4: see original paper].

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

4.2 Basic System Architecture

The system adopts a B/S architecture model, developed based on JAVA platform technology using 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 Side):** Defines web interfaces for management and end users, containing various programs that can interact with browsers. Users access segment information by requesting data 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 create, select, and view relevant plans in the browser, and authorized users can directly feedback segment production status information on the page, which is automatically saved in the background and updates page display as needed.

(2) **Logic Layer (Service Layer):** Primarily responsible for business rule formulation and business process implementation related to business requirements, which can also be understood as data business logic processing or operations on the data layer. This layer defines main modules of various application systems, providing functions such as plan management, mate-

rial 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 manage database access. Using SQL Server database to centrally store enterprise data documents, detailed data and progress records are saved in a relational database. In simple terms, it performs operations such as Select, Insert, Update, and 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: see original paper].

The segment production management system consists of three main components: tablet computers or mobile phones, QR code labels, and the system website. Clearly, mobile devices and QR code label components are on the client side, while the system website is on the server side. Quality inspection records entered by segment 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, the system is divided into web and tablet versions. The web version is configured for desktop or laptop computers for system administrators and authorized users. The tablet version is configured for tablet computers, allowing quality inspectors and relevant personnel to carry mobile devices to production workshops for data entry, thereby replacing traditional paper report filling. Consequently, the tablet system module content is completely consistent with the paper inspection reports that originally needed to be filled out. The system structure exhibits good scalability and modularity, adopting a multi-layer component structure design for flexible system module assembly, with excellent expandability to effectively respond to current and future environmental changes.

5. Engineering Application

A certain metro tunnel project uses six segments per ring (one keystone block, two adjacent blocks, two standard blocks, and one invert block), with nearly 10,000 rings and an extremely large quantity of segments. In this project, the system was successfully applied (the web interface is shown in [Figure 6: see original paper]).

In the system, a production supply chain sample of 300 segments (50 rings × 6 blocks) was used to create two models: a "basic model" time statistics without the system and a "QR code model" time statistics using the QR code system, to analyze and compare differences and improvements. The modeled activity processes involve 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). The results demonstrate that for all activities related to segment identification, processing, and positioning—except for the label information writing 环节—the "QR code model" significantly reduced time compared to the "basic model." The information writing process in the "QR code model" requires longer time during production. However, when QR codes are used for storage yard management at production sites, the time spent is reduced from 5 hours to negligible.

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

Another significantly reduced activity time is the duration of expanded search scope (i.e., from 55h to 1h), achieving a time savings of up to 99%. This reduction occurs because segments are clearly positioned during initial searches without requiring expanded scope, and because the system' s automatic positioning capability and accuracy are substantially higher than manual on-site searches, greatly saving time. Time consumption for segment identification, scanning, transportation scanning, and inspection processes at construction sites also decreased by over 70%.

Table 3 shows the probability of various events for the "basic model" and "QR code model" (unit: %). The results show that the "QR code model" significantly reduces the probability of incorrect loading/transportation and identification. The probability of correctly positioning segments in initial storage yard searches increased from 65% to 99.5%, while the probability of missing segments during dispatch decreased from 0.5% to 0.1%, and the probability of segment loading errors also substantially decreased from 2.5% to 0.2%. Incorrect segments delivered to construction sites cannot be used as they fail to meet current shield tunneling requirements or cannot be properly assembled. These segments occupy already tight construction sites or may be directly scrapped. QR code usage effectively eliminates these situations, along with delays caused by incorrect identification and loading, work stoppage time costs, and additional transportation expenses.

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

(1) **Standardizes segment manufacturing processes** and improves production, dispatch, and transportation methods, with clear visibility of age reminders, inventory status, and material conditions.

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

(3) **Reduces manual operation errors**, saving labor and time costs and reducing expenses.

(4) **Provides integrated, manageable, updatable, maintainable, and rapidly retrievable, transferable, and analyzable data** for segment manufacturers, 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, schedule, and investment control requirements at different construction stages. Additionally, it enables management and optimization of segment production progress, labor, materials, equipment, quality, safety, and site layout, rapidly generating production project cost plans for efficient and accurate cost prediction and analysis, effectively improving cost control capabilities, enhancing coordination between segment production and shield tunneling construction, and improving construction efficiency.

Currently, QR codes are only used during segment production and transportation phases. Since paper QR code labels have a very short service life and cannot be applied throughout the tunnel lifecycle, developing durable, embeddable QR code labels for each segment that can be used during construction and operation phases will enable integration of enterprise management systems with tunnel BIM technology for full lifecycle tunnel construction.

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Note: Figure translations are in progress. See original paper for figures.