Automation in Construction 46 (2014) 64–73

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

A BIM-based construction quality management model and its applications

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ARTICLE INFO

Article history:
Received 24 September 2013
Received in revised form 4 May 2014
Accepted 13 May 2014
Available online 2 June 2014

Keywords:
Construction quality management
4D BIM
Construction codes and specifications
Product
Organization and process modeling
Collaboration

ABSTRACT

The potential of Building Information Modeling (BIM) to support a transformation of the processes of design and construction has been evident in the construction industry. Although BIM is considered helpful in improving design quality by eliminating conflicts and reducing rework, there has been little research into using BIM throughout the project for construction quality control and efficient information utilization. Due to the consistency of design data with quality data and construction process with quality control process, the potential of BIM implementation in quality management lies in its ability to present multi-dimensional data including design data and time sequence. This paper explores and discusses the advantages of 4D BIM for a quality application based on construction codes, by constructing the model in a product, organization and process (POP) data definition structure. A case study is provided to validate the use of the proposed 4D BIM application for quality control during the construction phase of the Wuhan International EXPO Center.

1. Introduction

The quality of a product is reflected in its ability to satisfy stated or implied needs and internal characteristics of a finished product in addition to its external design [1]. Therefore, construction product quality can be defined as: the degree to which the stated or implied needs and the internal characteristics are guaranteed during the process of construction [2]. This research defines quality as compliance with construction codes and specifications.

1.1. Research background

In official records, there were 882 cases of construction quality and safety incidents in China in 2006 [3]. During 2007–2008, at least 37 fatal accidents were due to quality failures on projects. During the first half of 2009 there were 257 cases of construction quality and safety production accidents in which 306 people died [4]. According to the statistics, of the 147 engineering accidents collected by researchers, about 1/3 of low-rise building collapses were caused by improper construction methods or materials. Most building quality accidents during the construction phase occur in multi-story projects [5]. 29% of the construction project accidents in Germany are directly due to construction quality problems. Project-site accidents due to poor quality are significantly worse in China [6].

Due to the uncertainty and complexity of construction management and variability within project environments, quality should be closely scrutinized and controlled throughout each stage of construction [7]. Based on experience from construction experts and extensive literature review, there are three factors which contribute to difficulties in quality management. First, the quality control criteria for individual components are scattered in different national, industrial and local quality control codes for construction. It is also common for these specifications to cross-reference each other, creating complex dependencies between specifications [37]. For example, during jet grouting, there are more than 3 codes for the requirements of size, shape, and mechanical properties. Second, it's difficult to identify the responsibility for an accident because project participants form a complex web of relationships [14]. Third, the current focus of quality control is on the final component with much less attention given to quality control during the process of construction. These problems greatly increase the difficulties of construction management and contribute to quality defects. Because of these scattered and conflicting codes, highly mobile project participants follow only a subset of quality codes, without full understanding. Therefore, hidden quality dangers are buried deep in the system which can create the potential for future construction disasters.

Other researchers have used computer-based information technology to develop quality management programs for quality assurance [8], to construct a web-based quality management system for effective information sharing [9] and to integrate scheduling with inspection

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http://dx.doi.org/10.1016/j.autcon.2014.05.009
0926-5805/

and testing, nonconformance reporting, and with corrective actions during the construction phase [10]. Previous studies have been conducted to facilitate information sharing and to link scattered information. However, these studies failed to fully utilize digital information in the design documents by automatically passing quality related information to the construction phrase, and to sufficiently consider the interrelationship between the three main factors in quality management: product, organization and process. Because change orders and inspection schedules change continuously throughout the process of construction, the quality control plan should be adjusted based on both spatial and temporal data. The complex nature of these factors indicates that a 4D (3D model plus time) visualization technology would be advantageous for quality assessment during construction. The use of Building Information Modeling (BIM) technology on construction projects has the potential to improve not only the construction process but also the quality control process by changing the way project participants interact with each other [13].

1.2. BIM and its applications in project quality management

BIM is most frequently perceived as a tool for visualizing and coordinating AEC (architecture, engineering and construction) work, avoiding errors and omissions, improving productivity, and supporting scheduling, safety, cost and quality management on construction projects. It incorporates all the building components, including geometry, spatial relationships, properties and quantities [11]. BIM can also generate and maintain information produced during the whole life cycle of a building project—from design to maintenance—and can be applied to various fields [12]. Examples of this research are BIM-based: cost planning and estimating, safety checking integration for dynamic safety analysis [17–19], and dynamic construction site safety management [20]. Research indicates that BIM is beneficial in the preparation of schedules and estimates, tracking and managing changes, and managing site logistics [21]. More informed decisions by a project's stakeholders can be made due to the, now feasible, open communication and exchange of data after easily verifying design requirements [15] and performance can be analyzed through BIM [16]. However, there are no best practice studies that demonstrate implementation of a 4D BIM application to increase the quality of construction projects [28].

The use of BIM has provided a means of increasing total project quality [22]. It improves design quality in the following ways: 1) Increases efficiency and precision and improves design evaluation and communication [16,23]; 2) reduces errors due to better coordination between documents and the entire team, thus minimizes conflicts [24,25]; 3) simulation and optimization can be conducted for better performance, lower costs, and shorter lead times [26]; 4) automatic generation of engineering documents produces precise and consistent information [24]; 5) reduces maintenance costs and time by providing timely and relevant information to facility management (FM) as early as the design stage [27].

Researchers agree that BIM can be helpful to improve project quality and that more projects are likely to use BIM in the future to pass information from the design phase to the construction trades. However, there is no clear guidance about the use of BIM to improve quality [28]. In view of this, this paper proposes a 4D BIM-based application for quality management in the construction phrase, which can benefit the project in following ways: (1) Ensure information consistency from the design through the construction phase. BIM is a parametric modeling effort that provides tabular views of components and characteristic interactions with their elements such as: name, type, attributes, relationships and metadata [15,29]. The extensive data for each construction product can be used as the basis to automatically assess the significance of deviations between the design and as-built conditions instead of manually evaluating individual drawings and change orders. (2) Process control consistency during construction. The percent completion of each activity in the construction schedule can be continuously viewed in the BIM application [30]. Therefore, quality inspections can be scheduled immediately after the completion of one task, before the next task begins, making the quality inspection process timely and consistent with the construction process; (3) collaboration between participants. The use of BIM technology on construction projects has the potential to improve the process by allowing all team members to collaborate more accurately and efficiently than when using traditional processes [15,16]; (4) unlimited extension of the use of BIM information when combined with other advanced technologies. These advanced technologies link the digital to the physical entities [31]. Research has already been conducted to investigate the combination of BIM and other technologies such as AR (augmented reality) for quality defect management [32].

Considering the above advantages of utilizing BIM in construction quality management, this paper explores the implementation of BIM for construction quality management and proposes to integrate BIM with the existing POP data structure to improve current quality management process.

2. Research objective and methodology

The objective of this research was to develop a comprehensive, informative and practical 4D BIM-based application for the purpose of construction quality management and to investigate how it can fit into the current construction practice. Also, the research identified potential problems with using BIM technology with current quality management methods, and proposes solutions. During the research, quality models that contained process, organization, and product (POP) information were built using national, industrial and local quality standards and codes. Then, a scheduling model and the quality model were integrated into a virtualized 4D BIM-based application to identify quality control criteria and responsibility assignments in the construction process. This application includes inspection and testing, analysis during the construction phase, and feedback of inspection results.

A case study approach was adopted to explain the dynamic quality control model that was developed from a comprehensive review of the literature and site investigation. The inspection template is derived of Construction Quality Integration System® and the CQIS is the foundation of this research. In the case study, the inspection data was acquired from the project general contractor and CAD drawings and the construction schedule were obtained from the project owner and from contractors.

The research consists of four major sections: (1) Investigation of quality control strategies in large infrastructure construction through site survey; (2) creation of the 4D BIM model by Autodesk Revit® and Navisworks®; (3) formulation of the method to match the quality data structure with BIM based on theoretical research; (4) development of a 4D BIM application workflow for quality management. Validation of the proposed model is obtained through a case study of the foundation construction at the Wuhan International Expo Center. The foundation work was completed with no delay due to major quality defects. A brief explanation and application of the four-step approach of this research is presented in the following sections.

3. Quality management plan in large infrastructure construction

Quality control covers inspection and testing, nonconformance reporting, and corrective action taken during the construction phase [10]. The quality control process begins with making quality management plans based on the design drawings and specifications, which establish the quality of the material and equipment, the acceptance criteria for the work in place, and the inspection and testing to be performed. Then, through coordination between material engineers and project engineers, all the technical and quality data in the procurement requisition for material and equipment have been transmitted for procurement. During construction work, the subcontracted work is monitored for conformance by the general superintendent and the field engineer. They also monitor all work and identity deficiencies beyond tolerable limits. Upon completion of the work, acceptance inspection and validation testing are conducted to verify conformance with the requirements of the approved construction documents [35]. In general, the control of quality on a construction project consists of field inspections which guarantee that workmanship, physical properties, equipment, and material supplied by the contractor conform to the design plans and specifications [36].

In the current practice in China, checklists in the form of electronic templates are used for quality inspections. Each checklist contains quality control criteria categorized based on national, industry and locally-based quality control codebooks for each inspection lot. Each inspection lot can be considered as a product. The responsibilities of each organization that participates in constructing the final product are identified and recorded along with the lot checklist. Construction quality acceptance is divided into the unit (sub-units) project, the segment (sub-segment) project, the sub-project and the inspection lot. An inspection lot is composed of a certain number of samples that are reproduced in the same conditions and pooled in a prescribed manner for testing. The sequence of acceptance is in the opposite direction from traditional acceptance methods — from the bottom lot to the whole project. The inspection lot is the smallest unit and can be considered as a construction product equal to a component in a BIM model.

Fig. 1 shows the overall process of quality inspection plan utilizing a BIM quality model. First, the quality control plan is developed based on the work plan, the inspection plan and project characteristics. Second, the corresponding quality checklist is retrieved from the 4D BIM-based construction quality model, according to work classifications and the process of construction activities, when requested by a contractor. Third, the inspection is conducted by recording the field measurements and test results required in the checklist. Fourth, an objective comparison between design requirements and construction results is automatically generated. Fifth, decisions are made whether to accept and proceed to next process or to reject this lot and issue a nonconformance report (NCR) with specific requirements from the BIM-based quality model. Finally, the inspection work results in feedback, and it is reflected in the model. Subsequently the model and the inspection plan are updated.

Quality management is a precise and complex process which requires knowledge and work experience. The mobility of construction practitioners and the lack of accurate understanding of quality codes lead to negligence or failure to conform to quality requirements. Therefore, research and development of a construction quality management model are necessary for barrier-free quality data circulation between different trades at all stages of the project. The integration of 4D BIM and construction quality codes provide accurate and consistent data for the whole process, allowing the participants to fully understand the quality requirements.

4. Architecture of BIM-based construction quality model

In a standard BIM, each element is only defined with geometry attributes; this does not include the detailed information necessary for quality management such as construction process, method, material, and participants. In order to contain all available information elements, evaluation criteria and relationships, the quality model consists of a standard BIM, scheduling and the standard POP model.

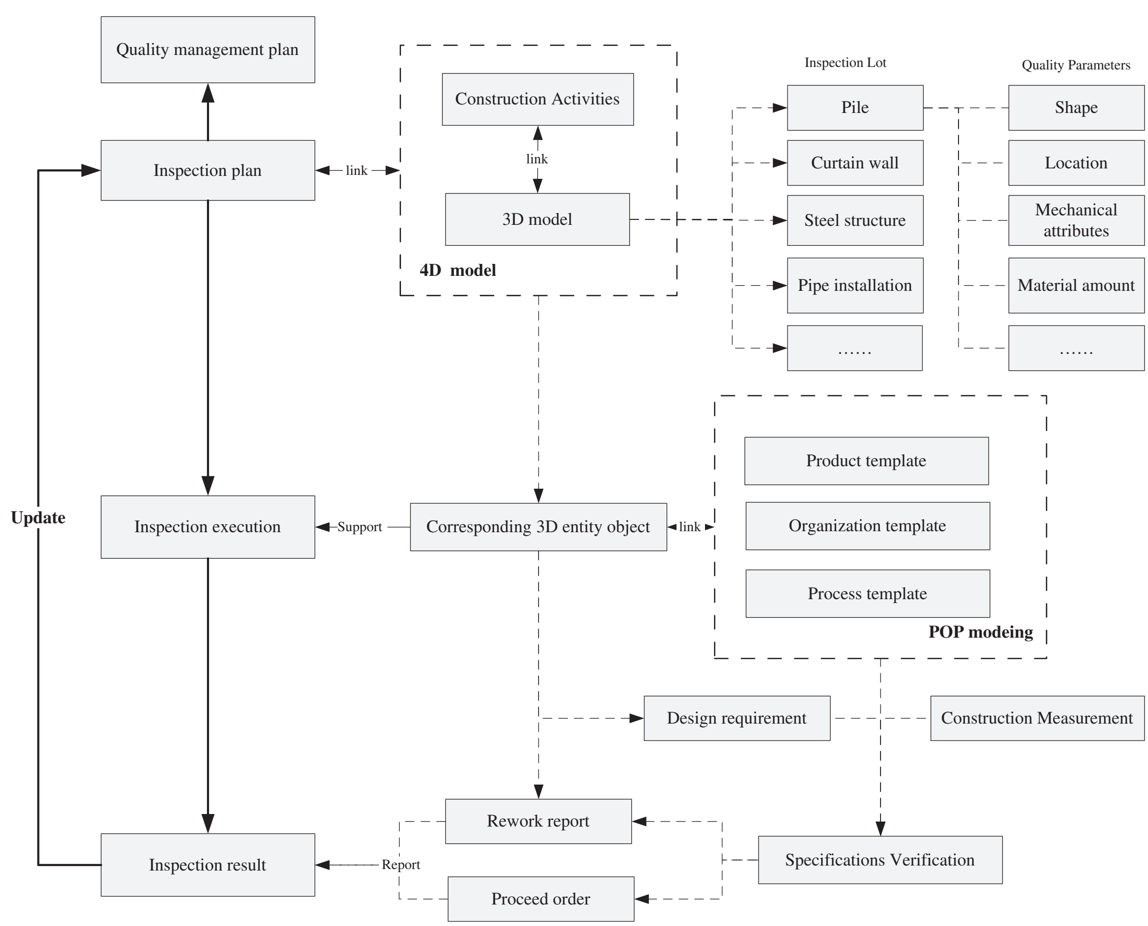


Fig. 1. The execution of construction quality management inspection plan using BIM quality model.

4.1. POP modeling method

In order to better construct the full data interrelationships for quality management purposes in BIM, the data from BIM should be carefully organized and enriched. The product, organization, and process (POP) modeling method to complement 3D product models with process and organization models to support design and construction was proposed [34]. 4D modeling is an example of product–process modeling and organization–process modeling. The latter is used to construct and simulate the interaction among teams and/or organizations, and their associated responsibilities, in different phases of a project [33]. The prior work of constructing an electronic checklist database is accomplished to structuralize codes and will be used as the foundation of this research. The quality model includes more than 300 types of control items and more than 1000 control templates, covering control codes and standards for the whole quality control process in the construction industry.

4.1.1. Product template

Product control is a branch of statistical quality control; it consists of various inspection procedures to help make decisions about the disposition of individual lots of finished products. The inspection lot is a certain quantity of a particular item chosen at random for quality testing. It should consist of material produced under similar conditions and using similar materials, personnel and methods. The lot will be accepted or rejected by inspectors according to a quality checklist template, as shown in Fig. 3. The lot checklist contains quality control criteria defining the permissible deviation between design parameters and construction results for each construction product. Because organization chart names and responsibilities are contained in the existing POP which has been integrated into the BIM application, the lot checklist also identifies the party responsible for each item. The spaces in the form that are marked as DGXXX are numbered and left blank for deviation results generated by comparing as-built construction data with as-designed data from the BIM model.

The product template consists of three parts: entity object, quality properties, and corresponding inspection criteria based on construction codes. Although a normal BIM can provide basic design and construction information, the information must be structurally organized and enriched to be detailed enough for effective decision making.

The quality properties include critical inspection criteria which play an important part in safety, health, environmental protection and public interests. Also included are common inspection criteria such as geometry size, mechanical properties, and construction methods. Quality control criteria are quantitative and qualitative indexes in construction codes that are integrated, categorized and standardized based on national, industrial and local quality control codes. There are clear deviation limits between design and construction.

4.1.2. Organization template

The contactor queries the BIM-based construction model to identify the work that needs inspection and then issues an inspection request. After confirmation of the inspection request, the project manager, contractor, superintendent, full-time quality inspector, and job foreman assigned to these activities are identified in the template. The quality inspector evaluates the quality level for the inspection report. Finally, the inspection lot must be accepted by the superintendent and relevant architect/engineers, so that the next construction procedure can begin. In the construction stage, accurate and efficient coordination between construction participants is needed. In order to implement quality management in the construction phase, when quality defects happen, the relevant person can be identified for responsibility by searching inspection lot records and engineering survey data.

4.1.3. Process template

In order to facilitate quality management processes with BIM, so that the inspection plan can be arranged and adjusted dynamically along with the actual construction process, scheduling information should be integrated with the 3D model. In addition, the construction process can be virtually presented in time sequence by attaching start and finish times to each construction activity. Fig. 4 shows the relationship between construction activities and construction products, and that construction activities are defined with sequential start and finish times. This provides the basis for logical analysis as uninspected products can be identified virtually to avoid the negligence so common on construction sites. For construction process control, inspection criteria are identified by order in the construction process. Then, the quality acceptance time is forecast according to the schedule for each control item in a construction period.

4.2. BIM-based construction quality model

A BIM-based construction quality model is constructed with combination of a POP model method and a BIM model, where the construction product from POP model is constructed to match the BIM component from BIM as shown in Fig. 5. Components in the BIM model are

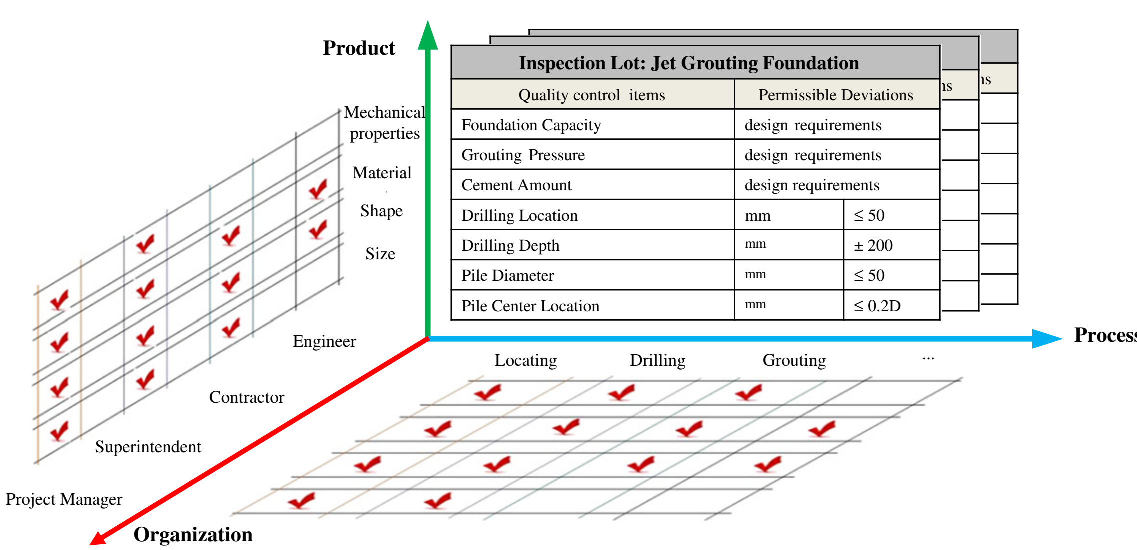
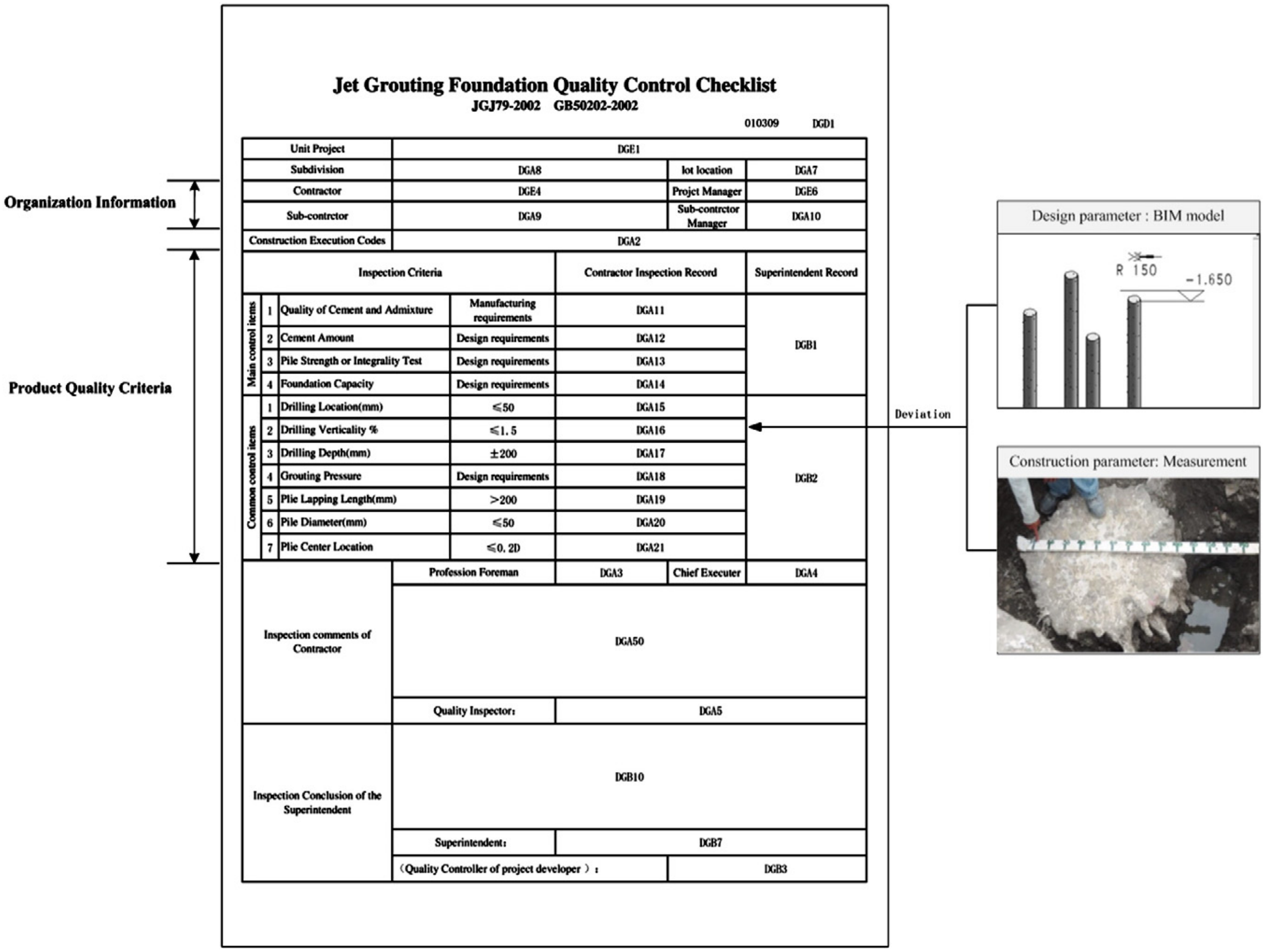


Fig. 2. Interrelationship of product, organization and process model for jet grouting foundation inspection lot.



Jet Grouting Foundation Quality Control Checklist

JGJ79-2002 GB50202-2002

010309 DGD1

Unit Project	DGE1			
Subdivision	DGA8		lot location	DGA7
Contractor	DGE4		Projct Manager	DGE6
Sub-contrctor	DGA9		Sub-contrctor Manager	DGA10
Construction Execution Codes	DGA2			
Inspection Criteria			Contractor Inspection Record	Superintendent Record
Main control items	1 Quality of Cement and Admixture	Manufacturing requirements	DGA11	DGB1
	2 Cement Amount	Design requirements	DGA12	
	3 Pile Strength or Integrality Test	Design requirements	DGA13	
	4 Foundation Capacity	Design requirements	DGA14	
Common control items	1 Drilling Location(mm)	≤50	DGA15	DGB2
	2 Drilling Verticality %	≤1.5	DGA16	
	3 Drilling Depth(mm)	±200	DGA17	
	4 Grouting Pressure	Design requirements	DGA18	
	5 Pile Lapping Length(mm)	>200	DGA19	
	6 Pile Diameter(mm)	≤50	DGA20	
	7 Pile Center Location	≤0.2D	DGA21	
Inspection comments of Contractor	Profession Foreman	DGA3	Chief Executer	DGA4
	DGA50			
	Quality Inspector:	DGA5		
Inspection Conclusion of the Superintendent	DGB10			
	Superintendent:	DGB7		
	(Quality Controller of project developer):		DGB3	

Fig. 3. Quality inspection checklist for jet grouting foundation.

reorganized into inspection lots that establish a correspondence between inspection lots and BIM elements. Considering the uniqueness of each engineering project, the rules for dividing inspection lots and the creation of the BIM model would be different for each project. Normally the parameters in a BIM only cover geometric attributes which is not enough information to connect the component to an inspection lot. Therefore, it is best to extend the quality attributes when creating and updating the model information with the construction method and material requirements that are usually specified in the design of overall instruction in a 2D design environment. Therefore, the BIM model must be created with significant quality attributes for each building element, such as material and construction method. So that the BIM elements

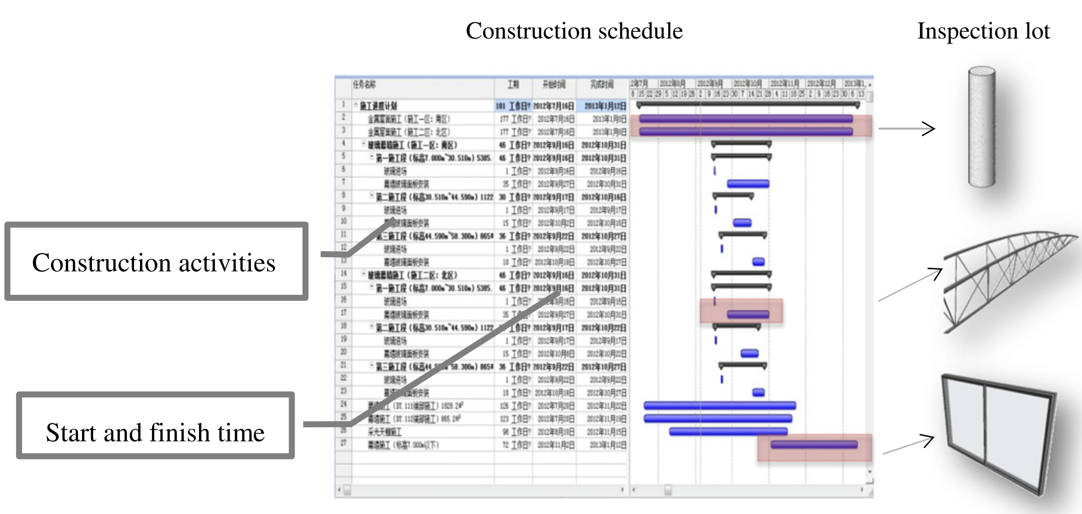


Fig. 4. Relationship between construction activities and BIM components.

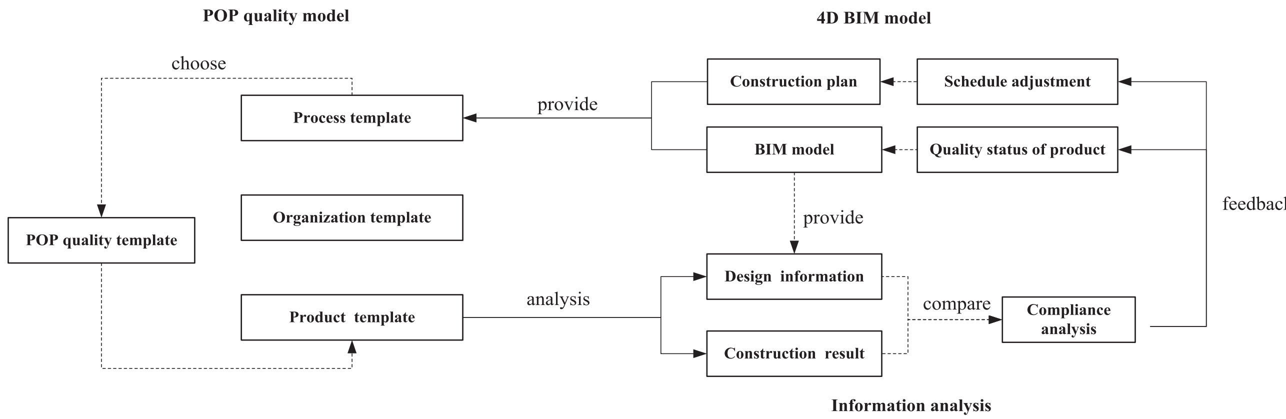


Fig. 5. Framework of BIM-based construction quality model.

can be identified and match with corresponding inspection lot. Take cast-in-place reinforced concrete beam as an example, with the information of material and construction method, the quality checklist for cast-in-place reinforced concrete is located and pulled out for use.

All quality control criteria are fully covered in a hierarchical information structure in the quality model that reflects both the dependency and interaction among relationships during the quality control process and between organizations. The model is computable and compatible with multimedia data applications (engineering drawings, photographs and images) to better present quality related information.

The framework and interrelationships are generally described in Fig. 5: (1) Choosing the appropriate product template for inspection according to the actual progress in the 4D BIM-based construction; (2) completing the template with on-site data required by the template; (3) analyzing of data integrity and deviation are carried out for compliance analysis; (4) providing quality inspection results for the 3D virtualized model feedback as well as the schedule adjustment required by the inspection results.

5. Workflow when using a BIM-based construction quality model

After the construction of a BIM-based construction quality model, the workflow order is developed, as shown in the flowchart in Fig. 6. The quality control process starts with the request for acceptance after the completion of an inspection lot for the last task completed but before the next one begins. Then the data collected from the construction site is inputted into the template for continuous and real time data integrity analysis, deviation analysis and compliance analysis. Finally, if the inspection lot passes the acceptance inspection, the project proceeds to the next task; if the inspection lot fails, a NCR report with corrective actions will be issued. After the corrective actions are completed, the whole process will cycle again. The result is visually displayed in the BIM for enhanced readability and ease of use for quality managers. Because data input is from the BIM-based quality model and shared among construction participants throughout the construction process, the need to repeat the input of data in different forms for data analysis, data sharing and communication is greatly reduced.

The information collected onsite is also entered into the BIM-based quality model and processed. Quality analysis is illustrated along with construction progress, as follows:

(1) Logic analysis. The construction quality inspection process in the BIM quality model is nested in successive stages according to the sequence of construction in the same construction set. Each sub-unit inspection must be completed before proceeding to the next unit. The first level of acceptance testing is at the inspection lot level and each entry is completed by personnel with the necessary professional background and responsibility.
(2) Integrity analysis. Data integrity is maintained because the BIM quality model verifies input data with established data validity rules to prevent input errors. The data validity rules contain reasonable data expectations and will cause the model to reject wrong data or not to continue until the data is complete.
(3) Deviation analysis. The actual quality control data is compared with the design data in this process. The BIM-based application

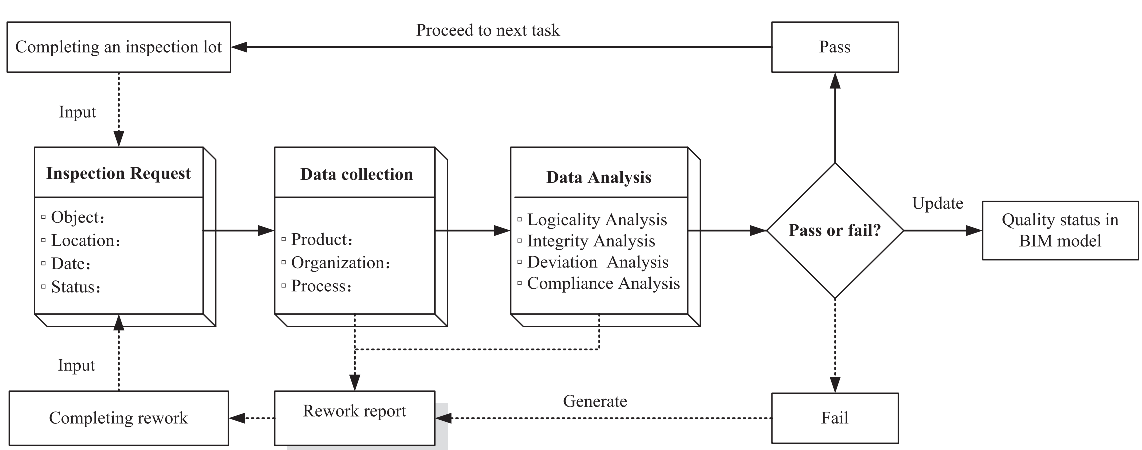


Fig. 6. Workflow of BIM-based construction quality model.

Table 1
Color metaphor of quality status in BIM-based quality model.

Quality state		Color coded metaphor
Before inspection	Before construction	
	Under construction	
	After construction	
After inspection	Failed	
	Passed	

contains the design and construction parameters and official construction codes as reference data. The BIM-based quality model compares the actual quality testing data to these standards. The BIM-based application displays value deviations and the degree of deviation by using different warning symbols (triangle, circle, etc.) so unacceptable inspection results are obvious. For example, the location of the grouting foundation should deviate less than 1.5% from the design parameter based on construction codes.

(4) Compliance analysis. The BIM-based quality model provides management for the whole construction project quality process in a multi-level acceptance sequence. The model provides analysis for every quality control item and displays whether the actual quality testing results meet the requirement of corresponding codes in the quality model. Take interior decoration as an example, eligibility criteria of inspection lot is listed as follow: 1) Each dominant item should be quality tested by sampling inspection; 2) general items should each be qualified by sampling inspection, during the counting inspection. Allowable defect items are less than 80% of total samples and the maximum deviation must be no more than 1.5 times the permissible deviation; 3) quality inspection records must be completed during construction operations. The lot will be accepted if the selected samples meet the system defined requirements.

(5) Quality status feedback. As schedule information is integrated in the model, a status for the construction product is defined as: before construction or under construction before inspection. After the inspection is performed, the results are displayed in the model with color metaphors and NCRs or rework orders are generated if necessary. The 3D BIM describes quality status in different colors as shown in Table 1. When the lot is accepted, the next procedure can start; if the lot fails an inspection, the lot will be marked red and then a nonconformance report that states the violation of codes that fail to deliver the consistency of design intent and construction results will be issued for corrective action.

6. Implementation

Wuhan International Exhibition Center is the largest facility of this type in the Midwest China and the third largest exhibition venue nationally with an exhibition area of 130,000 m^2. The total cost for this project was approximately 3 billion dollars. The exhibition venue has 12 single halls which are designed without columns. Due to the large investment, tight schedule, complexity of construction and large amount of participants, the project quality had to be closely scrutinized and strictly controlled according to relevant construction codes throughout the construction phase to prevent the value of the end product from being compromised and off schedule.

The proposed BIM-based quality model of this paper was applied to the construction process for the foundation of work. After one month of high pressure jet grouting foundation work, 156 jet grouting piles were completed in accordance with the schedule as shown in Fig. 7. The contractor requested inspection since 28 days of completion according to the code for acceptance of construction quality of building foundations (GB50202-2009).

When the inspection request for specific objects in the model was accepted, the corresponding checklist template for high pressure jet grouting foundation was identified based on the information about construction method and material from BIM model. The professional quality inspector completes the checklist with the organization information and inspection data obtained from the construction site. Then, site data was analyzed, and compared with the design parameters in the BIM-based quality model. Any data with a deviation beyond tolerated variance will be identified and marked with symbols. Then an acceptance rate for each row of quality control items in the checklist will be generated and compared with the codes, as shown in Fig. 8. The template in Chinese in English refers to the same template in Fig. 3. Finally, the decision is made whether the inspection results are in accordance with construction codes, then reflected in 3D model. The next construction activities in this area may proceed, if the lots are accepted. Otherwise, the lots that failed inspection would be displayed in red, and a nonconformance report or rework order will be issue to provide the

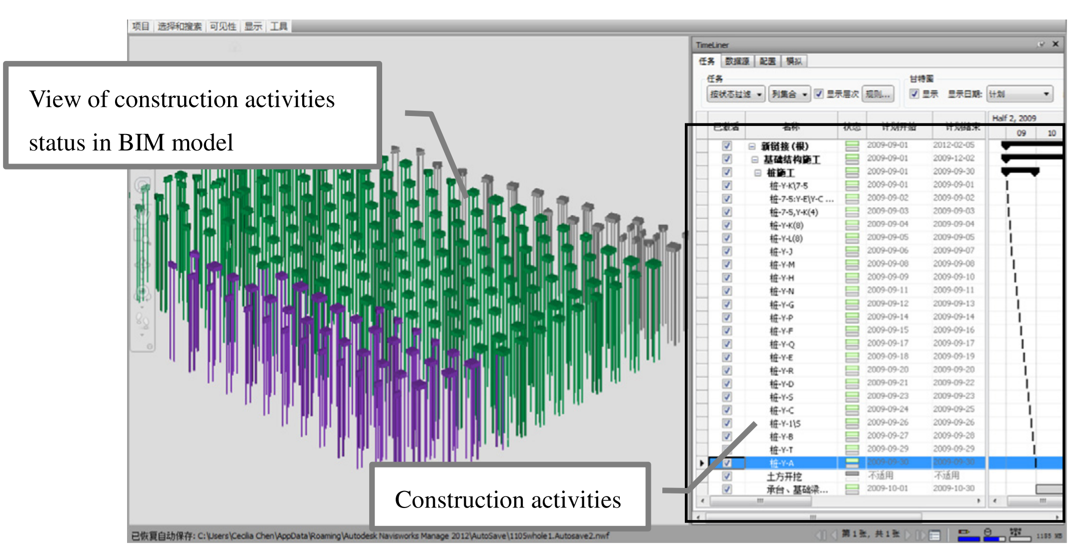


Fig. 7. Color-coded inspection lot of high-pressure jet grouting foundation and corresponding time schedule in BIM.

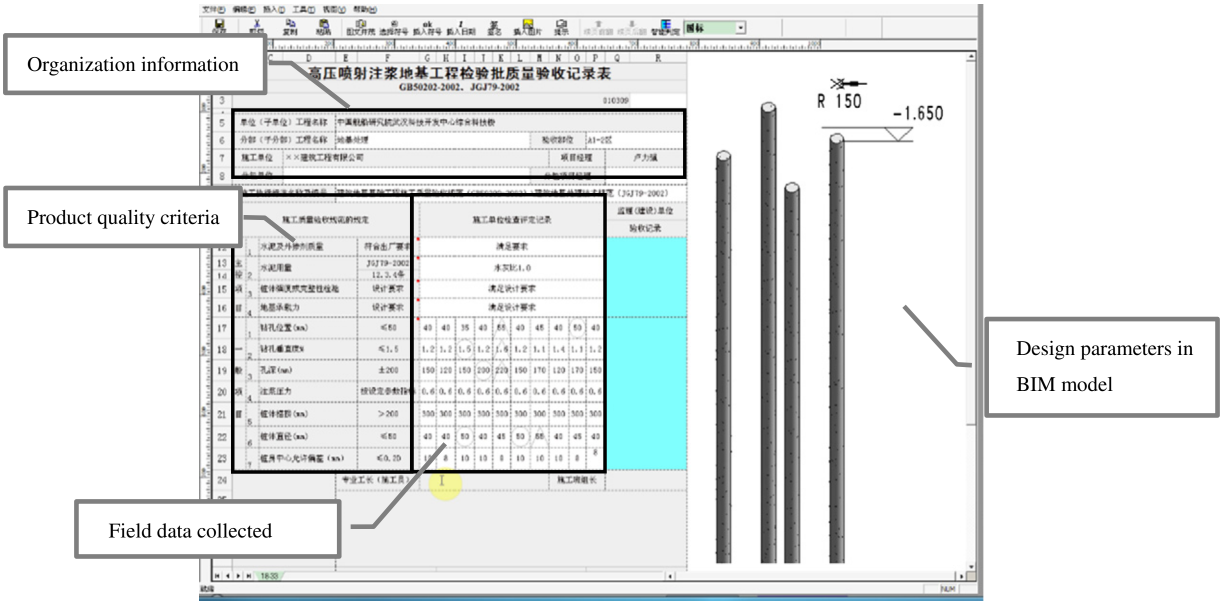


Fig. 8. Quality data analysis screenshot of high pressure jet grouting foundation inspection lot.

basic information of lots, description of violation in material, workmanship or procedure as well as plans for corrective action as is shown in Fig. 9. The coding method of blank space in the rework order in Fig. 9 is consistent with the original checklist in Fig. 2. Then, the result of the corrective action is reviewed and approval is given to proceed with successive activities.

In this way, design information in the BIM is fully utilized in data analysis and report generation. The field photos and model images are attached in the report to better illustrate the defects and the new schedule is defined. Therefore, the BIM-based construction quality model is effective and reliable for participants to understand problems of the quality defects or non-conforming works and track the corrective action. This is especially important for concealed works before it is concealed. There was a case on the project which was not covered in this research. The internal structures of the support columns were completed and proceeded to the external formwork without completing the required quality inspection. When the consultant discovered that the formwork was completed, he filed to suspend work and remove the formwork. Utilizing a BIM quality model prevents such mistakes or negligence because tasks are arranged in time sequence and the uninspected zone is flagged in green for easy identification.

7. Conclusions and recommendations

The presented findings contribute to the understanding of the potential use of BIM in construction quality management and fill an existing gap in the knowledge on the use of BIM for construction quality management. This paper explored the implementation of BIM in quality management and proposed integrated solutions to improve current quality management processes with assistance of a BIM working environment. A BIM-based quality model has been proposed to combine BIM and the existing quality POP model. Also this paper discusses how these two models will work together to facilitate construction quality management. It helps the project participants to better understand the quality progress and to collaborate more effectively thanks to a visualized data format.

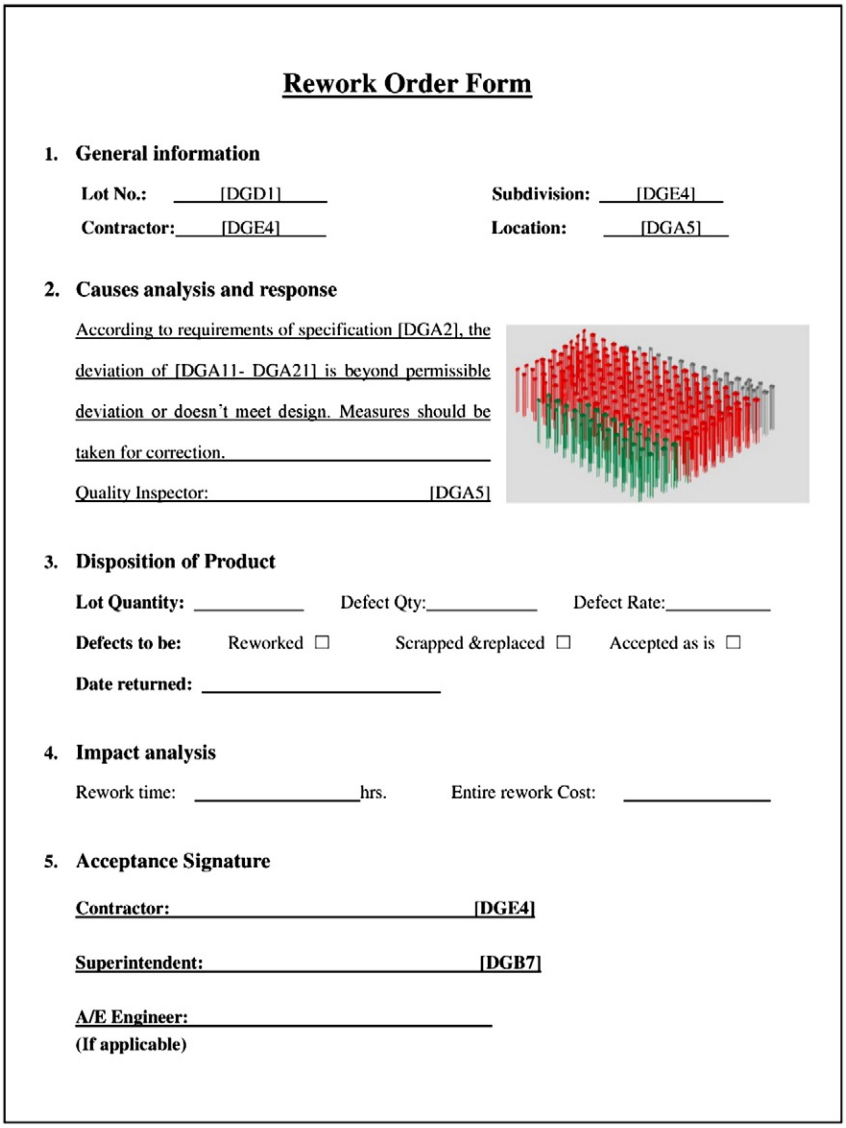
The key benefits of the construction quality model proposed in this paper lie in the following aspects: First, the utilization of design information ensures information consistency and facilitates quality management process. Second, the fully standardized and structured construction codes are integrated in the model to provide clear construction task requirements for instruction and verification. Typical errors caused by misunderstanding of cross-reference codes can be avoided. Third, 4D application ensures the timely inspection and virtualization of the whole process, which helps the project participants to better understand the quality requirements acceptance, and to collaborate in a visualized manner.

It can be concluded that the BIM-based construction quality application is suitable and helpful in quality compliance management. First, due to data consistency, it is possible and feasible to apply BIM for quality management and to fully utilize design information through virtualization of the construction process. Second, BIM can be fit into the current industry standard practices in quality management and validated through a case study. Although quantitative results are not given due to the limitation of this research project, comparisons are made between BIM-based and non BIM-based projects. Traditional quality management failed to dynamically interact with scattered design drawings and the quality management process. In this case study, with the application of BIM-based construction quality model, the information is accumulated and abstracted from the same data source to fully coordinate and communicate between the design and the construction phase. As complete construction requirements are clarified in a 3D format for better understanding, the project was delivered on time related to foundation works.

However, the BIM-based quality model does have the following limitations: (1) A BIM model developed for design purposes does not contain temporary structures, such as external formwork, and scaffolding. Therefore, temporary structures must be added to the original BIM design-oriented model. (2) The use of computers onsite is not convenient at this time with the proposed method and mobile devices should be used in the future for improvement in recording field data and direct data transfer to BIM.

Acknowledgments

We would like to express our gratitude to Wuhan New City International Expo Center Co. Ltd. as well as to site engineers in our research group for their contributions to this research project.



Rework Order Form

1. General information

Lot No.: [DGD1] **Subdivision:** [DGE4]

Contractor: [DGE4] **Location:** [DGA5]

2. Causes analysis and response

According to requirements of specification [DGA2], the deviation of [DGA11- DGA21] is beyond permissible deviation or doesn't meet design. Measures should be taken for correction.

Quality Inspector: [DGA5]

3. Disposition of Product

Lot Quantity: ____ Defect Qty:____ Defect Rate:____

Defects to be: Reworked ☐ Scrapped &replaced ☐ Accepted as is ☐

Date returned: ____

4. Impact analysis

Rework time: ____hrs. Entire rework Cost: ____

5. Acceptance Signature

Contractor: [DGE4]

Superintendent: [DGB7]

A/E Engineer: ____
(If applicable)

Fig. 9. BIM-based construction quality model.

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