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A 6D BIM INTEGRATED DATA MANAGEMENT SYSTEM IN CONTROLLING CONSTRUCTION QUALITY THROUGHOUT PROJECT LIFE CYCLE

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Abstract

The implementation of Building Information Modeling (BIM) in quality management (QM) is critical for improving project efficiency and reducing reworks. However, the current applications of BIM in QM are primarily limited to the design stage. This study proposes a 6D BIM integrated lifecycle QM framework that provides retroactive data management throughout the project lifecycle. The integrated platform includes three components: infrastructure as a service (IaaS) for storing hybrid databases with physical and virtual data, platform as a service (PaaS) for providing BIM data and model interfaces, and software as a service (SaaS) for data-model management with BIM API and applications.

Introduction

Building Information Modelling (BIM) is a technology that has revolutionized the Architecture, Engineering, and Construction (AEC) industry by providing a digital representation of constructed facilities. BIM is crucial in sharing and processing construction project information and assists stakeholders make efficient decisions, by integrating all elements and creating progress timelines, visualizing information updates, and documenting quality data. BIM plays a critical role in managing a project, including design, process, cost, and quality. Quality defect is a significant concern in the AEC industry, as it can lead to substantial costs and project delays (Kim et al., 2019). Studies have shown that quality defects can account for up to 4% of the contract value for new residential construction (Mills et al., 2009). Moreover, the direct and indirect costs of defects can add up to 2-6% of the project cost (Josephson and Hammarlund, 1999). The negative impact of construction defects on project costs and schedules has been addressed in several academic studies. BIM for QM was proven to be effective in infrastructure (Lee et al., 2014) and facility construction (Chong et al., 2014), as well as for corrective maintenance (Shalabi et al., 2017). The implementation of BIM was crucial in managing data, by applying BIM technology to quality inspection and defect management, recognizing the significant issues in construction defect management, including protracted procedures, data entry redundancies, confusion, and inefficient information management (Lin et al., 2016).

In general, academic research reveals that in addition to representing the geometric model, BIM also integrates different information during different phases of the project life cycle. Practical approaches that apply BIM technology to quality inspection and defect management have been reviewed. However, the question of how to establish a more robust link between BIM and quality control across the entire project life cycle remains unresolved. The necessary effort is needed to explore strategies for enhancing the practical application of BIM and optimizing its potential benefits for quality control and other aspects of construction QM.

Research methodologies and objectives

This research is conducted in three stages. The first stage involves a literature review. Relevant studies on BIM and data management in the AEC industry were analyzed. The review identified a research gap regarding the implementation of BIM in QM in the entire process management cycle. This stage provides a foundation for further investigation of BIM in QM and serves as a guide for the following two stages. The second stage introduced a data collection strategy, raw quality data was obtained from the on-site records and checked according to quality inspection standards. A quality checklist was proposed as the foundation for evaluating quality performance. The third stage is the establishment of the integrated BIM QM system, which proposes a solution to resolve the research gap and outlines the future benefits for the construction industry.

The main objectives of this study are threefold. Firstly, to provide a justification for the current gaps and opportunities of BIM implementation in QM in the AEC industries and to suggest the possible implications of BIM practices in construction projects. Secondly, to propose an integrated conceptual framework that aims to enhance the overall construction performance throughout the project process, and to validate its efficiency through the application. Lastly, to provide guidance for AEC industries to implement the proposed framework systematically.

Literature review

BIM has been recognized as the pioneering technology that visualizes and outputs the digital demonstration of construction projects, it rotates the project design, deliverables, and management of projects (Eastman et al., 2008). The definition of BIM is diversified in terms of concepts and usages. In this study, a definition proposed in RIBA BIM Overlay Report (2012) was applied,

“BIM is a digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition.”

Different dimensions of BIM are concomitant with the specific applications, including the physical meaning, the achievements in cost, time and energy, maintenance, and sustainability. The BIM model is capable of integrating all the elements of a project and helps designers and managers to make decisions more accurately by creating process timelines, visualizing information updates, and documenting quality and quantity data in each stage of the project (Porier et al., 2015). The implications of BIM and parametric design on contemporary architectural practices have been invested with the associated changes in roles and responsibilities (Holzer, 2015). The opportunities of utilizing BIM technology in the design stage of prefabrication construction from the perspective of designers were explored, which increases efficiency (Wang et al., 2022). Challenges were also identified in BIM implementation in contract and legal barriers, cultural problems, management systems, and economic and security issues. (Musa et al., 2018**).**

As discussed in the introduction section, quality defects are crucial to project performance and can result from internal or external failures (Rose, 2005). Internal failures occur before products are delivered to customers, while external failures happen after delivery. One common issue in construction QM is the inefficiency of traditional data management practices, which can be improved by applying BIM technology to quality inspection and defect management. The use of BIM models has been shown to improve construction productivity by facilitating accurate decision-making and data management. These studies also propose using BIM along with other technologies such as image-matching and augmented reality (Kwon et al., 2014) to develop defect management systems. These systems include image-matching systems for remote quality inspection and mobile apps for automatic error detection. The possibility of collaborative BIM was discussed in the extension of a construction quality database's interoperability in the evaluation process using the industry foundation classes (IFC) data model (Xu et al., 2018). However, the majority of the discussions are about QM in the design and plan phases, and there is a lack of applying QM strategies throughout the project lifecycle. In this research, a specialized BIM model with cloud data management is proposed as an effective framework for QM during different phases of the project life cycle.

Quality data collection

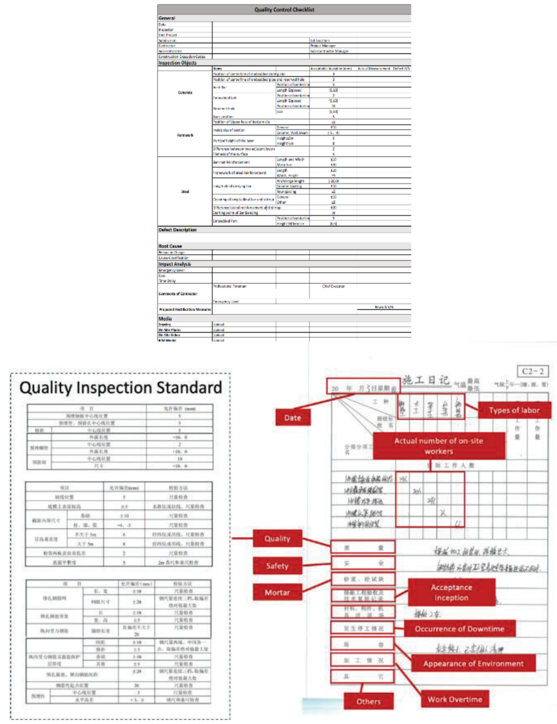

Figure 1: Example figure layout

This section proposed the methodology for collecting and assessing the onsite quality data and formulated the quality control checklist (QCC), based on the quality data collected from the site diary and quality inspection standards, the major structural quality standard is ‘Code for acceptance of the constructional quality of concrete structures’ (Figure 1). The QCC provides a systematic and credible guardian against poor records. Furthermore, the contents of the quality checklist can be digitalized with the BIM quality control framework as proposed in the following section. The entities of QCC are subdivided into six parts, which are summarized in Table 1:

Table 1: Categories of quality information

Information Category	Description
General Information	The project relevant information such as the date, quality inspector, unit project, lot location, and the person in charge (contractor, sub-contractor, project manager, etc.). The execution code is also included, and this information is based on the project schedule and can be formalized following the integrated project information.
Inspection Objects	Three main parts of the construction project are inspected, including concrete, formwork, and steel. Each part has separate criteria that follow the code, and the inspector records the actual measurement every day

	and evaluates whether there is a defect or not.
Defect Description	The defect description explains the detailed information of the defects checked by inspection on the specific date, which describes the comprehensive circumstances or condition of the defect, such as the location and corresponding details.
Root Cause	In order to define how the defects form, as well as who should be responsible for the defects, this part analyzes the detailed information of the causes. For example, it can be explained that 'the concrete leakage resulted from the inadequate joint sealing.
Impact Analysis	Impact analysis includes the emergency level, which indicates whether the defects are urgent to be resolved, and the priority sequence when there are multiple defects. It also estimates the cost and time delay for the defect, which is based on the emergency level and defect type. The contractor can also provide efficient advice, and their comments are included in this section.

The QCC serves as a standard for quality control based on BIM throughout the project life cycle. It not only captures daily defect information but also provides a retrospective platform for on-site workers, contractors, quality managers, clients, and other relevant parties to share real-time information, review content, provide feedback, claim responsibility, and track the rework process. It is important to note that the content should be formalized to simplify its use through mobile devices. For example, general information can be pre-filled for a specific sub-project, and templates for root causes and impact analysis can be pre-input into the cloud for extraction and recording. Refinement in recording would enhance the implementation of QCC in the construction industry. By analyzing the frequency of quality issues and their root causes, it is possible to identify weak areas in construction quality. This information can be used to focus on specific aspects and conduct quality control throughout the entire project process.

The proposed integrated framework for lifecycle QM

Database services in AEC industries

Database management system is a fundamental tool that plays a vital role in various fields for the collection and analysis of large volumes of data (Yin and Kaynak, 2015). Xu et al. (2018) emphasize the significance of developing a collaborative database platform by integrating, visualizing, and formatting precise project information in the AEC industries. Effective data collection and processing are critical factors for improving project performance. Three types of database services are commonly utilized in construction database management, namely software as a service (SaaS), platform as a service (PaaS), and infrastructure as a service (IaaS) (Mahmood, 2011). The three services differ in the content they provide. SaaS offers third-party services and applications to customers for use or rent via the network, including traditional computers and Tablet PC. Examples of typical software are Autodesk BIM 360, Tekla BIMsight, Revit, and Navisworks. PaaS provides cloud platforms for users to execute integrated programs, create, develop, and test their applications, which reduces maintenance and purchasing expenses on middleware servers. Examples of typical PaaS services are Windows Azure, Heroku, Force.com, Google App Engine, and Apache Stratos. IaaS offers cloud service providers or customers-only hardware, including storage service, data virtualization, and capacity processing. Typical examples of IaaS providers are DigitalOcean, Linode, Cisco Metapod, Microsoft Azure, and Google.

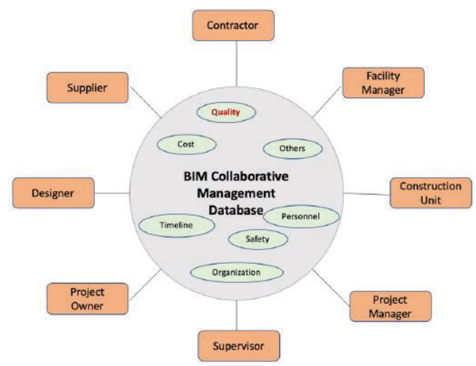

Figure 2: Construction quality information flow

BIM collaborative management database (BCMD) is introduced as a solution to incorporate project information related to cost, quality, timeline, safety, personnel, and other aspects (Figure 2). It provides an accessible channel for various stakeholders, including designers, suppliers, contractors, facility managers, construction units, project managers, supervisors, and project owners to establish standards, share information, and control the project.

The BCMD enables mass data storage, fast speed of look-up, control of concurrent-access anomalies, data safety, and integrity, resulting in time and cost savings. Moreover, the system remains operational throughout the project lifecycle. For instance, quality data can be input and stored, and feedback can be provided from quality inspection, control to assurance, conveying information in a specific sequence. Additionally, the database from the entire process can be shared with the stakeholders.

6D BIM system

The utilization of BIM technology in project management has undergone significant evolution, from the initial 3D visualization to comprehensive data management throughout all project stages, including planning, design, construction, operation, and maintenance (Eastman et al., 2011; Edirisinghe et al., 2017). The consistency of data over the entire project life cycle and the convenience for users to capture the required information from the visualized model have presented BIM as a potent tool for presenting multidimensional data, such as cost, progress, and digital asset management. 6D BIM is a project lifecycle model that is made up of all attributes related to projects to optimize project performance, including information such as data on maintenance, energy, and sustainability (Edirisinghe et al., 2017). This integration is achieved through data collection and sharing processes, which enable the application of 6D BIM in construction management. Integration of models and data can be carried out using various tools, techniques, and software available in the market on mobile and PC platforms. For instance, cost analysis can be conducted through quantity surveys, installation surveys, and valuation. Program planning can be scheduled using software such as MS Project and Zebra Progress, while the project's digital assets can be presented using a component library, technology, and construction methods library, cost quota, and construction performance.

To visualize the data and 3D models, software such as Revit, AutoCAD, Navisworks, and SketchUp can be employed. The combination of Revit and Navisworks is widely accepted by the construction industry for modeling and testing buildings, hydroelectricity, and High Voltage Alternating Current systems. These software tools offer clash detection, graphic model integration, and material quantity survey capabilities, among others. Information management is vital for promoting the transformation and upgrading of the construction industry, and BIM technology is the key means of achieving this.

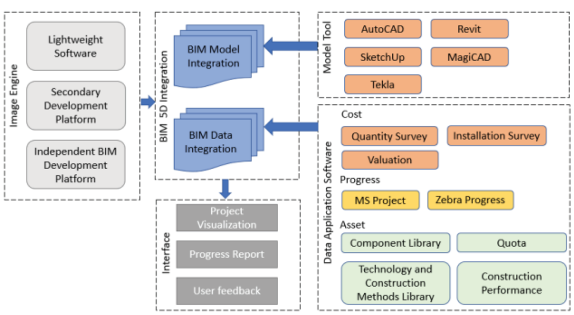

Figure 3: Example figure layout

The current visualization of BIM models primarily relies on three types of image engines (Figure 3). Firstly, the lightweight software is designed to facilitate simple and quick modeling tasks. This software has low system requirements and can be easily installed on most computers. It is typically used for basic 3D modeling and visualization, making it an ideal option for small-scale projects or users with limited experience in BIM software. Secondly, the secondary development platform is a BIM image engine that provides advanced customization capabilities, allowing developers to create custom tools, interfaces, and workflows on top of the BIM software. This platform requires programming knowledge and is typically used for large-scale projects that require complex modeling and data management. Thirdly, the independent BIM development platform is a fully customizable and extensible BIM image engine that provides complete control over the software's functionality. It allows developers to create their own BIM software from scratch or modify existing open-source BIM software.

This study proposes 6D BIM with a focus on quality retroactive management. Information management is vital for promoting the transformation and upgrading of the construction industry, and BIM technology is the key means of achieving this. By systematically exchanging and processing the quality data, BIM technology is not only an application point of the project but also a quality information platform plus a management mode that serves as an integration platform.

The progress report is recorded by onsite workers and handed to the management level. User feedback from involved parties in different phases is presented in the model. The information process is vital for promoting the transformation and upgrading of the construction industry, and BIM technology is the key means of achieving this. By systematically exchanging and processing quality data, BIM technology serves as application point of the project and quality information platform with management mode.

Quality data management

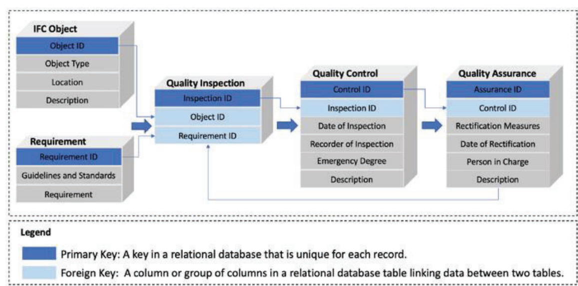

Figure 4: Construction quality information flow

This section explains the mechanism for transmitting quality information. From a basic quality inspection (QI) conducted on on-site activities, quality control (QC) on products and quality assurance (QA) that incorporates process control, the current QM system is matured into a comprehensive and retroactive management system that aims to improve well-round quality throughout project whole processes at the company or organizational level (Mangelsdorf, 1999). This study proposed a retroactive process based on the comprehensive QM system to manage quality data, aiming at increasing project efficiency and minimizing quality defects. The process of quality information transmission is depicted in Figure 4.

The first stage involves defining the objects to be inspected, analyzing potential problems, and determining possible response measures. To simplify the data collection process for recorders and improve efficiency and accuracy, a standardized pre-record format is provided for quality managers to input data. Object information, consisting of object location, type, and description, is combined with a list of conditional requirements to form two datasets with two primary keys: requirement ID and object ID. In the QM process, the primary keys are the unique data record, such as object and quality requirement, that are used to establish relationships between two datasets in the QM procedures, it ensures the integrity and consistency of the processes. The foreign keys refer to the primary key collected in the previous procedure, allowing data to be retrieved and linked.

After the QI data is summarized as Inspection ID, these datasets are then transferred to the QC system as foreign keys. In a relational database, a primary key is a column or set of columns that uniquely identifies each row in a table. It is a constraint that enforces data integrity, meaning that the values in the primary key column(s) must be unique and not null. Primary keys are used to establish relationships between tables in the database.

The QC system is the central component of the QM system, providing the means to monitor and control construction project quality from start to finish. It also links inspection results with other information, including inspection date, inspector and recorder information, quality defect emergency level, and defect description. The QC system creates a platform for communication and information sharing among involved parties. The QC system's output must be organized in a methodical manner associated with the set of quality information, ensuring participants' synchronized information acquisition and enhancing information processing timeliness and accuracy. The results of the QC system are identified as Control ID and transferred to the QA system for further processing.

The QA system integrates the output from the QC system with feedback and proposes rectification measures, including the date of rectification, the person in charge, and the final description. The feedback mechanism continuously checks and adjusts project quality conditions with timely responses. This ensures that any improvements are rechecked in the quality information system to minimize cost loss and time delay. The system manipulates QC data to enable storage, access, and retrieval when necessary, extending the useful life of the information and providing future advantages. The transfer flow of quality data can be used to evaluate the frequency, location, and types of quality defects. Table 1 provides an explanation of the five main sets of data: Object ID, Requirement ID, Inspection ID, Control ID, and Assurance ID.

Table 2: The primary keys and foreign keys description

Key	Description
Object ID	The contents for specific objects are imported in advance in the database, including data on the location, type, and description. The pre-defined table will be easy for retrieving and extracting.
Requirement ID	Following the 'Code for acceptance of the constructional quality of concrete structures', the requirements for formwork, concrete, and steel are made on the acceptable range for the elevation, length, size, etc.
Inspection ID	The inspected object and the associated requirement are combined in this stage for daily inspection.
Control ID	Based on the information collected in the inspection stage, QC combines the inspection data with the relevant control parameters such as data, recorder, defects emergency level, and description. It should be mentioned that the quality checklist will be used in quality control to generate a comprehensive list of daily control data.
Assurance ID	Collected QC data and corresponding feedback are combined in this stage.

After the quality information is captured by the QA system, the results are transmitted and presented in a user-friendly format at the interface.

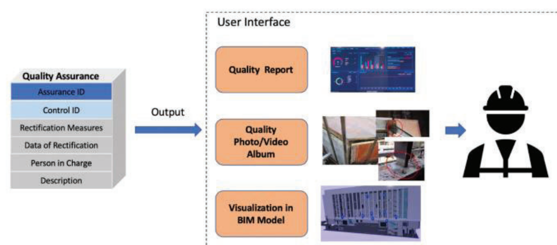

Figure 5: User interface

This interface integrates previously-stored QI and QA data with proposed feedback from quality managers and clients and includes a quality report, quality photo/video album, and visualization in the BIM model, which is easy to read and understand for the users (Figure 5). It is worth noting that the emergency degree collected in the QC system can be considered an important index for the users to make suggestions. Furthermore, the QA system allows users to input information to describe the quality defect and share it with other participants in an interactive manner. This system also allows for long-term analysis of overall project improvement, including manufacturing techniques, materials, and ineffective processes, which can provide guidance for future projects with similar patterns.

The current study proposes a QM process that enables effective management of quality from both a spatial and continuous improvement perspective. It is important to note that the success of this process depends on the collaboration of all involved parties (Arditi and

Gunaydin, 1997), who need to be integrated into a communication and information-sharing platform to facilitate effective coordination. In the event of a quality defect, the inspector on site should record detailed information using a Quality Control Checklist. The quality manager then takes charge of mitigating the quality problems and minimizing the adverse impacts of cost and time delay. Based on the remedial strategies provided by the quality manager, the contractor is responsible for executing the rework and remedial process, ensuring that the strategies align with the owner's requirements. Finally, the quality report, including re-check conditions, rework reports, and relevant onsite photos or videos, is collected and presented to the contractor and/or supervisor, who provide feedback to complete the QM process.

BIM collaborative data management system

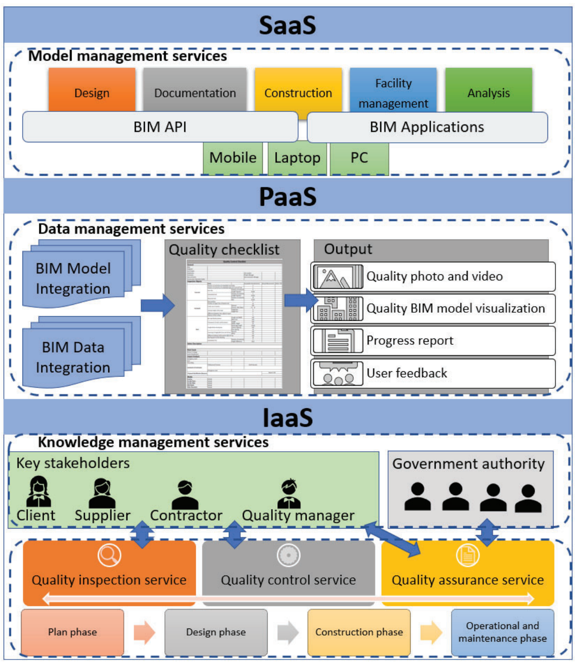

Figure 6: Integrated data management system

As a strategy to manage the BIM information in the database, an integrated system was proposed with three levels of categories (Figure 6).

(1) IaaS

IaaS module provides server space, networking, data storage, retrieval, and the capability to run multiple operating systems, covering the information from projects plan, design, construction, to operational and maintenance (O&M) phases. By utilizing private and public hybrid databases to store physical and virtual information, this module enables the virtualized BIM model to be presented via the internet, giving the stakeholders, such as clients, suppliers, contractors, quality managers, and government authorities direct control over the operating system. In the QM process, quality defects can be traced and visualized.

(2) PaaS

Data management services are realized at the PaaS layer and are the core concept of controlling and managing project quality. BIM integrates models with corresponding data to optimize performance in construction by adjusting ahead of starting construction, trimming cost and waste, detecting conflicts, and anticipating construction possibilities throughout the project lifecycle. QCC is applied to check the model and data compliance to identify the quality defects, and the user interface will be presented with quality on-site photos and videos, model visualization, progress report, and user feedback.

(3) SaaS

The model management services are in the SaaS layer, and it offers web-based BIM applications for processing project parameters in the design, documentation, construction, facility management, and analysis. Users are able to obtain collaborative information on projects, and designs, then make adjustments correspondingly. SaaS minimizes the possibility of errors and clashes by providing host applications available on the internet and accessible by mobile devices, laptops, or PCs. For example, users can view specific model objects on construction sites in the application with relevant material and program information. The SaaS module also provides a source for project managers to refer to the location and elements of a specific defect.

Discussions

The QM process is implemented with a record of the quality checklist, ensuring that the QC process is effective and efficient. The project owner's primary responsibility is in the operational and maintenance stages, where controlling quality has been achieved, and QA is in progress. Data accumulated from the QC stage is collected in a database, including quality photos and videos, defect visualization in BIM, remedy measures, and rework reports. The project owner can provide feedback on the results based on this data. It is essential to note that quality audits, supervised by relevant government authorities, are conducted regularly, usually twice or once a month, to assess the ongoing condition of project construction quality. However, there are challenges in making BIM models useful for building operations, including the need for significant model adjustments that can be costly and time-consuming. Researchers have also identified quality issues in BIM projects and have categorized them according to different perspectives, involving drawn-out processes, redundant data entry, confusion, and poor information management (Lin et al., 2016), the potential reasons include inefficient or outdated processes, lack of proper training and documentation, and inadequate technology systems.

Therefore, to construct a solid pillar in managing project quality throughout the lifecycle, the proposed conceptual framework must meet the following three requirements:

(1) Comprehensive coverage of information: The framework must have comprehensive coverage of

information, including the BIM model, material types, code and provisions for all construction materials, and project progress. This strengthens the logic flow for managing quality by retrieving and extracting information in an efficient and convenient manner. The database should be accessible to users during the whole process of the project since the QM system integrates the design phase, construction phase, and operational and maintenance phase.

(2) Dynamic data input and processing: The QCC must be compatible with the real-time update of the project condition, usually recorded once per day. After the data is collected in the checklist, the user interfaces of BIM are updated with relevant information, such as location, type, and description. This integration between the BIM model and data updating ensures the quality defects are monitored and controlled with project progress simultaneously, thereby reducing potential problems that result from the postponement of information and concurrency problems from the original defects.

(3) Defined responsibilities of participants: It is essential for the key stakeholders to understand their roles and responsibilities. Architects and engineers are responsible for providing recommendations and guidance during the design phase, which aligns with quality inspection. As such, they must conduct a thorough analysis of where, when, and how to examine quality performance, while also providing the necessary tools such as 6D BIM models, quality checklist templates, and mobile applications to facilitate the inspection process. This stage also entails establishing the sequence, emergency standards, and designated personnel responsible for quality inspection.

Conclusion

Although quality defects are unavoidable due to design, manual, and operational errors, systematic data management could be improved by 6D BIM in model visualization and lifecycle management.

This research proposed an integrated framework of 6D BIM technology in a retroactive QM system. The research methodology was first introduced, and the research sequence follows specific theoretical to practical processes. A quality checklist was then introduced to identify the standard that the quality is compatible with. Lastly. the system is developed in three stages: BIM collaborative management database is the technique to store and share information, quality data workflow depicts the information transmission process, and the integrated framework with IaaS, PaaS, and SaaS is established to provide model management services, data management services, and knowledge management services to stakeholders. The system enables the analysis of the frequency of quality defects and facilitates the implementation of corrective measures to address similar quality defects. In addition, by transmitting the information through QI, QC, and QA processes, the cyclic information processing loop manages the quality information, and provides feedback in the design phase, construction phase, and O&M phase.

BIM plays a critical role in optimizing design, ensuring sufficient data management, and providing an information exchange platform to improve project performance. The systematic collection, analysis, and retroactive feedback of data enable the visualization, control, and management of quality defects throughout the project lifecycle. The proposed framework not only amplifies the management abilities of all participants but also stores the data for future projects with similar patterns, thereby enhancing the overall efficiency of the construction industry

Despite the potential benefits of the proposed framework, limitations still exist in its validation, and further research is necessary to explore its application and data management workflow. Future research may also investigate the potential applications of BIM and databases in the construction industry, including safety, cost, project productivity, and other emerging technologies such as Virtual Reality, Augmented Reality, Geographic Information Systems, Robotics, drones, and others. In summary, this research highlights the critical role of BIM in promoting systematic data management and improving project performance in the construction industry.

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