BIM-based Construction Quality Control: A BIM-QRC-ACQCR Framework Development (Part - I)

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Abstract
The construction industry is becoming more technologically advanced daily, and digitalization and automation strategies are playing a significant role. Accuracy, efficiency, and reliability are essential for a successful construction project. Throughout the project, various quality control onsite and offsite laboratory tests and inspections are conducted to ensure the highest standards are maintained. These reports and responses are kept as records, which can pile up and span volumes over time, making it challenging to handle and store all the reports. This research was conducted to introduce automation in the construction process via BIM. The completed work is presented in two parts: Part 1 focuses on developing the research aim, objectives, and framework, whereas Part 2 focuses on developing and implementing the system based on the framework, case study, and feedback. This specific paper aims to create a framework for introducing digitalization and automation processes in construction quality control information sharing and storing. This will make the whole reporting, recording, and visualization process effective and efficient, saving time and cost. Integrating BIM and Automation in construction quality control proposes a new and practical approach. Implementing this framework will increase the transparency and validity of quality control and its documented information.

Keywords
Building Information Modeling (BIM), Automation, Quality Assurance (QA), Quality Control (QC), Construction Industry.

1. Introduction

The construction industry contributes significantly to a country's GDP but lacks quality standards and poor quality control (Bakar et al., 2011). It is an information-intensive industry as a massive amount of information is transferred and exchanged (Y. Chen & Kamara, 2011). The ineffective use of technology can lead to increased rework in a construction project due to uncoordinated information gathering, reporting, and management, resulting in wasted time, cost overruns, and errors (P. E. d. Love, 2002). Managing project-related information can be challenging for organizations due to differences in size and technological capabilities (P. E. D. Love & Irani, 2003). Defining quality can be a complex and challenging (Barrett, 2000). It can be defined as the process of evaluating and ensuring that work meets predefined standards, which is crucial to the success of any construction project. (Battikha, 2002). During construction, quality control is an essential process that involves inspection and testing of the materials and products being used, reporting any nonconformance, and taking corrective action to address any issues that come up (Chin et al., 2004). Field inspections are critical in ensuring that the contractor's workmanship, materials, and equipment meet the design specifications and standards. These inspections help identify and correct deficiencies early on, minimizing the risk of costly rework and delays. By adhering to strict quality control procedures, construction projects can be completed safely, efficiently, and to the client's satisfaction (L. Chen & Luo, 2014). Ensuring the required quality standards in construction projects has been a challenge to manage consistently. The lack of effective quality management methodologies has resulted in the wastage of monetary capital and crucial resources such as manpower and materials in many observed cases (Arditi et al., 2015).

Construction quality control systems can be costly, involve multiple stakeholders, and generate excessive paperwork (Griffith, 2000). Traditional construction quality control methods based on site visits and 2D design drawings are often time-consuming, laborious, and prone to errors (Akinci et al., 2006). Laboratory engineers and staff typically create quality test reports through manual documentation. The traditional method of tracking a specific report or inspection certificate is through manual paper-based record management. However, this conventional system of quality reporting has several inefficiencies that make it unreliable, inaccurate, and resource-intensive (L. C. Wang, 2008). Numerous studies suggest that the current quality control methods are not efficient. These ineffective methods are used to generate and interpret data, leading to a waste of time and causing delays in the project schedule. As a result, project managers cannot access complete and accurate information. This, in turn, affects the proper management and control of construction projects, as manual data interpretation is often used, which is not always reliable (Akinci et al., 2006). Real-time quality control is vital for reducing delays and cost overruns in construction projects. Robotics and automation can help detect defects early on (Martinez et al., 2019). Advanced construction technologies have the potential to enhance the quality management of construction projects significantly (Tam et al., 2000). The automated document management system can help manage project-related documents efficiently (Eloranta et al., 2001). The computer program simplifies and speeds up data capture compared to the paper-based reporting system currently in use (Fernandez et al., 2003).

This research aims to develop a BIM-based system that introduces automation in construction quality control reporting and a repository for real-time information collection and processing. Moreover, three objectives designed to be achieved for this study are: (1) To identify issues and inefficiencies in traditional practices of construction quality control reporting and repository, (2) To devise a BIM-based framework for integration of automation in construction quality control reporting and repository, (3) Validation of developed framework using case study and (4) Evaluation of the developed system by industry experts. The article presenting "Part 1" of this research focuses on objectives 1 & 2, whereas the second article, "Part 2" of the research, focuses on objectives 3 & 4.

2. Literature Review

Automation refers to operating or regulating machines, tools, devices, installations, and systems without human intervention. The term "automation" originates from the Greek word "automatos," which means acting on its own, by its own will, or spontaneously. In essence, automation involves using platforms developed by humans to carry out specific activities without human involvement during the execution of those activities ("Springer Handbook of Automation," 2009). Automation refers to using machines or programmable devices to carry out tasks that would otherwise require human labor or intervention (Kamaruddin et al., 2016). Automation in construction is a novel approach to enhance quality control. In the context of construction scheduling, it enables the management team to access sufficient information to manage time, cost, and resources. The construction schedule is one of the most, if not the most, vital gears for managing projects (Faghihi et al., 2015). Digital and computer-based systems streamline work and reduce data capture time compared to traditional paper-based reporting systems (Fernandez et al., 2003). As the construction industry advances digitally, automation is increasingly applied to streamline development processes and save time (Sandberg et al., 2016).

Building Information Modeling (BIM) is the process of creating a detailed digital model that includes all the physical and functional aspects of a building. The 3D model created through this process provides a comprehensive view of a building's technical features. BIM offers several advantages to the building industry by enabling designers, technicians, and managers to share building information seamlessly during the construction process. This helps to reduce communication and coordination challenges between the various groups involved in the project, including design, construction, and management teams (Rezaei et al., 2019). BIM enables the creation of multidimensional models incorporating various aspects such as space constraints, time, costs, materials, design and manufacturing information, and finishes. These models allow for real-time information sharing and collaboration. Additionally, BIM can be integrated with other technologies, such as augmented reality, virtual reality, radio-frequency identification (RFID), and 3D printers, to enhance its functionality (Lester, 2014). BIM is a cutting-edge technology that streamlines construction processes, improves conditions, and models links to mitigate communication issues among relevant parties (Xu et al., 2018). BIM involves integrating all project data into a single database that can be accessed by all team members seamlessly and sequentially (Ozturk, 2020). There are several BIM tools available, including Autodesk Revit, Graphisoft ArchiCAD, Nemetschek Allplan, BricsCAD, and Edificius (Bouška, 2016). Autodesk Revit is a software designed specifically for BIM. It provides a complete solution for architectural design and documentation, supporting all phases of the design process, including architectural drawings and schedules required for a building project. From initial massing and conceptual studies to the most detailed construction drawings and schedules, Autodesk Revit offers a comprehensive package for architects and designers (Hijazi ETH Zurich et al., 2013). Autodesk Revit has added analytical modeling to its Building Information Modeling (BIM) environment. The software provides a well-documented API (Application Programming Interface) that allows for easy integration with other programs. Additionally, Dynamo is a software extension that works with Revit and acts as an interface between the visual programming environment and the Revit API (Salamak et al., 2018).

BIM is a cutting-edge technology used to construct a precise digital model of a building's physical and functional attributes (Azhar, 2011). Computational methods like BIM provide efficient and effective ways to approach various tasks (Kalyan et al., 2016). Visualizing construction sites in 3D improves communication among stakeholders, ultimately leading to better decision-making (Anwar et al., 2024). BIM, combined with other technologies, such as Augmented Reality (AR), can enhance construction quality control and quality management (Lou et al., 2017). In BIM, the model is a digital representation of a construction product that contains precise data. The model can obtain construction-oriented data and link information crucial to manufacturing and quality control (Martinez et al., 2019). A quality control system that utilizes LiDAR-based real-time tracking and integrates BIM-based checking can automatically collect data, compare the built data to the planned BIM model, and assess construction quality on-site (J. Wang et al., 2015). The application of BIM in construction is integrated with quality control to enhance the efficiency of the Quality Management System (QMS) (Cheng, 2018). The QMS necessitates the creation of quality records for each phase of a construction process. It is imperative to monitor the work performed during the planned job. To accomplish this task, the BIM/QR codes (Quick Response Codes) technology can be utilized (Vasilyev et al., 2019). During the literature review, several research articles were analyzed, and various issues and inefficiencies were identified. These issues were then sorted based on the frequency of their occurrence, starting with paper-based data and manual work. Other issues included a lack of conceptual reporting knowledge and unreliable methods, inefficient and difficult information updates, labor-intensive and bulky documents, proneness to errors, complexity, poor information sharing and communication, time consumption, data handling, conflicts and errors in documents, inefficiency and errors in information extraction, data loss, and difficult data re-entry, and increased cost.

In any construction project, efficient quality assurance and effective quality control are among the significant factors that reduce the number of project delays and cost overruns, and with the integration of automation and robotics in construction, quality control is becoming more effective and reliable with real-time monitoring (Martinez et al., 2019). Working with newer technologies like building information modeling can reduce the manual re-entering of data to a minimum and enable the consequent re-use of digital information. Laborious and error-prone work is avoided, increasing productivity and quality of construction projects (Borrmann et al., 2018).

3. Methodology

The methodology adopted for achieving the aim and objectives of this research is given in the Figure 1. The research is designed in compliance with the detailed research process (including literature review, framework development, validation, and evaluation).

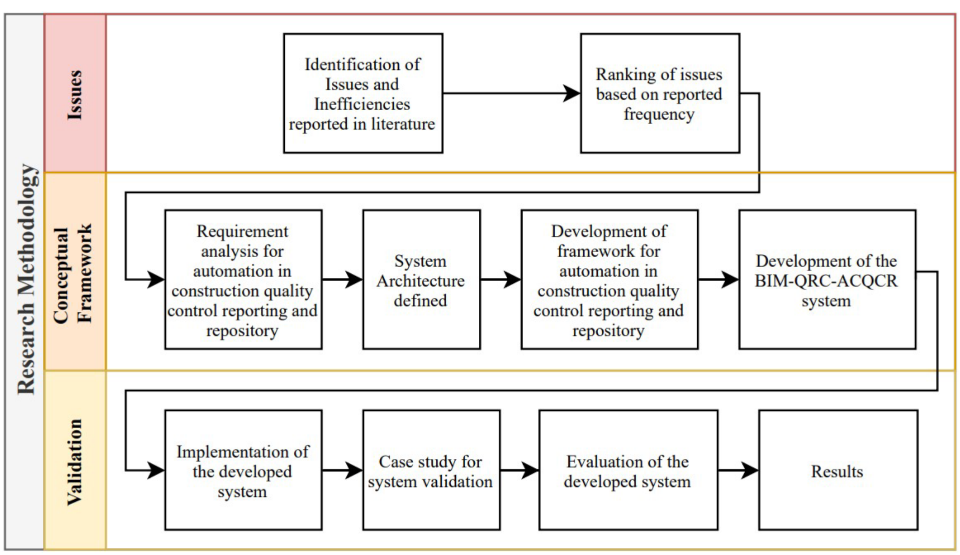

Fig. 1. Research Methodology.

This research will be conducted in two parts. Part 1 describes the formation of the system framework, whereas Part 2 portrays the system's development and validation. The following are the research steps for both parts of the research.

3.1 Research Steps (Part 1)

The study aims to find the drawbacks and inadequacies associated with the conventional practices of quality control reporting and repositories in construction. To identify these drawbacks and inefficiencies, an extensive literature review was conducted. The issues and inefficiencies were extracted from various research articles and categorized based on their similarities. This identification facilitated a better understanding of the prevailing problems. The issues and inefficiencies were then ranked based on their frequency of occurrence in research articles as presented in the literature review.

The process of construction quality control reporting and repository will be analyzed and refined to identify issues and inefficiencies in traditional practices. A framework will be proposed to minimize and mitigate them, and a requirement analysis will be conducted to understand how automation can be introduced. The framework's elements will be determined based on the construction quality control reporting and repository process, and system architecture will be defined for the workflow from BIM to system plugin and from system plugin to QR codes and online database. The contents of the framework will include construction quality control reporting and repository process, BIM, automation, QR codes, and database. After a complete background study, a framework will be prepared to refine the working knowledge of plugins and databases. The features will be subdivided in detail based on the construction quality control reporting and repository procedure. The BIM-based Quick Response Codes (QRC) & Automated Construction Quality Control Repository (ACQCR) system will be created using assistive tools like Dynamo, Dyno Browser, Microsoft Excel, Wamp database server, and Microsoft Visual Studio Code.

3.2 Research Steps (Part 2)

The second article, "Part 2," will provide an in-depth explanation of the development of the system that will be tested by implementing the designed framework in a pilot construction project. A comparison will be made between the traditional reporting and repository procedures and the automated ones. The article will also detail how experts will be briefed on the work and how semi-structured interviews will be conducted to gather their opinions on the developed system. The identified issues and inefficiencies in the conventional construction quality control reporting and repository were ranked based on experts' opinions. Finally, the analysis of the results will show that most of the identified issues and inefficiencies can be successfully minimized and mitigated with the proposed framework and the BIM-QRC-ACQCR system.

4. Framework for BIM-based construction quality control reporting and repository

Our system uses a BIM-based framework to improve the efficiency of construction projects. This framework begins with creating a BIM model of the project to provide a better understanding of the project and its details. The model is focused only on the major concrete elements such as the foundation raft, column, beam, and slab. Once the system is run, all the concrete elements are identified; it then groups them according to their pre-assigned level number and generates QR codes for each group. This ensures that the construction process runs smoothly and efficiently.

BIM-QRC plugin is linked with BIM-supported software specifically designed to work with BIM, like Autodesk Revit (Hijazi ETH Zurich et al., 2013). The BIM-QRC plugin generates QR codes with the required information in the form of a URL (Uniform Resource Locator). The QR code is the most widely used two-dimensional barcode in the world, and it has been successfully applied in many applications in manufacturing and construction (Chou & Wang, 2020). It is a type of matrix barcode that can be easily scanned by a smartphone or tablet. It consists of black modules arranged in a square pattern on a white background. The information encoded in the QR code can be in the form of text, a URL, or any other data (Shin et al., 2012)(Lorenzo et al., 2014). QR codes hold varying amounts of info based on pixel count. A minimum pixel count is necessary to recognize patterns. More info requires more pixels, while minimal info needs fewer pixels. High-capacity info requires high-resolution devices. Fewer pixels improve the recognition rate (Kim et al., 2021). In Revit, metadata is defined for each building object, allowing the identification of object data such as geometry and materials. The system gets all the required data and corresponding metadata, such as Element ID, and inserts them into the QR codes. For every selected key in metadata, such as Element ID in our case, the complete object data, including the object's position and materials, is accessible through the QR code (Du et al., 2018). A new parameter by the name of Concrete Strength is introduced in the hosting BIM software, which is inserted into the BIM model as a parameter by the user, and its required value is inserted before the generation of QR codes. Also, the plugin requires the construction project schedule in the form of a CSV (Comma Separated Value) file to extract the pouring dates for the concreting. Then the plugin combines the project schedule and concrete pouring dates with model elements. After all the prerequisites required for the QR codes are collected, the plugin then generates QR codes and saves them into a desired folder which has been already defined using pouring dates as names of files.

Figure 2 shows a BIM-based framework developed to automate construction quality control reporting and repository.

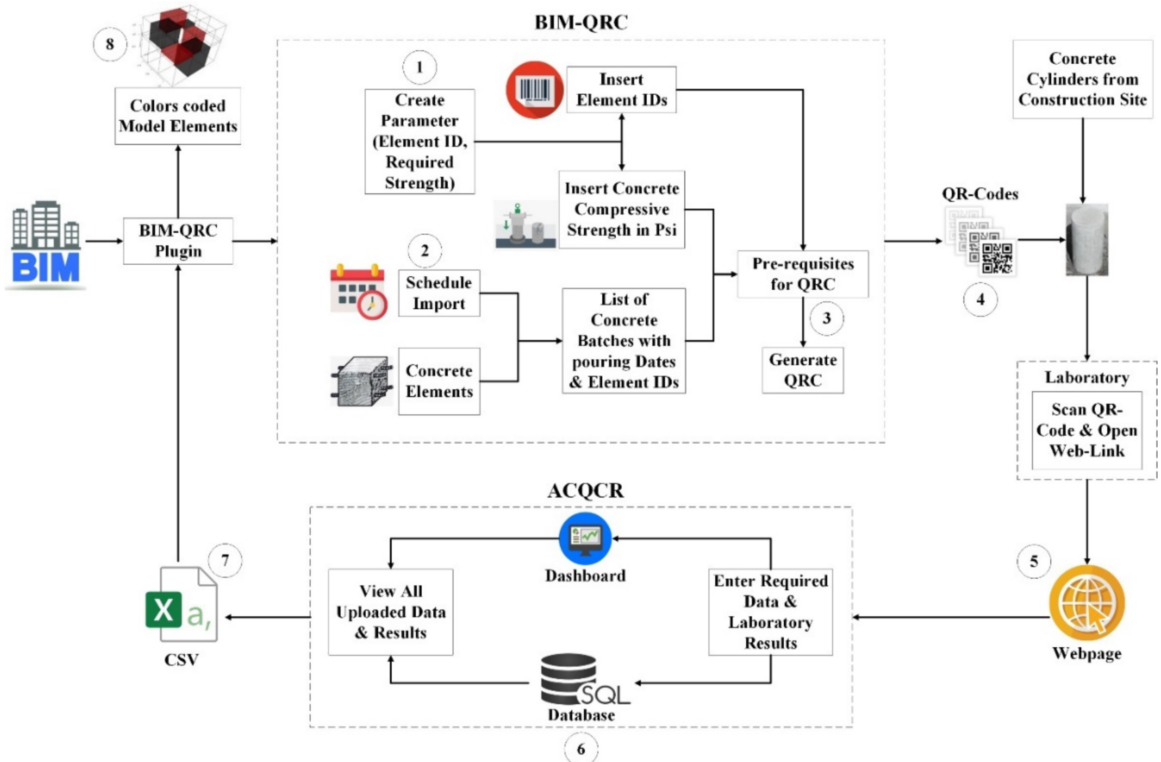

Fig. 2. BIM-QRC-ACQCR Framework.

As the project's construction begins, every concreting concrete cylinder is made for strength testing in laboratories to fulfill the predefined compressive strength criteria. Hence, before cylinders are moved to a laboratory for testing, they are pasted with QR codes accordingly. When QR attached cylinders arrive in the laboratory, they are scanned with dedicated QR code readers, any smartphone or tablet. All the information previously stored in QR code will appear with a link. After opening the link, a webpage opens that asks for Laboratory results and details of the concrete sample. When uploaded, results are saved in a database, which is an organized collection of structured information or data, typically stored electronically in a computer system. The uploaded data can be viewed on a dashboard directly connected to the database. A CSV file can be exported from the database using the dashboard webpage. To visualize the concrete elements that might have failed the compressive strength test in the laboratory, the plugin asks for a database CSV file. After importing the file into the plugin, it displays the failed concrete elements in the BIM model in red.

5. Discussion

The study aimed to address the shortcomings of conventional practices in construction quality control reporting and repositories. Through an extensive literature review, various issues and inefficiencies were identified and categorized based on their frequency of occurrence in research articles. This process provided a comprehensive understanding of the prevailing problems in quality control reporting.

To mitigate these issues, a framework was proposed and refined, focusing on automation through integrating BIM, QR codes, and database systems. The development of the "BIM-QRC-ACQCR" framework aimed to streamline construction quality control processes by leveraging BIM-based automation tools and QR code technology. The BIM-

QRC plugin, integrated with a supported software like Autodesk Revit, was designed to generate QR codes containing essential project information. These QR codes facilitated efficient tracking and management of concrete elements throughout the construction process. By encoding metadata such as Element ID, object data, and concrete strength parameters, the QR codes ensured easy access to vital information during the construction and testing phases.

Furthermore, integrating QR codes with laboratory testing procedures enabled seamless data capture and storage. Upon scanning QR coded concrete cylinders, laboratory technicians could access pertinent information and input test results directly into a centralized database. This streamlined data management process improved traceability and transparency in quality control reporting. Visualizing failed concrete elements within the BIM model provided valuable insights for project stakeholders, allowing for proactive decision-making and remedial actions. Overall, implementing the BIM-QRC-ACQCR framework demonstrated significant potential in enhancing the efficiency and reliability of construction quality control practices.

6. Conclusions

In conclusion, the study successfully identified and addressed the drawbacks and inefficiencies associated with conventional construction quality control reporting and repositories. By developing and implementing the BIM-QRC-ACQCR system, significant improvements were achieved in automating quality control processes, enhancing data traceability, and facilitating informed decision-making.

Integrating BIM technology, QR codes, and database systems offers a robust framework for streamlining construction quality control procedures. The system efficiently tracks and manages concrete elements from project inception to laboratory testing, providing a comprehensive solution for enhancing project efficiency and reducing quality control risks.

Moving forward, further research presented in the second article, “Part 2,” of this research shows a real-world implementation of the BIM-QRC-ACQCR system on a construction project warranted to validate its effectiveness and scalability. Continued refinement and optimization of the system's functionalities will be essential for maximizing its potential in revolutionizing construction quality control practices and fostering sustainable project outcomes.

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