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BIM-ENABLED QUALITY CONTROL FRAMEWORK FOR OFF-SITE CONSTRUCTION (OSC)

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Abstract: Off-Site Construction (OSC) relies on the factory-based production of building components, where effective quality control is essential to prevent defects from propagating into transportation, installation, and on-site assembly stages. Within this context, Inspection data generated through Non-Destructive Testing (NDT), constitutes a key input to quality control, providing systematic inspection techniques that enable the evaluation of material integrity, fabrication quality, and assembly accuracy without damaging or altering prefabricated components. NDT is particularly suited to OSC environments as inspections must be performed on high-value elements under tight production schedules, where destructive testing is impractical and economically prohibitive. NDT offers practical tools for identifying defects and construction-related discontinuities in prefabricated elements; however, inspection outcomes are often disconnected from Building Information Modelling (BIM) workflows used for design coordination and construction planning. This disconnect limits the use of inspection data for construction decision-making and lifecycle quality management. This paper presents a construction-oriented framework for integrating NDT inspection results into BIM-based workflows for OSC projects. The proposed approach aligns factory-level inspections with BIM models to support defect traceability, quality documentation, and coordination across design and manufacturing phases. NDT methods applicable to prefabricated construction components are mapped to BIM elements, enabling visualization of inspection results and systematic tracking of quality issues throughout the project lifecycle. An application scenario based on a prefabricated steel welded joint system is used to illustrate the implementation of the framework. Inspection methods are applied to detect and characterize weld defects such as lack of fusion (LOF), lack of penetration (LOP), porosity, and cracking in weld joints. The inspection data are processed and mapped to BIM components using a structured workflow. The application scenario demonstrates how NDT inspection data can be integrated into BIM workflow to support defect visualization, traceability, and quality control in steel structures used in off-site construction. The study highlights the role of BIM-enabled inspection integration as a practical pathway toward more reliable, efficient, and data-driven quality control processes in off-site construction.

Keywords: Off-site construction (OSC), Non-destructive testing (NDT), Building Information Modeling (BIM), Quality control, Defect detection

1 INTRODUCTION

Off-Site Construction (OSC) has gained interest across the Architecture, Engineering, and Construction (AEC) sector due to its potential to improve productivity. However, research has consistently identified multiple challenges to its wider adoption, with quality-related issues highlighted as a key concern (Gan et al., 2017). Construction quality is one of the three key project management objectives, alongside time and cost. However, because the impact of quality control is often hidden and difficult to quantify, research has largely focused on schedule and cost optimization in OSC (Basu, 2014; Jin et al., 2018). Quality control (QC) involves a series of processes designed to ensure that OSC projects comply with established quality standards and meet relevant building codes and regulatory requirements (Vähä et al., 2013).

Quality challenges remain a critical concern in OSC, as studies indicate that, on average, one out of every six modules contain defects (Johnsson and Meiling, 2009), and approximately 5–16% of project costs are spent on rework due to quality issues (Kim et al., 2014). These problems stem from factors across design, production, and construction stages (Gan et al., 2017), emphasizing the importance of effective quality management supported by skilled teams, high-quality materials, and modern construction practices (Azman et al., 2019).

Various QC techniques have been developed to address the limitations of traditional inspection methods in construction projects. Conventional approaches, such as visual inspection and simple mechanical testing (e.g., tap testing), are often subjective, limited in accuracy, and incapable of detecting internal defects (Liu et al., 2022). In contrast, advanced inspection methods enable more detailed and reliable assessment of structural integrity by providing insights into internal geometry, defects, and damage. Despite their advantages, challenges such as material heterogeneity, limited resolution, and lack of standardization still affect their widespread implementation (Dorafshan et al., 2018; Chen et al., 2020). Based on the literature review by Liu et al., (2022) the integration of information technology and OSC is considered a critical step toward more efficient, accurate, and data-driven quality control in modern construction.

This study addresses the gap in digital quality control by positioning NDT as a structured data acquisition tool integrated with BIM. The proposed workflow involves collecting, processing, and mapping inspection data to BIM components for defect identification and quality assessment, enabling improved traceability and informed decision-making. The implementation focuses on design and manufacturing stages, where quality control is most critical, while later lifecycle phases are identified for future work. Overall, the integration of NDT with BIM and digital twin concepts supports more reliable, efficient, and data-driven quality assurance in OSC.

2 LITERATURE REVIEW

OSC has gained increasing attention as an effective approach to improve productivity (Kamali & Hewage, 2016), reduce construction time (Tam et al., 2015), and enhance quality and safety through factory-based production of building components (W. Zhang et al., 2018). However, several studies highlight that QC remains a key challenge, particularly in ensuring consistency across design, manufacturing, transportation, and installation stages (Chen & Luo, 2014; Park et al., 2013) . Defects generated during manufacturing stage can propagate through the project lifecycle if not identified early, leading to costly rework, delays, and even catastrophic failure. The issues reported in the literature—such as cracking in wall insulation, water leakage, inadequate acoustic performance, elevated moisture levels, and component incompatibility—have contributed to a negative perception of OSC within the AEC industry (Gan et al., 2017; X. Zhang et al., 2014).

Historically, quality control in OSC has relied heavily on traditional construction management practices, where inspection processes are largely manual, time-consuming, and often subjective (Liu et al., 2022). In addition, the integration of advanced technologies into quality control systems has progressed slowly, limiting the efficiency and reliability of quality assessments (Cheng et al., 2015). According to Liu et al., (2022), key challenges affecting construction quality include lack of standardized QC rules, immature quality management systems, fragmented processes, and insufficient technical capabilities. In recent years, however, there has been growing recognition of the importance of quality governance and the role of digital technologies in improving construction quality. As a result, research efforts have increasingly focused on developing advanced QC techniques for OSC that enable faster, more objective, and more reliable quality evaluation (Chen & Luo, 2014; Yin et al., 2019).

Within this context, Non-Destructive Testing (NDT) plays a key role as a primary quality control (QC) tool. According to ASTM E1316-24, NDT comprises techniques used to evaluate materials and components without causing damage. Common methods—including Visual Testing (VT), Ultrasonic Testing (UT), Radiographic Testing (RT), Magnetic Particle Testing (MT), Liquid Penetrant Testing (PT), and Eddy Current Testing (ET)—are widely applied to detect internal and surface defects (Malhotra and Carino, 2004; ACI Committee 228, 2013; ASTM International, 2024). The selection of appropriate methods depends on material type, defect characteristics, inspection accessibility, and inspection stage (ASTM International, 2024; IAEA, 2019; Shull, 2016), and a multi-modal approach is often required for comprehensive quality assurance in OSC (Shull, 2016; Yin et al., 2019).

Ultrasonic techniques are particularly effective for weld joint inspection. Ultrasonic Testing (UT) employs a single high-frequency transducer to transmit sound waves into a material and detect internal defects based on reflected signals. In contrast, Phased Array Ultrasonic Testing (PAUT) utilizes multiple transducer elements, enabling electronic control of the ultrasonic beam. This configuration allows beam steering, focusing, and scanning at various angles, resulting in improved inspection coverage and enhanced defect characterization. The Total Focusing Method (TFM) further advances ultrasonic inspection by reconstructing high-resolution images from full matrix capture (FMC) data, enabling more accurate defect detection, localization, and sizing (Bajgholi et al., 2021; Bajgholi et al., 2023a; Bajgholi et al., 2023b). Complementary methods are also widely used: RT employs X-rays or gamma rays to visualize internal features, MT detects surface and near-surface defects in ferromagnetic materials using magnetic fields, PT reveals surface-breaking flaws through dye penetration, and ET identifies defects in conductive materials using electromagnetic induction. Together, these methods provide a comprehensive and reliable framework for ensuring structural integrity and quality. Based on the above-mentioned reviewed literature, different NDT methods that can be associated with specific prefabricated components and defect types in OSC are illustrated in Table 1.

Table 1. Recommended NDT and inspection methods for prefabricated components in OSC

Component/System Type	**Common Defects**	**Suitable NDT Methods**	**References**
Steel structures and welds	LOF, LOP, porosity, cracks, inclusions	VT, MT, PT, RT, UT (including PAUT and TFM)	CSA W59, CSA W47.1, CSA W178.2, AWS D1.1
Precast concrete elements	Voids, delamination, honeycombing, rebar misplacement	GPR, UPV, IE	CSA A23.1/A23.2, ASTM C597, ASTM D4748
Timber / Mass timber (CLT, GLT)	Cracking, delamination, voids, moisture ingress	IRT, AE, RD, MC	CSA O86, ASTM D4442, Ross (2015)
Building envelope systems	Insulation defects, thermal bridging, air leakage, moisture intrusion	IRT, BDT, ULD, ST	CSA F280, ASTM E779, ISO 6781
Mechanical connections (bolted joints)	Improper preload, loosening, fatigue cracks	UT,TT, ECT	CSA S16, ASTM F959, ASME PCC-1

Note: VT = Visual Testing; UT = Ultrasonic Testing; PAUT = Phased Array Ultrasonic Testing; TFM = Total Focusing Method; MT = Magnetic Particle Testing; PT = Dye Penetrant Testing; RT = Radiographic Testing; ECT = Eddy Current Testing; GPR = Ground Penetrating Radar; UPV = Ultrasonic Pulse Velocity; IE = Impact-Echo; IRT = Infrared Thermography; AE = Acoustic Emission; RD = Resistance Drilling; MC = Moisture Content Measurement; BDT = Blower Door Test; ULD = Ultrasonic Leak Detection; ST = Smoke Testing; TT = Torque Testing.

In parallel with advancements in inspection technologies, digital technologies such as BIM and digital twin systems are transforming the way construction data are managed and utilized. BIM enables the creation of detailed digital representations of physical assets, while digital twins extend this capability by integrating real-time data to simulate and predict structural behavior. Recent studies have demonstrated that integrating inspection data with BIM environments can effectively capture structural defects and map them into digital models, thereby improving documentation accuracy and supporting maintenance planning (Chen et al., 2020; Kritzinger et al., 2018). Furthermore, digital twin frameworks combine NDT data with sensor information to enable predictive assessment of structural performance and deterioration, supporting a transition from reactive to data-driven infrastructure management (Kritzinger et al., 2018; Dorafshan et al., 2018).

Previous BIM-based quality management frameworks have primarily focused on construction defect management, quality documentation, and maintenance planning through the integration of manually collected inspection records and checklist-based assessments (Park et al., 2013; Chen and Luo, 2014). More recent studies have demonstrated the integration of NDT information with BIM and digital twin environments for infrastructure monitoring and maintenance applications (Chen et al., 2020; Kritzinger et al., 2018). However, these approaches generally treat inspection results as isolated datasets and provide limited guidance on how NDT data can be systematically integrated into quality control workflows during the manufacturing stage of OSC. In contrast, the proposed framework focuses specifically on OSC manufacturing environments and establishes a structured workflow that links component-level NDT inspection results to BIM elements through unique identifiers, enabling defect traceability, quality visualization, and quality control management across design and manufacturing stages.

Despite these advancements, a critical gap remains in effectively integrating NDT inspection data into digital construction workflows, particularly in OSC and prefabrication systems. Existing approaches often treat NDT outputs as isolated inspection results, limiting their usability within BIM and digital twin environments. This limitation is especially significant in prefabricated structures, where QC must be performed during manufacturing and accurate, traceable inspection data are essential for ensuring structural reliability across the entire lifecycle.

3 RESEARCH METHODOLOGY

3.1 Research approach

The framework was developed using three main inputs: literature review, industry-oriented practices, and an application scenario in OSC, as illustrated in Figure 1. First, relevant literature on OSC quality control, NDT applications, and BIM-based information management were reviewed using major academic databases and industry standards. Sources were screened for relevance to quality assurance, inspection technologies, and digital integration in OSC, and the findings were used to inform framework development. Second, Industry-oriented practices were derived from established OSC quality management workflows, applicable construction and inspection standards (e.g., CSA, ASTM, AWS), and the authors' professional experience in NDT implementation, welding inspection, and quality management. These inputs were used to ensure that the proposed framework reflects practical inspection and manufacturing processes commonly applied in industrial environments. Third, an OSC-oriented application scenario was used to demonstrate how inspection data could be linked to BIM elements and tracked across design and manufacturing stages.

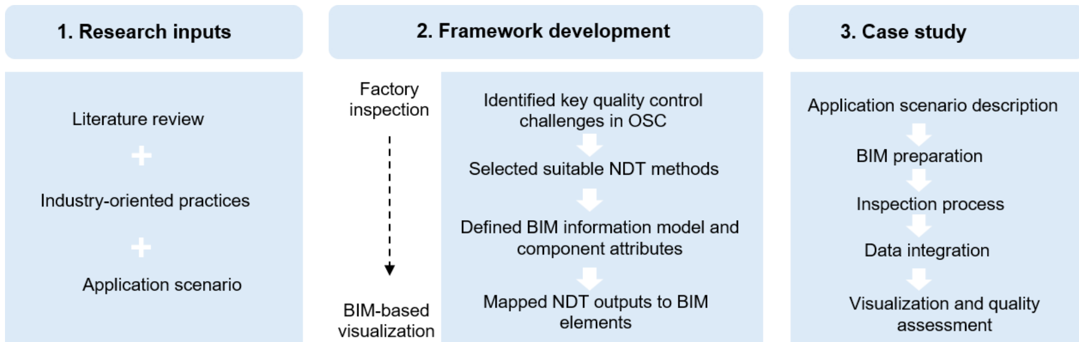

Figure 1. Methodological framework

3.2 Framework development

The framework development followed a step-by-step approach. First, key QC challenges in OSC were identified from different literature and industry-oriented practices, particularly those related to defect detection, reporting, and communication between factory and site teams. Second, suitable NDT methods for common prefabricated components were identified based on material type and inspection purpose as mentioned in literature review section. Third, NDT outputs were mapped to BIM elements to define how inspection results could be associated with digital building components. Finally, a workflow was developed to show how inspection information could move from factory inspection to BIM-based visualization and lifecycle tracking. Within the proposed framework, inspection information is linked to BIM components through unique component identifiers and associated attribute fields. Typical attributes include inspection method, inspection date, defect type, defect location, defect severity, and inspection status. The unique identifier serves as a common reference between the physical component, inspection records, and BIM object, enabling traceability across design and manufacturing processes. The framework is intentionally platform-independent and can be implemented using IFC-compliant data structures or native BIM object properties available in commonly used BIM authoring tools. The present study focuses on the conceptual information model rather than a software-specific implementation.

3.3 Application scenario development

A prefabricated steel welded joint system was selected as a representative application scenario to demonstrate the implementation of the proposed NDT–BIM integration framework. The scenario illustrates how inspection data may be acquired, processed, and linked to BIM elements for structured quality control and traceability. The objective is not to validate the framework experimentally but to demonstrate its potential application within an OSC manufacturing environment.

4 PROPOSED FRAMEWORK

4.1 Framework overview

The proposed BIM-enabled QC framework focuses on the integration of design and manufacturing phases within OSC, as illustrated in Figure 2. BIM is used as the central platform to define, manage, and link component-level information from the design stage to QC processes in manufacturing. In the design phase, BIM models are developed to represent prefabricated components, including their geometry, specifications, and unique identifiers. These digital representations establish the foundation for tracking quality-related data throughout the manufacturing process. The manufacturing phase forms the core of the framework, where prefabricated elements are produced and inspected using NDT methods. Inspection results are systematically linked to BIM elements, enabling component-level quality visualization and traceability. This study focuses on the integration of design and manufacturing stages, where QC has the highest impact in OSC. While the framework can be extended to transportation, installation, and maintenance phases, these stages are beyond the scope of the current study and are proposed as areas for future work.

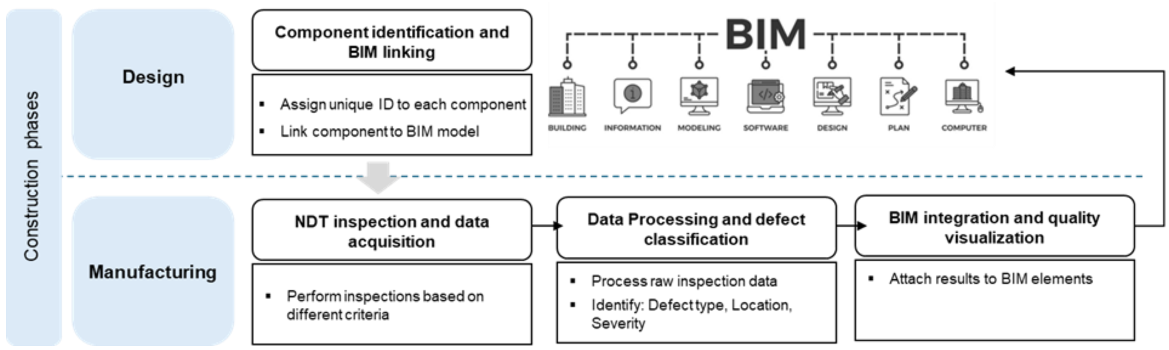

Figure 2. BIM-enabled QC framework focuses on design and manufacturing integration in OSC, highlighting the incorporation of NDT inspection data into BIM for component-level quality tracking and visualization (BIM illustration adapted by the authors based on Chen and Luo 2014; Yin et al. 2019)

4.2 Design-to-manufacturing integration

According to Knyziak, (2016), errors identified at the design stage can be corrected at the lowest cost before impacting later phases, so the framework establishes a direct connection between design information and manufacturing QC. Each component defined in the BIM model is assigned a unique identifier, which is maintained throughout the production process. This enables inspection data collected during manufacturing to be accurately associated with the corresponding digital element. By linking NDT inspection results to BIM components, the framework ensures that quality information is no longer isolated in reports but becomes part of the digital model. This integration improves coordination between design and manufacturing teams and allows early identification of potential issues before components leave the factory.

4.3 Manufacturing-based NDT-BIM workflow

As shown in Figure 2, the manufacturing stage follows a structured workflow for integrating NDT data into BIM. First, prefabricated components are defined and linked to their corresponding BIM elements through unique identifiers. Next, NDT inspections are performed based on component type and material characteristics, as mentioned in Table 1 section 2. The collected inspection data are then processed to determine defect type, location, and severity. These results are integrated into the BIM model as component-level attributes, including inspection method, status, and quality classification. Finally, the BIM environment enables visualization of inspection outcomes, allowing stakeholders to identify defects and assess component conditions in a clear and structured manner.

This study focuses on the integration of design and manufacturing stages, where QC has the highest impact in OSC. While the framework can be extended to transportation, installation, and maintenance phases, these stages are beyond the scope of the current study and are proposed as areas for future work.

5 FRAMEWORK APPLICATION SCENARIO: STEEL STRUCTURE WITH WELDED JOINTS

5.1 Application scenario description

A steel structure with welded joints is presented as an illustrative application scenario to demonstrate how the proposed framework can be applied within an OSC manufacturing environment. The scenario represents a typical prefabricated steel assembly where weld quality is critical and NDT inspection data can be integrated with BIM-based quality management workflows.

5.2 Inspection strategy

Surface inspection methods, such as Magnetic Particle Testing (MT), Visual Testing (VT), and Liquid Penetrant Testing (PT), are commonly used to detect surface and near-surface defects. In contrast, volumetric inspection techniques, including Ultrasonic Testing (UT) and Phased Array Ultrasonic Testing (PAUT), are used to identify internal defects. Among advanced ultrasonic techniques, the Total Focusing Method (TFM) reconstructs a full high-resolution image of the inspected region by processing complete full matrix capture (FMC) data, resulting in significantly improved flaw detection, resolution, and characterization (Bajgholi et al, 2021).

Table 2. Mapping of welded steel components, NDT methods, and detectable defects.

Component	NDT Method	Detectable Defects
Weld joints (internal detection)	UT / PAUT / TFM	LOF, LOP, porosity, Slag inclusions, Crack
Weld joints (surface detection)	MT / PT	surface & near surface flaws
Fabricated Steel members	VT	misalignment, dimensional deviations, geometric defects

5.3 Data acquisition and processing

As a practical example, ultrasonic inspection provides detailed information on internal defects in welded joints. Ultrasonic inspection data are acquired using specialized equipment, where signals are captured in the form of A-scan, B-scan, C-scan, or full matrix capture (FMC). These signals are subsequently processed using dedicated software to reconstruct images of the weld joint region. Advanced imaging algorithms, such as the Total Focusing Method (TFM), are applied to enhance defect resolution and improve detectability. The processed data are then analyzed to determine the type, location, and severity of defects.

5.4 BIM integration workflow

Each inspected welded joint is assigned a unique identifier (ID) within the BIM model to ensure traceability throughout the QC process. The processed ultrasonic inspection results—obtained from UT, PAUT, or TFM—are mapped to the corresponding BIM elements as structured attribute data. These attributes include defect type (e.g., lack of fusion, porosity, cracking), spatial location within the weld, defect size and severity, inspection method, and inspection timestamp. These attributes are linked to BIM objects through the component identifier defined within the framework.

This integration enables the direct visualization of weld joint quality within the BIM environment, where defects can be represented spatially and linked to specific structural components. In addition to geometric and inspection data, probabilistic metrics such as Probability of Occurrence (POO) and Probability of Detection (POD) can be incorporated to support risk-informed assessment in components (Bajgholi et al, 2023). As a result, stakeholders can efficiently identify critical defects, assess their impact on structural integrity, and make informed decisions regarding repair or acceptance. Furthermore, the incorporation of inspection data into BIM enhances digital traceability, supports systematic quality documentation, and improves coordination between design and manufacturing teams. This integrated approach ultimately leads to improved inspection efficiency, enhanced product quality, and increased productivity by reducing rework, minimizing inspection time, and enabling proactive QC. The overall workflow of BIM model development and NDT-based inspection integration for welded steel joints is illustrated in Figure 3.

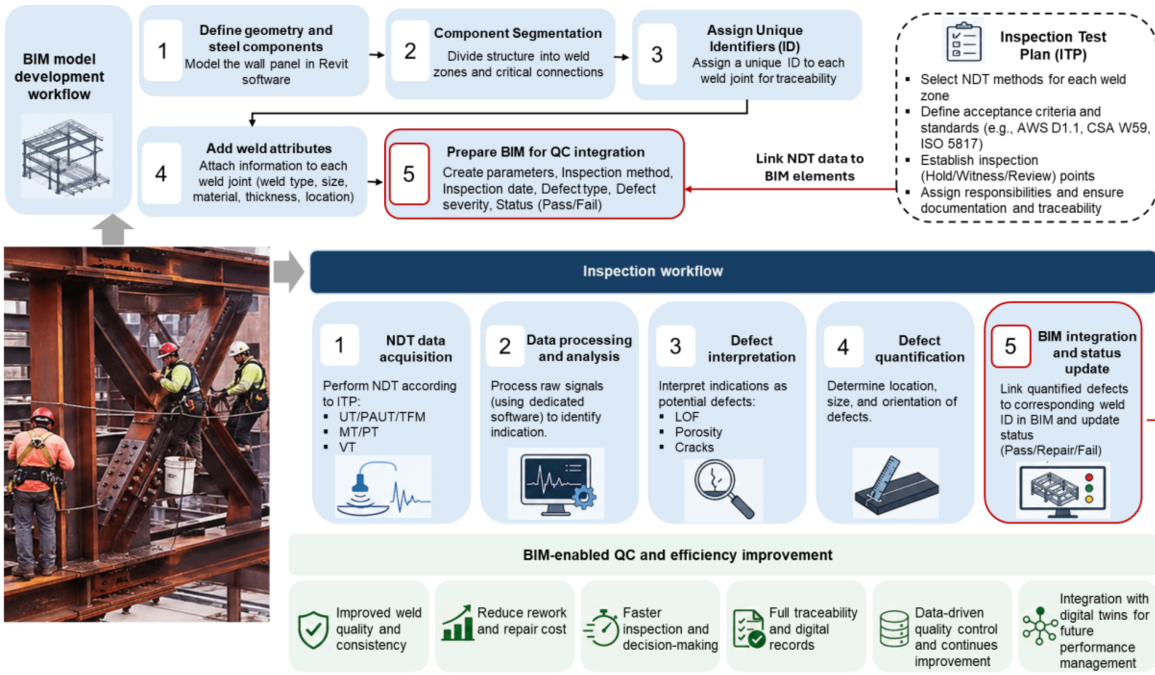

Figure 3. Workflow of BIM development and NDT–BIM integration for welded steel joints in OSC

5.5 Key contribution of application scenario

The presented application scenario is intended to demonstrate the workflow and information flow associated with the proposed framework rather than provide experimental validation. The objective is to illustrate how NDT inspection results can be linked to BIM components through a structured process for quality control and traceability. Future work will focus on validating the framework using actual inspection datasets, BIM implementations, and industrial OSC projects.

6 DISCUSSION

The proposed framework provides a structured approach for integrating NDT data into BIM-based workflows in OSC. The framework suggests that linking inspection outputs to BIM components could improved traceability, visualization, and coordination of quality information at the component level.

Compared to existing BIM-based quality management approaches, which primarily rely on checklist-based or manually entered inspection data (Chen and Luo, 2014; Park et al., 2013), the proposed framework introduces a data-driven approach by incorporating real NDT measurements into the digital model. This allows not only defect identification but also quantitative characterization of defects, improving the reliability of quality assessments. In addition, previous studies have highlighted that QC in OSC is often fragmented and poorly integrated with digital systems (Liu et al., 2022). The present study addresses this gap by establishing a direct link between inspection data and BIM elements, enhancing data continuity across design and manufacturing stages.

From a technical perspective, the use of advanced ultrasonic methods such as PAUT and TFM provides significant advantages over conventional inspection techniques. These methods enable volumetric inspection, high-resolution imaging, and improved defect detectability, particularly for critical welded joints. When integrated with BIM, these capabilities support more informed decision-making and enable a transition toward data-driven QC. Similar trends have been identified in recent studies on BIM–NDT integration and digital inspection systems (Chen et al., 2020).

Furthermore, the integration of NDT data with BIM provides a foundation for the development of Digital Twin systems, where inspection data can be continuously used for monitoring and predictive analysis (Kritzinger et al., 2018). This represents a shift from traditional reactive QC toward proactive and predictive quality management in OSC.

The current framework is demonstrated conceptually rather than validated through large-scale experimental implementation. Future work should focus on real-time data integration, standardization of data formats, and validation across multiple projects to assess practical performance and scalability.

6.1 Limitations and future works

The framework has been demonstrated conceptually through a single application scenario involving steel welded joints and selected NDT methods. Interoperability across BIM platforms and information exchange standards has not been evaluated. Future work should focus on framework validation using real project data, broader application to other OSC components and inspection technologies, and interoperability testing across digital platforms.

7 CONCLUSION

This study presented a BIM-enabled quality control framework for OSC that integrates NDT data into digital workflows. The proposed approach establishes a structured process for linking inspection results to BIM components, improving traceability, visualization, and coordination between design and manufacturing stages.

An application scenario on prefabricated steel welded joints was presented to illustrate the implementation of the framework and the associated information flow. The framework highlights the potential of NDT–BIM integration to enhance defect detection, support component-level quality assessment, and enable more data-driven decision-making in OSC.

While the framework shows strong potential, it is currently limited to design and manufacturing stages and has not been validated through large-scale applications. Future work should focus on extending the approach to later lifecycle stages and addressing challenges related to real-time data integration, standardization, and interoperability. Overall, the proposed framework contributes to advancing digital quality control and supports the transition toward more efficient and reliable construction practices. It should be noted that the present study is conceptual in nature and uses an illustrative application scenario; therefore, no claims regarding measured performance improvements are made at this stage.

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