Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 07 July-2026, Page No.- 10995-10999
DOI: 10.47191/etj/v11i07.24, I.F. – 8.595

Evaluating the Potential of 3D Concrete Printing to Revolutionize Quality Control in Construction

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ABSTRACT: The construction industry continues to face persistent quality control challenges arising from material inconsistencies, human error, dimensional deviations, construction defects, and project delays. Three-dimensional concrete printing (3DCP), also known as additive manufacturing in construction, has emerged as a promising technology capable of addressing many of these issues through automation and digital fabrication. By depositing cementitious materials layer-by-layer directly from digital models, 3DCP enhances dimensional accuracy, improves material consistency, reduces dependence on manual labor, and enables real-time monitoring of construction processes.

This study examines the potential of 3D concrete printing to improve quality management and quality control practices in construction projects. A structured literature review was conducted using major academic databases, including Scopus, Web of Science, Google Scholar, ScienceDirect, ASCE Library, SpringerLink, and Wiley Online Library. Relevant publications were screened based on predefined inclusion and exclusion criteria. The selected studies were analyzed to identify quality performance indicators, including dimensional accuracy, material consistency, rework costs, inspection costs, productivity, and material waste.

The findings indicate that 3DCP offers significant opportunities to improve construction quality through automation, digital monitoring, Building Information Modeling (BIM) integration, and sensor-based quality assurance systems. Case studies from Dubai, the Netherlands, and the United States demonstrate practical applications of automated quality control, dimensional precision, and real-time process monitoring. However, challenges related to standardization, regulatory acceptance, long-term durability, and high initial investment costs continue to limit widespread implementation. The study concludes that 3D concrete printing has considerable potential to transform construction quality management while contributing to sustainability and productivity objectives.

KEYWORDS: 3D Concrete Printing; Quality Control; Additive Manufacturing; Construction Automation; Digital Construction; Building Information Modeling

1. INTRODUCTION

Three-dimensional concrete printing (3DCP) has emerged as one of the most promising innovations in construction automation and digital fabrication. Unlike conventional construction methods, which rely heavily on manual labor, formwork systems, and sequential construction processes, 3D concrete printing creates structural elements through the automated layer-by-layer deposition of cementitious materials according to digital design models [1] [2]. Technology has attracted considerable interest because of its potential to improve productivity, reduce material waste, shorten project schedules, and enhance construction quality.

Over the past two decades, significant advances have been made in construction-scale additive manufacturing systems and printable concrete materials [3] [4]. Researchers have investigated material properties, structural behavior, printability, sustainability, and reinforcement strategies associated with 3D concrete printing [5]-[15].

However, comparatively limited attention has been devoted to examining the role of 3D concrete printing as a quality-control and quality-assurance tool within construction projects.

Quality control remains one of the most persistent challenges facing the construction industry. Defects associated with dimensional inaccuracies, material inconsistencies, inadequate workmanship, and inefficient inspection procedures frequently contribute to project delays, increased costs, and reduced performance [11] [18]. Because 3D concrete printing relies on computer-controlled fabrication and digital workflows, it offers opportunities to improve process consistency, enhance traceability, and reduce human-induced variability.

This study evaluates the potential of 3D concrete printing to improve quality management and quality control in construction. A structured review of the literature is conducted to identify key quality-control mechanisms, evaluate performance indicators reported in previous research, and examine real-world case studies demonstrating practical implementation of this technology. This study contributes to the growing body of knowledge on three-dimensional concrete printing by examining the technology from a construction quality-control perspective rather than focusing solely on material properties or structural performance.

Through a structured review of the literature, the study synthesizes existing research on automation, digital monitoring, Building Information Modeling (BIM), sensor-based quality assurance, and real-time process control in 3D concrete printing. In addition, key quality-performance indicators, including dimensional accuracy, material consistency, rework costs, inspection costs, productivity, and material waste, are evaluated to assess the technology's potential impact on construction quality. The study further draws upon documented international case studies to illustrate practical applications, implementation challenges, and opportunities for improving quality management in the construction industry.

2. BACKGROUND OF 3D CONCRETE PRINTING

2.1. Definition

Three-dimensional concrete printing is an automated construction process in which cementitious materials are deposited layer-by-layer through robotic systems to create structural components directly from digital models [1] [6].

2.2. Types of 3D Concrete Printing

The principal categories of 3D concrete printing include:

1. Extrusion-based printing;
2. Powder-bed printing; and
3. Robotic shotcrete printing.

Among these approaches, extrusion-based printing is the most widely adopted due to its lower implementation cost, flexibility, and compatibility with large-scale construction applications.

3. QUALITY CONTROL ISSUES IN TRADITIONAL CONSTRUCTION

Construction projects frequently experience quality-related challenges associated with manual processes, inconsistent materials, and limited monitoring capabilities. Common quality-control issues encountered in traditional construction are summarized in Table 1.

Table 1. Common quality control issues in traditional construction.

Problem	Primary Cause	Consequence
Dimensional errors	Manual measurement	Rework
Material inconsistency	Poor mixing practices	Reduced strength
Human error	Inadequate training	Structural defects
Delayed inspections	Inefficient monitoring	Project delays

Previous studies indicate that rework can account for approximately 5% - 15% of total construction costs, highlighting the importance of effective quality-control systems and process monitoring strategies [11] [18]. Human error, variability in field conditions, and inconsistent construction practices remain major contributors to construction defects and quality failures.

4. LITERATURE REVIEW

Researchers have emphasized the importance of precise material control and process automation in achieving reliable and repeatable construction outcomes [4] [10]. The current body of literature suggests that automation and digital fabrication can improve construction quality by increasing dimensional accuracy, reducing human error, enhancing material performance, and enabling continuous monitoring throughout the construction process [14][16] [17] [19].

Material performance remains one of the most important factors affecting the success of 3D concrete printing. Studies have demonstrated that rheology, buildability, workability, interlayer bonding, and fresh-state material characteristics significantly influence print quality and structural performance [4] [8] [10] [17]. Consequently, maintaining consistent material properties is essential for achieving high-quality printed structures.

Recent advances in sensor technologies, machine vision systems, and digital twins have further expanded the potential of additive manufacturing to support real-time quality assurance and automated defect detection [16] [18] [20]. Despite these developments, the lack of universally accepted standards continues to be one of the major barriers to widespread industry adoption [20] [22]

Existing literature consistently suggests that automation and digital fabrication can improve construction quality by increasing dimensional precision, reducing defects, and enhancing process reliability [2][3][16].

Key findings identified in the literature include:

1. Automation reduces opportunities for human error.
2. Digital models improve dimensional precision.
3. Continuous monitoring improves process reliability.
4. Material consistency is critical to print quality.
5. Sensor technologies improve defect detection.
6. BIM integration supports quality assurance.

Despite these benefits, a lack of universally accepted standards remains a major barrier to widespread adoption. Researchers have emphasized the importance of integrating artificial intelligence, digital twins, machine vision, and advanced monitoring systems into future quality management frameworks [20] [23].

5. METHODOLOGY

5.1. Research Design and Literature Selection

This study employed a structured narrative literature review to investigate the role of 3D concrete printing in improving construction quality control. Based on the numbers reported in this manuscript:

- Initial records identified = **65**
- Records after duplicate/non-relevant removal = **42**
- Full-text articles assessed = **42**

- Studies included in final analysis = **23**

5.1.1. Data Sources

Literature was collected from:

- Scopus
- Web of Science
- Google Scholar
- ScienceDirect
- ASCE Library
- SpringerLink
- Wiley Online Library

5.1.2. Search Strategy

The literature search used combinations of the following keywords:

- 3D concrete printing
- additive manufacturing in construction
- quality control
- quality assurance
- digital construction
- construction automation
- BIM
- real-time monitoring
- construction productivity

Example search strings included:

- "3D concrete printing" AND "quality control"
- "Additive manufacturing" AND "construction quality"
- "3D concrete printing" AND "real-time monitoring"

5.1.3. Inclusion Criteria

Studies were included if they:

1. Publications were peer-reviewed;
2. Were published between 2004 and 2025;
3. Addressed 3D concrete printing or construction additive manufacturing;
4. Discussed quality control, monitoring, productivity, or related performance measures; and
5. Were published in English.

5.1.4. Exclusion Criteria

Studies were excluded if they:

1. Focused solely on non-construction additive manufacturing applications;
2. Lacked technical details;
3. Were duplicate publications; or
4. Were non-peer-reviewed sources.

5.1.5. Screening Procedure

The selection process involved identification, title and abstract screening, and full-text assessment. Relevant publications meeting all inclusion criteria were retained for detailed evaluation.

5.3. Data Analysis

The selected studies were analyzed using a comparative thematic approach. Information relating to dimensional accuracy, material consistency, automation, monitoring technologies, quality assurance methods, productivity improvements, and sustainability performance was extracted and compared across the selected publications. Case studies were further evaluated to identify common quality-control benefits, implementation challenges, and emerging best practices associated with 3D concrete printing.

Initial database search yielded approximately 65 publications relevant to 3D concrete printing and construction quality control. After removing duplicate and non-relevant records, 42 studies remained for title and abstract screening. Following full-text review, 23 publications met the inclusion criteria and were selected for detailed analysis. The final dataset consisted primarily of peer-reviewed journal articles supplemented by conference proceedings and scholarly books.

5.3. Definition of Quality Performance Indicators

5.3.1. Dimensional Accuracy

The degree to which completed structures conform to design dimensions.

5.3.2. Rework Cost

Expenditures associated with correcting defects or non-conforming work.

5.3.3. Material Consistency

Uniformity of concrete properties, including workability, printability, and strength.

5.3.4. Inspection Cost

Resources required for quality monitoring and verification activities.

5.3.5. Material Waste

Unused or discarded material generated during construction.

5.3.6. Productivity

Construction output relative to labor, time, or resources utilized.

Figure 1 illustrates the conceptual framework adopted in this study, demonstrating how Building Information Modeling (BIM), digital design models, 3D concrete printing, real-time monitoring, sensor-based data collection, artificial intelligence, and quality assurance systems interact to improve construction quality and support automated quality-control processes.

Figure 1. Conceptual framework for quality control in 3D concrete printing.

5.4. Operational Definitions of Quality Performance Indicators

5.4.1. Dimensional Accuracy

Dimensional accuracy refers to the degree to which the dimensions of a constructed component conform to the dimensions specified in the design model. Within the reviewed literature, dimensional accuracy was typically evaluated by measuring deviations between the as-built geometry and the digital design model using laser scanning, photogrammetry, or direct measurement techniques. Lower dimensional deviations indicate higher construction precision and improved quality control.

5.4.2. Rework Cost

Rework costs refer to the financial resources required to correct errors, defects, or nonconforming work after construction activities have been completed. According to the reviewed studies, rework costs were generally reported as either a percentage of total project cost or as additional labor and material expenditures required to achieve design compliance. Lower rework costs were interpreted as an indicator of improved construction quality and process reliability.

5.4.3. Material Consistency

Material consistency refers to the uniformity of concrete properties throughout the production and printing process. In the reviewed literature, material consistency was commonly evaluated based on workability, printability, rheological behavior, compressive strength, interlayer bonding, and fresh-state material characteristics. Previous research has demonstrated that the properties of fresh cementitious mixtures play a critical role in achieving reliable extrusion, layer stability, and overall print quality [8]. Consistent material performance is essential for minimizing variability during printing operations and reducing the likelihood of quality defects. Consequently, higher levels of material consistency are associated with improved construction quality, enhanced process reliability, and greater repeatability of printed components.

5.4.4. Inspection Cost

Inspection cost refers to the labor, equipment, and administrative expenses associated with quality assurance and quality control activities. Studies reviewed in this research evaluated inspection costs based on the frequency of inspections, the number of personnel involved, and the level of technology employed for monitoring and verification. Reductions in inspection cost were interpreted as evidence of more efficient quality management processes.

5.4.5. Construction Defect Rate

Construction defect rate represents the frequency of quality-related deficiencies identified during or after construction. Examples include dimensional deviations, material defects, structural imperfections, and workmanship errors. Studies reporting lower defect frequencies were interpreted as demonstrating superior quality control performance.

5.4.6. Material Waste

Material waste refers to the amount of construction material discarded, unused, or rendered unusable during the construction process. In the reviewed studies, waste was commonly expressed as a percentage of total material consumption. Lower material waste was considered an indicator of improved operational efficiency and sustainability.

5.4.7. Productivity

Productivity refers to the quantity of work completed within a specified period of time. Measures reported in the literature included construction duration, labor hours per unit of output, and overall project completion times. Improvements in productivity were interpreted as evidence of more efficient construction processes.

5.4.8. Quality Assurance Capability

Quality assurance capability refers to the ability of a construction system to monitor, detect, document, and correct quality deviations during project execution. Indicators included the use of real-time sensors, automated monitoring systems, machine-vision technologies, data collection systems, and digital documentation. Greater quality assurance capability was considered a major advantage of 3D concrete printing due to its integration with automated and digital workflows. The comparative analysis presented in this study was based on these operational definitions to ensure consistency when evaluating findings across multiple sources, technologies, and case studies.

5.5. Study Limitations

This study has several limitations that should be considered when interpreting the findings. First, the reviewed studies employed different research designs, performance metrics, measurement techniques, and reporting formats, making direct comparison across studies challenging. Second, due to the limited availability of standardized quantitative data, a formal meta-analysis was not feasible. Consequently, the findings are based on qualitative and comparative synthesis rather than statistical aggregation. Third, many of the reported outcomes originate from pilot projects, prototype developments, and demonstration-scale applications, which may not fully represent large-scale commercial construction environments. Fourth, the rapidly evolving nature of 3D concrete printing technology means that some findings may change as new materials, monitoring systems, and construction standards emerge. Therefore, the performance improvements identified in this study should be interpreted as indicative industry trends rather than universally applicable benchmarks.

6. CASE STUDIES

6.1. Case Study Selection Rationale

The selected case studies represent widely documented examples of practical 3D concrete printing implementation. The selected case studies were chosen because they represent some of the most widely documented and influential applications of three-dimensional concrete printing in the construction industry. In addition, each project demonstrates a distinct quality-control mechanism that supports the central argument of this study, namely that 3D concrete printing can improve construction quality through automation, digital monitoring, dimensional precision, and process standardization. Together, these cases provide practical evidence of how 3DCP technologies are being used to reduce defects, improve accuracy, and enhance quality assurance in real-world construction environments.

6.2. Dubai Municipality 3D-Printed Office Building

The Dubai Municipality office project represents one of the earliest large-scale commercial implementations of 3D concrete printing technology. The project demonstrated the feasibility of integrating automated fabrication systems into real-world construction activities while reducing labor requirements and material waste [22].

The primary quality-control mechanism demonstrated by this project was automated process control. Because structural elements were fabricated directly from digital design models, opportunities for dimensional errors and placement inconsistencies were significantly reduced. The project reportedly achieved labor reductions of approximately 50% - 60% while maintaining high construction precision [22].

Quality-Control Mechanism Demonstrated

Project Milestone in the Netherlands demonstrated the practical application of 3D concrete printing for residential construction. The project serves as an example of how digital fabrication can be used to construct geometrically complex structures while maintaining dimensional consistency and reducing defects [6] [22].

The primary quality-control mechanism demonstrated by this project was dimensional accuracy and geometric consistency. Computer-controlled fabrication allowed the production of complex forms with minimal deviation from design specifications.

Automated Process Control

Reported outcomes included:

- Approximately 50% - 60% reduction in labor requirements [22];
- Significant reductions in material waste [22];
- Improved construction precision [22].

6.3. Eindhoven, Netherlands—Project Milestone

Project Milestone was selected because it demonstrates residential implementation of 3D concrete printing.

Quality-Control Mechanism Demonstrated

Dimensional Accuracy and Geometric Consistency

The project demonstrated the ability of automated printing systems to reproduce complex geometries while maintaining accurate dimensional tolerances and reducing construction defects.

6.4. ICON Housing Projects, United States

The ICON housing projects in the United States provide evidence of the scalability of 3D concrete printing for residential construction applications. The projects demonstrated improvements in process consistency, construction speed, and material utilization while reducing reliance on traditional labor-intensive techniques [21].

Quality-Control Mechanism Demonstrated

The primary quality-control mechanism demonstrated in these projects was real-time process monitoring and material control through automated production systems and standardized printing procedures.

Real-Time Process Monitoring and Material Control

The projects demonstrated:

- Improved process consistency;
- Better material utilization;
- Improved dimensional tolerances;
- Faster project completion schedules [21].

6.5. Cross-Case Analysis

Collectively, these projects demonstrate three primary quality-control advantages:

1. Automated process control;
2. Improved dimensional precision; and
3. Enhanced monitoring and material consistency.

7. ECONOMIC AND SUSTAINABILITY IMPLICATIONS

7.1. Economic Considerations

Although a comprehensive economic analysis was beyond the scope of this review, existing literature consistently identifies several economic advantages associated with 3D concrete printing. Reported benefits include reduced labor requirements, lower material waste, decreased rework, and improved productivity [11] [21] [22].

Nevertheless, existing literature identifies several recurring economic trends. . A comparison of major economic considerations associated with traditional construction and 3D concrete printing is presented in Table 2.

Table 2. Comparative economic considerations.

Economic Factor	Traditional Construction	3D Concrete Printing
Labor Requirements	Higher	Lower
Material Waste	Higher	Lower
Rework Potential	Higher	Lower
Capital Equipment Cost	Lower	Higher
Digital Infrastructure Requirements	Limited	Extensive
Potential Long-Term Savings	Moderate	Potentially High

The reviewed literature suggests that 3D concrete printing can improve quality control through automation and digital integration, although the magnitude of these improvements varies across studies and project conditions.

Reported Performance Ranges

Reported performance improvements identified in the literature are summarized in Table 3.

Table 3. Reported performance improvements identified in the literature.

Performance Indicator	Reported Range
Labor Reduction	50% - 60%
Material Waste Reduction	30% - 60%
Dimensional Precision	Millimeter-level accuracy under controlled conditions
Construction Duration	Reduced relative to conventional methods
Inspection Requirements	Reduced through digital monitoring

Several studies have reported labor savings of approximately 50% - 60% and material-waste reductions ranging from 30% - 60%, depending on project type and implementation strategy [12] [13] [22]. However, these benefits must be balanced against the higher initial capital costs associated with printing equipment, software, and operator training [11] [20].

7.2. Sustainability Benefits

Sustainability has become one of the major drivers behind the adoption of additive manufacturing technologies in construction. By placing materials only where required, 3D concrete printing can significantly reduce waste generation and improve resource efficiency [12] [13]. Additional benefits include reduced transportation requirements, lower site disturbance, and opportunities to utilize recycled materials and alternative binders [7] [22].
Several studies have reported material-waste reductions ranging from approximately 30% to 60% compared with conventional construction approaches [12] [13] [22]. These findings suggest that 3D concrete printing may contribute to broader sustainability goals within the construction sector.
Three-dimensional concrete printing contributes to sustainability through:

1. Reduced material waste;
2. Optimized material utilization;
3. Lower transportation requirements;
4. Reduced site disturbance; and
5. Increased opportunities for recycled materials.

8. DISCUSSION

The literature reviewed indicates that 3D concrete printing has considerable potential to improve construction quality through automation, digital integration, and real-time monitoring. Unlike conventional construction methods, which rely heavily on manual operations and post-construction inspection activities, additive manufacturing processes enable continuous monitoring and immediate corrective actions during production [16] [18].
Robotic fabrication systems have demonstrated millimeter-level dimensional precision under controlled conditions, allowing structures to be produced with reduced geometric variability and improved conformity to design specifications [6] [20]. Furthermore, automated material dispensing systems contribute to improved consistency in concrete properties, reducing quality defects associated with material variability [4] [10].
Real-time monitoring technologies, including laser scanning, imaging systems, and embedded sensors, provide opportunities for automated quality assurance and defect detection throughout the printing process [16] [18]. Together, these technologies establish a digital quality-management framework capable of supporting improved reliability and traceability throughout the project lifecycle.
Despite these advantages, significant barriers remain. The lack of international standards limited long-term durability data, high equipment costs, and uncertainty regarding building code compliance continue to restrict widespread implementation [20] [22].

8.1. Improved Accuracy

Robotic systems have demonstrated millimeter-level dimensional precision under controlled printing conditions, reducing geometric deviations relative to conventional construction methods [6].

8.2. Enhanced Material Control

Automated batching and dispensing systems improve the consistency of rheological properties, printability, and interlayer bonding [4] [10].

8.3. Real-Time Quality Assurance

Laser scanners, cameras, machine vision systems, and embedded sensors can detect defects during fabrication, allowing immediate corrective action [18] [23]

8.4. Improved Documentation and Traceability

Digital construction workflows create detailed records of construction activities, facilitating maintenance, inspection, and lifecycle management.

8.5. Challenges

Several barriers continue to affect adopting

1. Lack of internationally accepted standards;
2. Limited long-term durability data;
3. High initial capital investment;
4. Shortage of specialized expertise; and
5. Building-code compliance uncertainty.

9. CONCLUSION

Three-dimensional concrete printing has emerged as one of the most promising innovations in the ongoing digital transformation of the construction industry. This review examined the potential of 3D concrete printing to improve construction quality control through automation, digital fabrication, Building Information Modeling (BIM) integration, and real-time monitoring technologies. The findings indicate that 3DCP can enhance dimensional accuracy, improve material consistency, reduce human error, minimize rework, and support more efficient quality-assurance processes compared with conventional construction methods.

The reviewed literature and international case studies demonstrate that the integration of automated printing systems, sensor technologies, machine vision, and digital workflows creates new opportunities for continuous quality monitoring and process optimization throughout the construction lifecycle. In addition to improving quality performance, 3D concrete printing offers complementary benefits related to productivity, material efficiency, and sustainability, making it a potentially transformative technology for future construction practice.

Despite these advantages, several challenges continue to limit widespread adoption, including the lack of internationally accepted standards, uncertainty regarding long-term durability, regulatory barriers, and the high initial investment required for implementation. Addressing these challenges will require continued collaboration among researchers, industry practitioners, equipment manufacturers, and regulatory agencies.

Overall, the evidence reviewed in this study suggests that 3D concrete printing has the potential to fundamentally reshape quality management in construction by shifting the industry from defect detection toward defect prevention through automation, data-driven decision-making, and real-time quality assurance. As Industry 4.0 technologies continue to mature, 3DCP is expected to play an increasingly important role in delivering safer, more sustainable, and higher-quality built environments.

Future Research Directions

Future research should focus on artificial-intelligence-driven quality assurance systems, digital twins, machine-learning-based defect prediction, long-term durability assessment, and the development of universally accepted standards for additive manufacturing in construction [18] [20] [23].

Author Contributions

The author conceived the study, conducted the literature review, analyzed and interpreted the findings, prepared the manuscript, and approved the final version for publication.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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