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Construction Quality Management Automation: Building Information Modeling (BIM) and Emerging Technologies (ET): A Review

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Construction productivity has been nearly stagnant for decades and traditional productivity metrics hinder progress. Addressing these challenges is critical for improving productivity. Emerging technologies like BIM present a viable solution for enhancing performance and productivity. Construction quality management processes (CQM) offer the potential for improving productivity; however, the construction industry is slow to adopt innovation. Manufacturing and other industries have seen productivity growth of 3.6% and 2.8% respectively because of the introduction of cutting-edge technology for reducing human errors compared to construction's that remains at 1% over the last two decades mostly due to conventional approach. Therefore, this paper reviews existing literature and identifies BIM integrative technologies that can enhance the CQM processes to improve productivity and reduce human errors. The study identified visualization modeling and automation systems technologies that can be integrated with BIM to guide stakeholders toward adoption and use for quality evaluation processes. Visualization modeling and automation system technologies that can be applied across various quality management categories are identified, offering insights for construction stakeholders. These technologies are positioned as key tools for improving the industry's efficiency and guiding stakeholders toward more effective quality evaluation and management practices.

Keywords: BIM, Emerging Technologies, Construction, Quality Management, Productivity

Introduction

Construction productivity has remained markedly lower than other industries for nearly two decades. According to McKinsey (2017), productivity growth in construction remains at 1% compared to 3.6% in manufacturing and 2.8% for other industries (McKinsey 2017). While numerous off-site factors could improve construction productivity (e.g., better procurement practices and improved design systems), poor specialty trade coordination, and insufficient quality control and assurance systems are all site-specific factors that could improve productivity (McKinsey 2017, Nguyen et al. 2020, Trupp et al. 2004). One way to improve productivity is to implement the integration of building information modeling (BIM) and cutting-edge emerging technologies that reduce or eliminate human error (Nguyen et al. 2020, Safa et al. 2015).

Quality is a foundational aspect of improved productivity and product delivery. To achieve increased productivity, required product quality, and ensure products perform their intended purpose, other industries have implemented emerging and existing innovations for decades, while retiring conventional/traditional methods (CTMs) heading toward Revolution 4.0 (Alaloul et al. 2020, Pan et al. 2020). Conversely, construction has relied on more conventional applications, with limited technological implementation into construction quality management (CQM) processes (Dixit et al. 2019, Selvam et al. 2020). Furthermore, current performance metrics like schedule, cost, safety, and quality management are insufficiently utilized and can result in rework – thus reducing overall productivity - or quality that does not align with project specifications (Nguyen et al. 2020, Trupp et al. 2004). According to these authors, rework occurs regularly, resulting in cost overruns of 2.3% to 9.4% of total project cost and can result in longer project durations. Given these outcomes, current construction QMPs appear insufficient.

Construction Quality Management

Construction quality management (CQM) concepts ensure project functionality is achieved through set plans and processes. Within construction, effective CQM supports a construction company's long-term competitiveness and survival by maintaining quality standards from inception to completion (Chin-Keng & Rahman, 2011). Construction is competitive and companies lacking effective CQM metrics could go out of business (Chin-Keng & Rahman, 2011). Therefore, an essential pillar of project delivery is ensuring CQM is focused on end-user satisfaction.

Quality management is the process of achieving quality levels by overseeing working processes and continually focusing on long-term goals by implementing short-term initiatives (Howarth & Greenwood, 2018, Ogunrinde et al. 2021a). According to the authors, short-term aggregation initiatives (policy, objectives, and responsibilities) help determine how the long-term quality goals (implementation) are managed and achieved. Both initiatives are critical and attained by implementing key quality categories: 1 planning, 2 assurance, 3 control, and 4 improvements. Conventional methods are traditionally used for these categories in construction which has hampered performance and productivity (Alaloul et al. 2020, Pan et al. 2020). It has been posited that technology adoption is a key solution to poor construction productivity, however, innovation acceptance is slow (Kamaruddin et al. 2016, Ma et al. 2018, Ogunrinde et al. 2021b).

To overcome these barriers, the authors developed a workflow for proper CQM processes (Figure 1) outlining evaluations for each work scope within specific category. The workflow comprises of preconstruction and construction and maintenance stages, the process map indicates required activities in each stage, and the flow of approvals and reversals. Quality assurance and control are key processes performed during each construction stage and approvals are needed before going to the next stage. According to Kamaruddin et al. (2016), Ma et al. (2018), and Nguyen et al. (2020), process documentation, product testing, report development, inspection, measurement and testing, and quality delivery evaluation should be automated to produce positive outputs in performance and productivity. The technologies identified in this study can be used for quality evaluation from construction to decommissioning stages. Therefore, it is fundamental to understand these QM categories and outline factors that could guide toward innovative applications.

Building Information Modeling (BIM)

BIM is an important tool in construction management as it provides a database that not only provides print visualization using 2D and 3D models, but conducts various model analyses (Howarth & Greenwood, 2018, Ma et al. 2018). Within a BIM, cost, schedule, safety, and quality management information can be stored or analyzed – both with and without collaborative technologies (Ma et al. 2018). This is very advantageous because it moves beyond a one-time process and creates an entire plan path from inception to maintenance. Construction is not the only adopter of BIM - automotive and aerospace industries were early adopters and still successfully utilize BIM systems (Howarth & Greenwood, 2018). BIM has continued to emerge and evolve over the last decade and supports high-quality and efficient construction management of facilities through the building's lifecycle (Chien et al. 2014, Won et al. 2013). As such, it continues to garner interest on its potential in numerous functional areas such as construction waste reduction (Won et al. 2013). According to an Accenture publication (Battle et al. 2017), BIM is gradually becoming mandatory within public procurement in multiple European countries, and early adoption in Nordic countries has made BIM strategies commonplace. In the US, over half of private-sector construction projects use BIM. BIM applications previously had restrictions that limited outside software application integration, but that is no longer the case (Battle et al. 2017, Ma et al. 2018, Won et al. 2013). BIM's functional capacities enhance the ease of information transmission among stakeholders, by creating an effective construction process and reducing offset that could lead to cost or schedule overruns (Ma et al. 2018). Despite the adoption rate and evidence of improved work rate for better construction productivity, shortfalls remain related to technical issues, investment, employee training, professional liability, organizational perspective, interoperability, etc. However, researchers have concluded that benefits outweigh shortfalls when compared to conventional methods (Ma et al. 2018, Nguyen et al. 2021, Won et al. 2013).

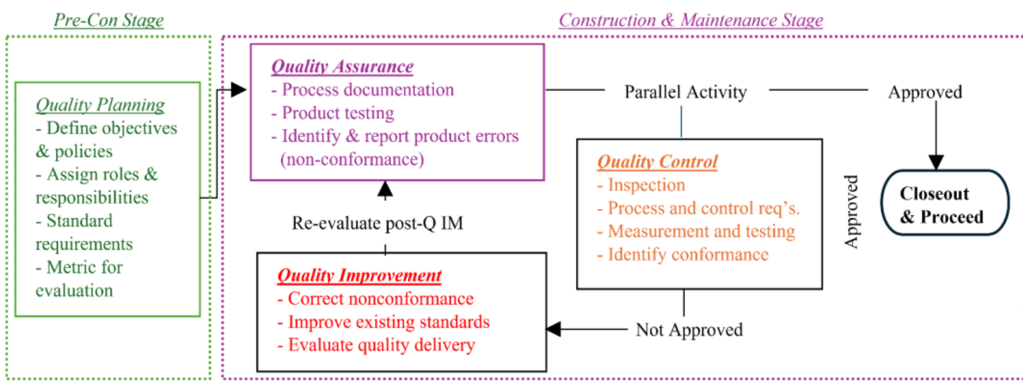

Figure 1. Construction Quality Management System Flow Process

Emerging Technologies (ET)

Emerging technologies are one of the best options available to change the trend of underperformance and declining productivity in construction (Ma et al. 2018, Ogunrinde et al. 2020, Won et al. 2013), and lessons from other industries provides insights into the possible positive outcomes of moving towards Industrial Revolution (IR) 4.0 (Alaloul et al. 2020, Ogunrinde et al. 2021a). Despite slow adoption of IR 4.0 in construction, there has been widespread adoption in the previous three eras which has improved preconstruction activities (Alaloul et al. 2020). Despite previous era acceptance, workers' inexperience, the need for training, technology cost and management acceptance are current barriers (Kamaruddin et al. 2016, Pan et al. 2020). Pan et al. (2020) and Alaloul et al. (2020) concluded that bridging the industry knowledge gap, training (in-house or college), lower cost of technology, client requirements, and senior management will play a critical role in ET acceptance. ETs are relatively new technologies that have not yet attained noteworthy dissemination across all industries and different industries have their perspective for classifying emerging and existing technologies depending on their level of use (Pan et al. 2020). This uses the term 'emerging' for all the technologies not fully integrated in construction with a focus on BIM integration for evaluating

CQM. The use of these technologies has recorded better performance in construction, including cost saving, eliminating human errors, quick defect identification, improved schedule performance, reduced claims, higher productivity, and reduced rework (Cheng et al. 2020, Desogus et al. 2021). The technologies are classified into two categories: visualization modeling and automated system technologies (Nguyen et al. 2020, Prabhakaran et al. 2020), and the same group name is used in this study. It is evident that the transformative nature of BIM and other emerging technologies has transcended the construction management domain, and there have been fragmented studies on their application to quality management. Additionally, there is limited empirical evidence demonstrating the integration of BIM with other ETs in ensuring real-time quality monitoring and control.

Research Question

The need to investigate issues relating to construction quality management automation for efficient project management and increased productivity is essential. Relying on conventional methods continues to dent performance, with virtually all metrics having one shortfall or another. Several researchers have found performance metrics (cost, schedule, safety, quality, etc.) positively impact others when proper procedures are followed (Ma et al. 2018, Pan et al. 2020). BIM is an effective tool that helps manage construction costs, schedules, procurement logistics, and quick change orders and the success of early adopters is encouraging later adopters (Howarth & Greenwood, 2018, Ma et al. 2018). It is important to note that in the last few years, there have been BIM and emerging technologies integration for monitoring, controlling, managing, and comparing as-built with as-planned (Nguyen et al. 2020, Schmitt et al. 2015, Vittorio et al. 2014). This is exactly where construction quality management should focus - using innovative means to verify quality before moving to subsequent tasks. There are studies about quality management technologies, but an emphasis on emerging technologies related to BIM integration and the stages in which construction technologies could be adopted and used to enhance productivity is limited. Another rationale for the study lies in the need to evaluate the interoperability of BIM with other emerging technologies to develop integrated solutions for predicting quality analytics, quality compliance, and rework prevention. Therefore, this study investigates the literature to find: 1) how and when technologies can be used for CQM in construction; and 2) how technologies that can be integrated with BIM.

Methodology

This study utilized a systematic review to analyze the direction and distribution of research on the adoption and use of technology in the quality management process by the mapping of BIM and ET's. According to Sadeghi et al, (2021), a systematic review has the potential to build research, practice, and policy initiatives that contribute to theory, thus helping in the development of practice and policy that could change perceptions and increase adoption. A four-stage review process was utilized. Stage 1: problem identification by reviewing the current literature to propose the existence of integration and the importance between two variables. Stage 2: literature scoping to identify existing publications that outline the problems identified in stage one. Stage 3: literature evaluation to screen for keywords in the theoretical and empirical work. Stage 4: data analysis of the eligible works and the presentation of the findings (O'Grady et al. 2021, Sadeghi et al. 2021). An extant review of literature was conducted to identify ETs that can be integrated with BIM in the construction industry. Database queries ran on several search engines like Web of Science, Google Scholar, etc., using specific keywords "quality management", and "construction management", and "BIM", and "building information modeling", "technology" in the title, abstract, keywords, and body of literature to select manuscript for this study (Ogunrinde et al. 2020, Trujillo & Holt, 2020). Combining the related keywords and the study focus subject matter on ETs for quality management automation, more than 500 articles were found combined from all databases (see Figure 2).

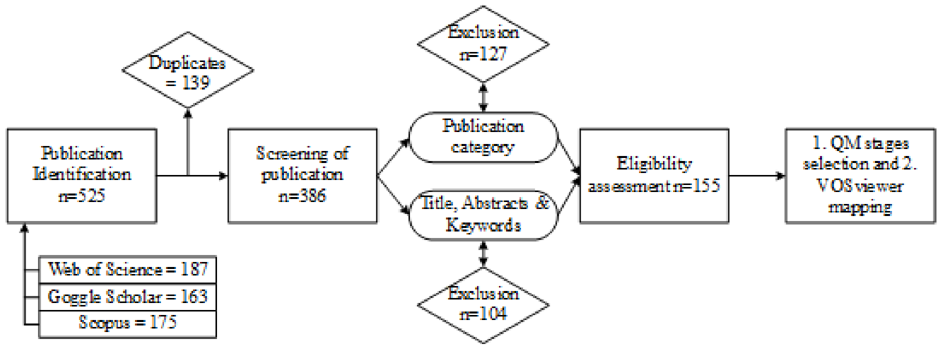

Figure 2. Research Flow Map

Publication searches were delimited to construction related (e.g., engineering, civil, construction, building, etc.), peer-reviewed publications in English between 2004 to 2024. This method is widely used in construction management studies (Cheng et al. 2020, Elqasaby et al. 2022). A total of 155 articles (see Figure 2) were used for QM stage selection. This study used VOSviewer for the visual keyword mapping, due to the software's ability to offer special features while normalizing information and data from most of the literature databases. The software is widely used in construction, health, and safety research due to its ease of use, functional features, and open-source availability (Akinlolu et al. 2020, Makabate et al. 2022).

Results

Emerging Technologies for CQM

Several technologies were identified that could be used for quality management at different construction stages; these were classified as visualization modeling technology (VMT) and automated system technology (AST). The classification is briefly discussed in the subsequent sections and technologies identified for the QM category and construction stage process are listed below.

Visualization Modeling (VMT): VMTs obtain information by employing 3D concepts such as point clouds. VMTs are accepted in construction because of their ability to actively improve hazard identification, resulting in safer and more controlled environments (Ma et al. 2018, Wang & Cho, 2015). Table 1 identifies the VMTs that could be used for evaluating CQM and those that facilitate effective communication by providing clarity to project stakeholders through 3D visualization and data collection. VMTs typically process data quickly and effectively facilitate communication, reducing errors common to conventional methods. Furthermore, the ability to create exceptional digital content helps to mitigate risk and improve several performance metrics (Wang & Cho, 2015).

Table 1. VMTs for CQM Processes and Stages

Types	QM Cat.	Constr. Stages	Authors
Virtual Reality (VR)	QP/QA/QC/QIm	Pre, During, & Maint.	(Eiris et al. 2018, Khor et al. 2016, & Noghabaei et al. 2020)
Augmented Reality (AR)	QA/QC/QIm	During & Maint.	(Cheng et al. 2020, Khor et al. 2016, & Noghabaei et al. 2020)

Mixed Reality (MR)	QP/QA/QC/QIm	Pre, During, & Maint.	(Cheng et al. 2020 & Prabhakaran et al. 2020)
Digital Twins (DT)	QA/QC/QIm	During & Maint.	(Meža et al. 2021 & Sacks et al. 2020)
Digital Close-Range Photogrammetry (DCRP)	QP/QA/QC/QIm	Pre, During, & Maint.	(Pepe et al. 2021 & Trupp et al. 2004)
Unmanned aerial system (UAS)	QP/QA/QC/QIm	Pre, During, & Maint.	(Rathinam et al. 2008 & Solla et al. 2020)

Automated System Technology (AST): ASTs are a combination of software and hardware, programmed to work automatically to achieve the predetermined requirements with limited human intrusion. They have the potential to address the shortcomings of inefficiencies by improving performance metrics and reducing human error, but acceptance remains a challenge. This study considers ASTs without immediate visuals (as seen in Table 2). AST data are transferred to corresponding computer packages while some can be seen automatically from a computer room. Some AST technologies can be integrated into (or with) construction equipment, with the requirements for effective CQM programmed directly into the system (Nguyen et al. 2020, Schmitt et al. 2015; Vittorio et al. 2014).

Table 2. ASTs for CQM Processes and Stages

Types	QM Cat.	Constr. Stages	Authors
Infrared thermography (InfraTherm)	QP/QA/QC/QIm	During & Maint.	(Schmitt et al. 2015, Solla et al. 2020, & Usamentiaga et al. 2014)
3D Laser scanner (3DLS)	QA/QC/Q Im	During & Maint.	(Nguyen et al. 2020 & Trupp et al. 2004)
Remote sensors (RS)	QP/QC/Q Im	Pre, During, & Maint.	(Desogus et al. 2021, Elqasaby et al. 2022, & Lari et al. 2015)
Ground penetration (GPR)	QP/QA/QC/Q Im	Pre, During, & Maint.	(Hossain & Yeoh, 2018 & Solla et al. 2020)

BIM and ET Integration for CQM

ETs that can be integrated with BIM for CQM processes were identified from the review and mapped using the VOSviewer, indicating which quality management categories and construction stages the technologies are useful. The VOS viewer uses lines that represent connections (or relationships) among items, clusters are groups of closely identified related items, and distinct colors visually categorize each cluster year classification. According to numerous authors, ETs are an essential solution to improve performance in construction with success achieved on projects that utilize the technology. Overall, technology costs have decreased with the ability to increase productivity and improve quality when properly implemented (Cheng et al. 2020, Desogus et al. 2021). While these factors justify the need for adoption and use, management acceptance and high upfront costs continue to be a barrier to automation growth in the industry. As some of the technologies identified can deliver all four QM categories and be integrated with BIM, there is a strong case for adoption. According to (Statista, 2017), BIM usage by construction professionals globally increased from 13%

in 2011 to 73% in 2020, but not so for automation and robotics in construction. Furthermore, the study found some visualization technologies (VR, AR, DT, and UAS) and automated system technologies (3DLS and RS) already being integrated with BIM (see Figure 3). The advent of modern design technology in the industry has experienced a series of developments – e.g., transitioning from CAD to BIM allowing efficient collaboration among the design team members – resulting in reduced errors. In the quest to better manage and deliver preconstruction activities, BIM technology has been incorporated into estimating and scheduling packages for a quick turnaround period from bidding to project delivery (Ma et al. 2018, Nguyen et al. 2021). In the same way, most ETs for CQM can be integrated allowing data in real-time and reducing human error in physical inspection (Nguyen et al. 2021, Safa et al. 2015). The technologies (Table 1 and 2) identified can be integrated with BIM, and they are efficient for evaluating CQM processes.

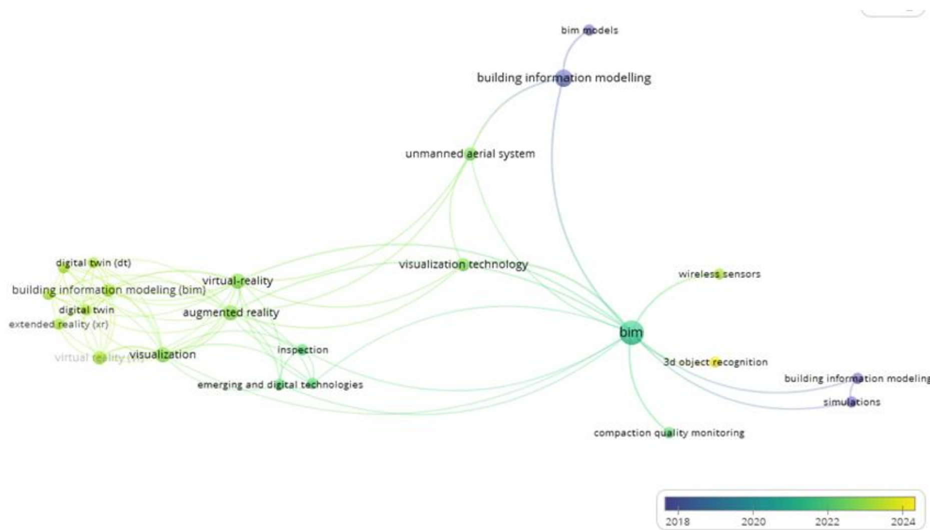

Figure 3. ET's Integrated with BIM

Conclusion and Future Studies

Productivity as a major concern in construction should prompt the adoption and use of ETs that can be integrated with BIM for CQM evaluation. This study identified visualization modeling technologies (VR, AR, MR, DT, DCRP, and UAS) and automated system technologies (InfraTherm, 3DLS, RS, and GPR) that can be used for any categories of CQM process and the construction stages. A second phase of the analysis found numerous visualization and automated system technologies already integrated with BIM. The benefits of using these ETs when integrated with BIM are cost-saving, better schedule monitoring, eliminating human error, and improved quality and these benefits should be motivators that encourage adoption and use. Also, potential limitations of these technology integrations include upfront cost, lack of expertise, integration issues, client requirements, policies, etc. However, barriers keep the construction industry behind compared to other industries that have recorded productivity improvement from technology utilization. Moreover, the issues that the industry faces from relying on CTMs should prompt the need to adopt and use technologies for CQM processes and should push toward the adoption and use of ETs. ETs have proven to be highly functional, offering better work performance and delivery than conventional methods. Therefore, the authors recommend that more ETs be used for CQM processes from inception to decommissioning and maintenance. The study also recommends for future studies the use of adopted commercial systems for real-time data and analytics capabilities of some emerging technologies such as Procore, SmartRock, IoT sensors, etc. with BIM models to improve compliance assurance, defect detection and predictive quality analytics in the delivery of construction projects. The findings of the study should help construction stakeholders to select technology that can be used for delivering projects within all requirements and standards from preconstruction to decommissioning. Most of the technologies identified are suitable for quality evaluation categories (planning, assurance, control, and improvement). Therefore, the findings should guide stakeholders in prioritizing investments for technologies (visualization modeling or automated systems) that have been found to the effective for evaluating CQM.

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