

Challenges to improving BIM competencies in railway infrastructure projects

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ARTICLE INFO	ABSTRACT
<i>Article history:</i> Received March 30, 2026 Received in revised form May 10, 2026 Accepted July 19, 2026 Available online September 01, 2026 <i>Keywords:</i> BIM competency improvement Dynamic capability theory Railway infrastructure projects Sensing Thematic analysis *Corresponding author: Nurul Sakina Mokhtar Azizi School of Housing, Building and Planning, Universiti Sains Malaysia, Penang, Malaysia Email: sakinamokhtar@usm.my ORCID: https://orcid.org/0000-0002-8011-3552	<i>This study examines challenges that hinder the improvement of Building Information Modeling (BIM) competencies in railway infrastructure projects through a Dynamic Capability Theory (DCT) sensing lens. A qualitative exploratory design was adopted, using 15 semi-structured interviews with clients, designers, contractors, and system-related participants engaged in railway BIM practice. Thematic analysis identified four interrelated challenge themes: (1) absence of process-embedded verification and authenticity-validation mechanisms; (2) breakdowns in cross-disciplinary interface coordination and model-field alignment; (3) fragmented change-version-data governance across platforms; and (4) misalignment between contractual verifiability and lifecycle usability expectations. Across these themes, project problems were visible but not consistently translated into capability-development priorities, due to delayed problem visibility, fragmented sensing infrastructure, weak problem-to-capability translation, and broken lifecycle feedback loops. The study offers a mechanism-based explanation of why BIM competency improvement remains difficult to routinise in railway delivery settings and highlights implications for verification, interface governance, and lifecycle-oriented information management.</i>

Introduction

Railway infrastructure projects are delivered through tightly coupled technical and organizational systems that extend across long asset lifecycles, multiple delivery stages, and numerous contractual interfaces. Their delivery depends on coordination among clients, designers, contractors, specialist suppliers, and, increasingly, operational stakeholders, all under strict safety, regulatory, and information-control requirements (Roehrich et al. 2023). In such settings, digitalization is often promoted as a way to improve coordination and information continuity, yet its effects depend not only on the adoption of digital tools but also on whether

project actors can use them consistently across disciplines, packages, and stages of delivery (Papachristos, Papadonikolaki, and Morgan 2024). Within transportation infrastructure, BIM has been widely presented as a lifecycle-oriented environment for design coordination, information exchange, and asset management (Belcher and Abraham 2023; Li, Li, and Ding 2024). Reviews of transport digitalization also point to the growing integration of BIM with digital twins and related data environments, suggesting a broader move toward connected digital delivery systems rather than stand-alone modelling applications (Gao et al. 2022). In railway settings, BIM has likewise been linked to inspection and maintenance functions, including defect



localization, indicating that its relevance now extends beyond design and construction alone (Sresakoolchai and Kaewunruen 2021). Even so, the practical value of BIM in railway projects still depends heavily on the competencies of those expected to produce, verify, coordinate, and use project information across organizational and disciplinary boundaries.

Existing studies have shown that the benefits of BIM in infrastructure are often constrained by interoperability problems, fragmented governance, unclear responsibilities, uneven digital maturity, and weak alignment between models, workflows, and downstream asset needs (Belcher and Abraham 2023; Hussain et al. 2024; Li, Li, and Ding 2024; Hagan, Aryanti, and Ilhamdaniah 2025; Hagan, Aryanti, and Saleh 2025; Mutaqi et al. 2026). In railway projects, these difficulties are amplified by strong interfaces among civil, track, signalling, electrification, and systems packages, as well as by the need to maintain reliable information from design through construction, commissioning, and operation (Roehrich et al. 2023). Current research has improved understanding of BIM applications, implementation barriers, and digitalization trajectories in transport and infrastructure contexts (Belcher and Abraham 2023; Gao et al. 2022; Hussain et al. 2024; Li, Li, and Ding 2024). However, it says much less about why recurring project problems do not reliably lead to competency improvement. This matters because BIM competency is not simply a matter of software skills. Earlier work has shown that it also involves process knowledge, organizational routines, evaluative practices, and the ability to align information work with project and asset requirements over time (Succar 2009; Giel and Issa 2016; Succar, Sher, and Williams 2013). In infrastructure delivery, where lifecycle information transformation and exchange are central to asset performance, the improvement of BIM competencies depends on whether lessons from repeated coordination, verification, and handover problems are actually converted into stronger routines and clearer capability priorities (Succar and Poirier 2020).

This study therefore distinguishes competency-improvement challenges from general BIM implementation barriers. A railway project may experience persistent model-field mismatches, version confusion across packages, unverifiable handover information, or repeated interface disputes without turning these problems

into sustained capability development. In other words, implementation difficulties do not automatically become learning priorities. A data exchange problem may remain an isolated technical issue; a coordination failure may be treated as a one-off delivery incident; and a handover dispute may be resolved contractually without improving the competencies needed to prevent similar failures later. This is where a dynamic capability perspective becomes useful. Dynamic capability theory explains adaptation in terms of how organizations identify changes, detect weaknesses, interpret signals, and respond by reshaping routines and resource commitments (Teece, Pisano, and Shuen 1997; Eisenhardt and Martin 2000; Teece 2007; Winter 2003). Within this perspective, sensing is particularly helpful for examining why competency improvement may stall in railway BIM practice: project problems may be visible, but not early enough, not clearly enough, or not in a form that allows them to be translated into capability-development action. In project-based digital environments, such sensing is shaped by governance arrangements, cross-organizational interfaces, and the quality of feedback carried from one delivery stage to another (Papachristos, Papadonikolaki, and Morgan 2024; Roehrich et al. 2023).

Against this backdrop, this study examines the challenges that hinder the improvement of BIM competencies in railway infrastructure projects through a Dynamic Capability Theory (DCT) sensing lens. The study adopts a qualitative exploratory design because the aim is not to test a predetermined causal model, but to explain how practitioners experience and interpret recurring obstacles to capability improvement in railway BIM practice. Thematic analysis is therefore used to identify patterned challenges across interviews and to develop an empirically grounded explanation of why competency improvement remains difficult to stabilise (Braun and Clarke 2006; 2021; Byrne 2022). This approach is also consistent with established guidance on qualitative adequacy, analytical transparency, and reporting quality in interview-based research (Guest, Bunce, and Johnson 2006; O'Brien et al. 2014). Using evidence from multiple stakeholder groups, the study contributes to current work on infrastructure digitalization by shifting attention from BIM adoption barriers to the mechanisms that block competency improvement. It also shows how a sensing-based reading of dynamic capability can help explain weak problem

recognition, fragmented feedback, and poor translation from project difficulty to capability renewal in railway delivery settings. Finally, it highlights the practical importance of verification, interface governance, change-version-data control, and lifecycle-oriented information management in strengthening BIM competency development.

Methods

This study adopted a qualitative exploratory design to investigate challenges associated with improving BIM competencies in railway infrastructure projects. Given the limited prior research explicitly addressing competency improvement mechanisms in this context, semi-structured interviews were employed to balance cross-case comparability with sufficient depth to capture role-specific and interface-specific experiences. A purposeful sampling strategy was combined with maximum variation sampling to ensure diversity in organizational type, professional role, and project-phase exposure. Participants included client representatives, consultants, contractors, system suppliers, and BIM managers who had direct involvement in railway BIM practice within the past 12 months. An initial series of interviews was conducted until thematic patterns began to stabilize, followed by five additional interviews to verify saturation. Saturation was considered achieved when no substantially new codes or thematic categories emerged during the final two interviews. In total, 15 interviews were completed, covering multidisciplinary design coordination, construction-stage model integration, systems interfacing, compliance oversight, and digital handover processes. Interviews lasted between 45 and 90 minutes. Participants were recruited through professional networks and formal

invitations. All interviewees received an information sheet outlining the research purpose and confidentiality procedures, and informed consent was obtained prior to data collection. Interviews were audio-recorded with permission, professionally transcribed, and anonymized through removal of identifiable project and organizational details.

Data were analyzed using thematic analysis (Braun and Clarke 2006), supported by NVivo software as a coding management tool rather than an automated theme generator. Analysis began with inductive open coding to identify meaning units related to BIM practices and competency-related challenges. Codes were iteratively refined through constant comparison and consolidated into a structured codebook. Higher-order themes were then developed by identifying recurrent patterns across cases. In the final stage, emergent themes were interpreted through a dynamic capability perspective, specifically mapped onto sensing-related constraints to explain how identified factors affected capability recognition, learning, and renewal processes. To maintain analytical focus, explicit boundary criteria were applied: only factors directly influencing mechanisms of capability identification, formation, transfer, evaluation, or sustained improvement were retained as core themes, while broader implementation barriers unrelated to competency evolution were excluded from the central analytical model. Credibility was enhanced through maintenance of an audit trail documenting coding decisions and theme development, and through periodic supervisory review of coding consistency to reduce interpretive bias. The additional interviews conducted after preliminary theme stabilization served as formal verification of thematic saturation. Representative quotations are presented in the findings section to ensure transparency between empirical evidence and analytical interpretation.

Table 1. Participant profile and interview coverage

Participant ID	Organizational role	Organization type	Primary interface exposure	Project phase involvement
P1	BIM Manager	Main Contractor	Design–Construction Coordination	Construction
P2	Digital Delivery Lead	Client Organization	Multi-package Integration	Design & Construction
P3	Systems Engineer	Signaling Supplier	Systems Interface Coordination	Construction & Commissioning
P4	Design Coordinator	Design Consultancy	Multidisciplinary Model Coordination	Design

Participant ID	Organizational role	Organization type	Primary interface exposure	Project phase involvement
P5	Project Information Manager	Main Contractor	Data Management and Handover	Construction
P6	Asset Integration Specialist	Client Organization	Lifecycle Data Continuity	Commissioning and Operation
P7	BIM Coordinator	Design Consultancy	Clash Detection and Interface Resolution	Design
P8	Construction Interface Manager	Main Contractor	Package Integration	Construction
P9	Systems Integration Lead	Joint Venture	Cross-Discipline Systems Integration	Construction and Commissioning
P10	Digital Engineering Advisor	Client Organization	Standards and Compliance Oversight	Design and Construction
P11	BIM Implementation Specialist	Contractor	Model Standardization	Design and Construction
P12	Rail Project Engineer	Contractor	Field-to-Model Feedback	Construction
P13	BIM Governance Officer	Client Organization	Digital Policy and Standards	Design
P14	Interface Planning Engineer	Contractor	Civil-Systems Coordination	Construction
P15	Information Control Lead	Design Consultancy	Data Exchange and Documentation	Design and Commissioning

Results and discussion

Based on iterative coding, cross-role comparison, and thematic aggregation of the interview materials, this study identified four challenge themes that are directly relevant to BIM competency improvement: (1) absence of process-embedded verification and authenticity-validation mechanisms; (2) breakdowns in cross-disciplinary interface coordination and model-field alignment; (3) fragmented change-version-data governance across platforms; and (4) misalignment between contractual verifiability and lifecycle usability expectations. These themes were not pre-defined categories; rather, they were retained because they recurred across stakeholder roles, helped explain why competency improvement is difficult to routinise, and showed strong explanatory value in railway infrastructure delivery. To reduce overlap, the themes were bounded analytically as follows: Theme 1 focuses on process verification and authenticity validation, Theme 2 on interface coordination and field alignment practices, Theme 3 on information-chain continuity and version/data governance, and Theme 4 on the disconnect between front-end specification and back-end operational use value. Accordingly, this section examines not generic BIM implementation barriers, but more specifically competency-improvement challenges, that is, recurring project

problems that are repeatedly observed yet insufficiently translated into sustained capability-development agendas and mechanisms.

Theme 1: Absence of process-embedded verification and authenticity-validation mechanisms

This theme indicates that the core issue is not whether model checks are conducted, but whether projects have process-embedded, executable, and accountable mechanisms to verify model-field consistency throughout delivery. An owner-side interviewee stated that the project lacked an executable acceptance mechanism running through the whole process and that checking only at the final node was “too late,” further clarifying that the practical problem concerns “how to check, who checks, and when to check.” In the station MEP example described by the same participant, the submitted model appeared coordinated, but site installation deviated from it due to schedule pressure and weak process control, eventually causing clashes and rework; the participant therefore recommended moving model-field consistency checks forward into routine supervision practice. Review-side evidence supports this interpretation: reviewers reported “false clashes” and “missed clashes,” including manipulated clash reports or relaxed tolerances, such that manual measurement and site verification were still required to identify

clearance problems after construction had proceeded.

From a competency-improvement perspective, these accounts suggest that when authenticity validation occurs mainly at the end of the process, organisations may struggle to determine whether the root cause lies in modelling, review, site execution, or supervisory control, thereby constraining accurate identification of competency gaps and targeted improvement. In railway infrastructure delivery with dense interfaces, strict milestones, and high rework costs, such weaknesses are more likely to escalate into schedule and quality risks. From a DCT-Sensing perspective, this theme points to weaknesses in the continuous capture and authenticity validation of high-value process signals.

Theme 2: Breakdowns in cross-disciplinary interface coordination and model-field alignment

This theme reflects not isolated technical errors but insufficient alignment mechanisms across multi-disciplinary coordination, model interpretation rules, and site execution. A design institute BIM manager noted that contractors' secondary development of design models often led to unsynchronised modifications and version confusion, and explicitly framed the key capability need as interface coordination capability, especially across bridge/civil and railway systems disciplines. A systems-interface design engineer provided a railway-specific example of a 50 cm mismatch between reserved/embedded components and cable-well positions, which eventually required concrete demolition and re-installation; the participant attributed this to inconsistent coordinate baselines and emphasised the need for early multi-disciplinary interface clash checks and interface-list formalisation during design. Site engineers and subcontractor representatives further reported unaligned coordinate-system conversion, inconsistent interpretation of dimensional references (e.g., bolt centreline versus edge), and delayed feedback of site deviations into models, resulting in embedded-component rework, structural concerns, and schedule delays.

These findings indicate a compound capability gap involving interface coordination, model interpretation, baseline-consistency management, and field-feedback integration, rather than merely a site execution problem. In Sensing terms, organisational attention appears to

remain overly concentrated on geometric clashes while under-sensing functional/maintenance space constraints, coordinate baseline consistency, and field deviation signals.

Theme 3: Fragmented change-version-data governance across platforms

Unlike Theme 1, which concerns process verification, this theme focuses on the inability to connect change information, model versions, and structured data across platforms and actors. An owner-side site representative described a typical pattern in which site work progressed first and the model was updated later, and summarised the situation as follows: change orders flowed through OA, model files through FTP, and site issues through WeChat groups, resulting in fragmented information; undocumented oral changes were described as especially damaging because they made it difficult to reconcile the model, as-built drawings, and actual site conditions. Quality/acceptance-side participants similarly reported that multiple model versions often broke the chain of accountability and that inconsistent equipment parameters affected variation procedures, acceptance efficiency, and payment processes. Data management and quantity-surveying roles extended this issue into coding and measurement: inconsistent coding undermined cross-package aggregation, and delayed model updates forced quantity take-off and settlement work back to manual calculation, increasing dispute risk. Their proposed remedies converged on contractual data dictionaries, milestone-based data compliance checks, and stronger "change-model-quantity" linkage mechanisms.

From a competency-improvement perspective, such fragmentation weakens an organisation's ability to generate stable performance evidence and credible problem attribution, making training, process redesign, and responsibility allocation harder to align with actual weaknesses. In railway infrastructure projects-characterised by multiple packages, long durations, and dense inter-organisational collaboration, this fragmentation is particularly likely to accumulate and propagate across stages. From a Sensing perspective, the issue is not the absence of signals, but the absence of a sensing infrastructure capable of connecting dispersed signals into an interpretable problem chain.

Theme 4: Misalignment between contractual verifiability and lifecycle usability expectations

This theme highlights insufficient linkage between front-end institutional definitions and back-end operational use, rather than a purely technical data-quality problem. Contract/procurement participants noted that even where model accuracy, delivery milestones, and attribute fields were included in contracts, clauses often lacked practical verifiability, for example, inconsistent interpretations of LOD or attribute requirements not specified at the parameter level, leading to acceptance disputes and schedule impacts at handover. Correspondingly, O&M/asset handover and maintenance roles indicated that their concern was not whether a model had been delivered, but whether it could be trusted and used continuously: missing fields, inaccurate fields, wrong locations, inconsistent IDs, and outdated updates reduced operational usability and, in some cases, introduced maintenance risks. One maintenance interviewee described a near-mistake caused by inconsistent valve numbering between the model and site labels, which led the team to stop fully trusting the model.

These accounts suggest that the challenge is not simply poor handover quality; rather, it may reflect a persistent overemphasis on modelling outputs during construction, with comparatively limited attention to capabilities for handover usability, data trustworthiness, and O&M update mechanisms. For long-life, safety-sensitive railway infrastructure assets, this mismatch is particularly consequential. From a Sensing perspective, this theme indicates that organisational sensing boundaries often remain confined to delivery milestones, without continuously absorbing value signals from downstream operational use.

Across the four themes, the findings point to a deeper mechanism: project problems are observable, but are often not stably translated into competency-improvement agendas embedded in routine organisational practice. Specifically, many high-cost problems become visible mainly at acceptance, inspection, settlement, or O&M stages, reflecting delayed problem visibility. In parallel, changes, versions, field deviations, coding practices, and O&M feedback are dispersed across platforms and actors, indicating a fragmented sensing infrastructure. In practice, many issues are treated as schedule-driven exceptions or individual mistakes rather than

elevated into interface, verification, or data-governance capability issues, representing a failure of problem-to-capability translation. Finally, downstream signals of unreliable or unusable information often fail to flow back into contract definitions, design rules, and construction controls, indicating broken lifecycle feedback loops. Together, these mechanisms help explain why similar problems may recur even when projects have introduced BIM requirements or staged training efforts.

From a DCT-Sensing perspective, the contribution of this study lies in moving beyond barrier listing (as is common in BIM barrier studies focused on adoption/implementation constraints) toward explaining why competency improvement routines fail to stabilise in practice. The interview evidence suggests potential breakdowns across signal capture, signal validation, and signal translation: weak process-embedded verification and end-stage acceptance orientation undermine sustained signal capture; false/missed clashes, version confusion, and model-field inconsistency weaken signal validation; and when rework, delays, handover disputes, and operational risks are not stably mapped into questions of which capabilities should be improved, by whom, and at what stage, signal translation remains incomplete. In this sense, the study does not merely add railway cases to existing BIM barrier discussions; it advances a mechanism-based explanation of why competency improvement remains difficult to routinise, in a manner consistent with the processual logic of DCT-Sensing.

From a built environment and infrastructure delivery perspective, these findings can be anchored to core concerns in design coordination, information handover, and cross-disciplinary governance. The interviews indicate that many apparent “model problems” are in fact manifestations of governance issues at the model layer, such as unclear design-depth boundaries, lack of interface lists, inconsistent coordinate/rule conventions, weak change-record mechanisms, unstable version authority, and insufficiently verifiable data requirements. Likewise, many handover failures are not only cases of missing attributes, but are linked to weak contractual verifiability and under-specified data dictionaries, which later surface as untrustworthy information, unusable models, or unsustainable update practices in O&M. For built-environment journals such as ARTEKS, the practical implication is

therefore not simply to add more BIM requirements, but to improve the quality of organisational sensing and problem translation through mechanisms such as earlier process verification, interface-list formalisation, stronger

change–model linkage, data compliance checks, and front-loaded O&M requirements and update mechanisms, thereby supporting more reliable lifecycle delivery and operational performance in railway infrastructure projects.

Table 2. Summary of challenge themes and competency-improvement relevance

Theme	Core Focus	Why It Constrains Competency Improvement	Representative Evidence
Theme 1: Absence of process-embedded verification and authenticity-validation mechanisms	Process-wide model–field consistency verification and authenticity validation	Delays/weakens accurate identification of competency gaps (e.g., modelling vs review vs execution vs supervision)	Owner (A1); Reviewer (D1); QA/Acceptance (D2)
Theme 2: Breakdowns in cross-disciplinary interface coordination and model–field alignment	Interface coordination, baseline/rule alignment, and field constructability	Repeated project deviations are not translated into capability agendas (interface coordination, interpretation, feedback integration)	Design/BIM manager (B1); Systems/interface engineer (B3); Site/Subcontractor (C2/C3)
Theme 3: Fragmented change–version–data governance across platforms	Information-chain continuity, version authority, and data standard consistency	Weak performance evidence and problem attribution reduce the precision of training/process redesign	Owner site representative (A2); QA/Acceptance (D2); Data/Quantity roles (E1/E2)
Theme 4: Misalignment between contractual verifiability and lifecycle usability expectations	Contractibility of BIM deliverables vs downstream operational usability	Sustains overemphasis on modelling outputs while under-developing handover usability and O&M update capabilities	Contract/Procurement (E3); O&M roles (F1/F2)

Conclusions

This study explored BIM competency-improvement challenges in railway infrastructure projects through a thematic analysis of cross-role interview evidence. Four interrelated challenge themes were identified: (1) the absence of process-embedded verification and authenticity-validation mechanisms; (2) breakdowns in cross-disciplinary interface coordination and model–field alignment; (3) fragmented change–version–data governance across platforms; and (4) misalignment between contractual verifiability and lifecycle usability expectations. Taken together, these findings indicate that the main difficulty is not simply the presence of BIM implementation barriers, but the weak routinisation of how project problems are recognised, validated, and translated into capability-development priorities. This difficulty is amplified in railway infrastructure delivery, where dense disciplinary interfaces, long delivery chains, strict milestone control, and lifecycle-critical information requirements make coordination and information reliability particularly consequential. By moving beyond barrier listing toward a cross-theme mechanism explanation, centred on delayed problem

visibility, fragmented sensing infrastructure, failure of problem-to-capability translation, and broken lifecycle feedback loops, this study offers a DCT-Sensing-informed account of why competency improvement remains difficult to stabilise in practice. In practical terms, it points to the importance of earlier process verification, stronger interface governance, more coherent change–model–data linkage, and better alignment between contractual requirements and downstream operational use.

Several limitations should be acknowledged. First, the study is based on a qualitative sample and is intended to provide analytical depth and mechanism explanation rather than statistical generalisation. Second, the findings are bounded by the railway infrastructure delivery context and may reflect institutional, contractual, and organisational conditions specific to the cases represented in the sample. Third, transferability is likely stronger for urban rail and other linear infrastructure projects with comparable interface complexity and lifecycle information demands, while more cautious interpretation is needed for small-scale single-building projects with simpler coordination structures. Future research may extend this work in three directions. One is to connect the identified challenge themes with

supporting factors and improvement strategies in subsequent studies, so as to build a more complete competency-improvement mechanism model. A second is to operationalise the identified challenge mechanisms into questionnaire-based measures and examine their prevalence and relative salience across a larger sample. A third is to conduct cross-region and cross-project-type comparative studies to test how governance arrangements, contract structures, and organisational maturity shape BIM competency-improvement dynamics across infrastructure contexts.

References

- Belcher, Ethan J., and Yewande S. Abraham. 2023. "Lifecycle Applications of Building Information Modeling for Transportation Infrastructure Projects." *Buildings* 13 (9): 2300. <https://doi.org/10.3390/buildings13092300>.
- Braun, Virginia, and Victoria Clarke. 2006. "Using Thematic Analysis in Psychology." *Qualitative Research in Psychology* 3 (2): 77–101. <https://doi.org/10.1191/1478088706qp063oa>.
- Braun, Virginia, and Victoria Clarke. 2021. "One Size Fits All? What Counts as Quality Practice in (Reflexive) Thematic Analysis?" *Qualitative Research in Psychology* 18 (3): 328–52. <https://doi.org/10.1080/14780887.2020.1769238>.
- Byrne, David. 2022. "A Worked Example of Braun and Clarke's Approach to Reflexive Thematic Analysis." *Quality & Quantity* 56 (3): 1391–1412. <https://doi.org/10.1007/s11135-021-01182-y>.
- Eisenhardt, Kathleen M., and Jeffrey A. Martin. 2000. "Dynamic Capabilities: What Are They?" *Strategic Management Journal* 21 (10–11): 1105–21. [https://doi.org/10.1002/1097-0266\(200010/11\)21:10/11<1105::AID-SMJ133>3.0.CO;2-E](https://doi.org/10.1002/1097-0266(200010/11)21:10/11<1105::AID-SMJ133>3.0.CO;2-E).
- Gao, Chao, Jianwei Wang, Shi Dong, Zhizhen Liu, Zhiwei Cui, Ningyuan Ma, and Xiyang Zhao. 2022. "Application of Digital Twins and Building Information Modeling in the Digitization of Transportation: A Bibliometric Review." *Applied Sciences* 12 (21): 11203. <https://doi.org/10.3390/app122111203>.
- Giel, Brittany, and Raja R. A. Issa. 2016. "Framework for Evaluating the BIM Competencies of Facility Owners." *Journal of Management in Engineering* 32 (1). [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000378](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000378).
- Guest, Greg, Arwen Bunce, and Laura Johnson. 2006. "How Many Interviews Are Enough?" *Field Methods* 18 (1): 59–82. <https://doi.org/10.1177/1525822X05279903>.
- Hagan, Daniel Ebo, Tutin Aryanti, and Ilhamdaniah. 2025. 'Challenges of BIM Integration in Construction Education: The Ghanaian Perspective'. *ARTEKS: Jurnal Teknik Arsitektur* 10 (3). <https://doi.org/https://doi.org/10.30822/arteks.v10i3.4320>.
- Hagan, Daniel Ebo, Tutin Aryanti, and Ilhamdaniah Saleh. 2025. 'Trends of BIM Integration in Construction Education: A Bibliometric-Based Visualization Analysis'. *ARTEKS: Jurnal Teknik Arsitektur* 10 (1). <https://doi.org/https://doi.org/10.30822/arteks.v10i1.3763>.
- Hussain, Osama A. I., Robert C. Moehler, Stuart D. C. Walsh, and Dominic D. Ahiaga-Dagbui. 2024. "Minimizing Cost Overrun in Rail Projects through 5D-BIM: A Conceptual Governance Framework." *Buildings* 14 (2): 478. <https://doi.org/10.3390/buildings14020478>.
- Li, Yaning, Yongchang Li, and Zhikun Ding. 2024. "Building Information Modeling Applications in Civil Infrastructure: A Bibliometric Analysis from 2020 to 2024." *Buildings* 14 (11): 3431. <https://doi.org/10.3390/buildings14113431>.
- Mutaqi, Ahmad Saifudin, Ariadi Susanto, Purnama Salura, Reginaldo Christophori Lake, and L. M. F. Purwanto. 2026. 'Integration of Virtual Reality and Heritage BIM for the Preservation of Buried Cultural Heritage Temples in Yogyakarta'. *ARTEKS: Jurnal Teknik Arsitektur* 11 (1). <https://doi.org/https://doi.org/10.30822/arteks.v11i1.4429>.
- O'Brien, Bridget C., Ilene B. Harris, Thomas J. Beckman, Darcy A. Reed, and David A. Cook. 2014. "Standards for Reporting Qualitative Research." *Academic Medicine* 89 (9): 1245–51.

- <https://doi.org/10.1097/ACM.0000000000000388>.
- Papachristos, George, Eleni Papadonikolaki, and Bethan Morgan. 2024. "Projects as a Speciation and Aggregation Mechanism in Transitions: Bridging Project Management and Transitions Research in the Digitalization of UK Architecture, Engineering, and Construction Industry." *Technovation* 132 (April):102967.
<https://doi.org/10.1016/j.technovation.2024.102967>.
- Roehrich, Jens K., Andrew Davies, Beverly B. Tyler, Anant Mishra, and Elliot Bendoly. 2023. "Large Interorganizational Projects (LIPs): Toward an Integrative Perspective and Research Agenda on Interorganizational Governance." *Journal of Operations Management* 69 (8): 1118–42.
<https://doi.org/10.1002/joom.1280>.
- Sresakoolchai, Jessada, and Sakdirat Kaewunruen. 2021. "Integration of Building Information Modeling and Machine Learning for Railway Defect Localization." *IEEE Access* 9:166039–47.
<https://doi.org/10.1109/ACCESS.2021.3135451>.
- Succar, Bilal. 2009. "Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders." *Automation in Construction* 18 (3): 357–75.
<https://doi.org/10.1016/j.autcon.2008.10.003>.
- Succar, Bilal, and Erik Poirier. 2020. "Lifecycle Information Transformation and Exchange for Delivering and Managing Digital and Physical Assets." *Automation in Construction* 112 (April):103090.
<https://doi.org/10.1016/j.autcon.2020.103090>.
- Succar, Bilal, Willy Sher, and Anthony Williams. 2013. "An Integrated Approach to BIM Competency Assessment, Acquisition and Application." *Automation in Construction* 35 (November):174–89.
<https://doi.org/10.1016/j.autcon.2013.05.016>.
- Teece, David J. 2007. "Explicating Dynamic Capabilities: The Nature and Microfoundations of (Sustainable) Enterprise Performance." *Strategic Management Journal* 28 (13): 1319–50.
<https://doi.org/10.1002/smj.640>.
- Teece, David J., Gary Pisano, and Amy Shuen. 1997. "Dynamic Capabilities and Strategic Management." *Strategic Management Journal* 18 (7): 509–33.
[https://doi.org/10.1002/\(SICI\)1097-0266\(199708\)18:7<509::AID-SMJ882>3.0.CO;2-Z](https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z).
- Winter, Sidney G. 2003. "Understanding Dynamic Capabilities." *Strategic Management Journal* 24 (10): 991–95.
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Author(s) contribution

Dahuai Zhao contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Nurul Sakina Mokhtar Azizi contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

Nazirah Zainul Abidin contribute to methodology, supervision, and validation.

Weiwei Wang contribute to methodology, supervision, and validation.

Rui Niu contribute to methodology, supervision, and validation.

Yana Zhang contribute to methodology, supervision, and validation.

Jiasheng Zhou contribute to methodology, supervision, and validation.

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