Review on Maturity Evaluation of Data Interoperability for Construction Robotics

Hou-Lin Wang
China Communications Information & Technology Group CO., LTD
Beijing, China
2011168717@ccccltd.cn

Bao-Yi Liu
China Communications Information & Technology Group CO., LTD
Beijing, China
liubaoyi1@ccccltd.cn

Kuan Chang
China Communications Information & Technology Group CO., LTD
Beijing, China
changkuan@ccccltd.cn

Guang-Lin Du
China Communications Information & Technology Group CO., LTD
Beijing, China
2022020453@ccccltd.cn

Ke-Xiao Yan
Department of Civil Engineering, Tsinghua University
Beijing, China
quincykx@tsinghua.edu.cn

Zhi-Zhou He
Department of Civil Engineering, Tsinghua University
Beijing, China
hezhizhou@tsinghua.edu.cn

Jia-Rui Lin*
Department of Civil Engineering, Tsinghua University
Beijing, China
lin611@tsinghua.edu.cn

***Abstract*—Amid digital transformation, construction robotics has advanced rapidly through BIM, yet systematic lifecycle management is still hampered by fragmented data flows. Robots act simultaneously as on-site sensors and actuators, generating and consuming data that are stored locally in standard formats and periodically pushed to management platforms via predefined protocols. However, cross-stage consistency and interoperability remain largely unaddressed; yet no maturity metric exists to evaluate how well robotic data interoperates with evolving data model resources. Compounding the problem are heterogeneous standards, disparate data sources, uneven quality, and weak cross-phase correlation. This study therefore reviews international information modelling standards and summarizes BIM Maturity Measure methods including leveling, model composition, application, and capability evaluation, to propose a maturity framework that specifically measures data interoperability for construction robotics. The framework guides practitioners in enhancing BIM-based data interoperability across the full project lifecycle.**

Keywords-evaluation; data interoperability; construction; robot; BIM

I. INTRODUCTION

Drawing on the taxonomy of construction robots based on functional features[1], six representative types are illustrated in Fig.1, encompassing those for rebar-tying[2], surface spraying[3], site inspection[4], earthwork operations[5], aerial inspection[6], and physically demanding task assistance[7]. In the CNKI database, a search was conducted using the subject term BIM, and a total of 500 documents were obtained. By analyzing the abstracts of each literature one by one, relevant literature from 2005 to 2025 was screened out, and the strongest citation bursts words were counted (Fig.2). The application of construction robots in projects is interrelated with the application of BIM technology, and the requirement for data interoperability is becoming increasingly obvious.

On modern construction sites where robotic operations are highly intensive, every action during a particular stage of a project is immediately converted into structured data streams[1,4,8]. For example, the robotic crane for material handling and precision positioning assigns a unique ID to each captured component[2]. It records the component's actual spatial coordinates, installation timestamp, and three-dimensional deviation (with millimeter-level accuracy) relative to the position in the BIM model. At the same time, it tracks the consumption of wire ropes, chains, or hydraulic energy. The rebar-tying robot reports the QR codes/barcodes, cutting lengths, and quantities of each stirrup and straight bar, while storing the precise x, y, z coordinates of every tie wire twisting point[2]. During reinforced concrete operations, the batching plant embeds a digital certificate (containing mix ratio ID, slump, temperature, and volume) into each transit vehicle. This data stream is subsequently extended with the layered thickness recorded by the pumping-spraying robot, and further augmented by the floor flatness, surface temperature, and per-square-meter timestamps documented by the leveling-finishing robot[3]. While laying each brick or wall panel, the masonry and wall panel installation robot writes the actual coordinates of the four corners into the file and measures the thickness of the adhesive or mortar joint with a laser ruler. The automatic template/trolley system transmits the instantaneous position, inclination angle and closing pressure of each hydraulic jack in real time[5]. The cutting robot imports the theoretical DXF contour, compares it with the actual size of the sheet metal, and records the width of the cutting seam and the verticality of the edge. Inspection drones and crawling robots incorporate displacement, crack width, corrosion area, concrete temperature, and ambient humidity into a unified federated model[9]. For specialized applications, aerial spraying/grinding robots record coating thickness, coverage area, and grinding depth in real-time beneath the boom; underwater milling units log milling depth, vehicle attitude (roll, pitch, yaw), and real-time slurry concentration; while post-trenching cable-laying robots track trench bottom elevation while storing burial depth and GPS trajectory data[10]. Thus, the operational essence of the four functional robotic groups, such as spraying and measurement, transportation and hoisting, processing and floor treatment, and special scenario inspection, lies in generating, sharing, and updating a continuous, timestamped, georeferenced, and component-level information model. This model is designed to support construction scenarios such as progress tracking, quality analysis, and predictive maintenance in real time[11].

Any robotic system equipped with positioning, sensing, or control functionalities inherently generates structured data[11,12]. Currently, mainstream construction robots are factory-equipped with API/IoT modules, enabling over 90% of the aforementioned tasks to produce data directly writable into BIM. This data subsequently serves as the foundational digital blueprint for digital twin models throughout the entire project lifecycle such as from detailed design and construction simulation to quality inspection, project handover, and operations maintenance.

However, there is a lack of integration of solutions that facilitate this transition[12]. Automating data-driven processes in construction is critical[13]. Life Cycle Assessment (LCA) in construction relies on the continuous data interoperability of construction and environmental databases; however, manual processes are time-consuming and error-prone. The adoption of open standards and protocols to ensure interoperability among diverse software and tools serves as one of the key approaches to achieving continuous data interoperability[12].

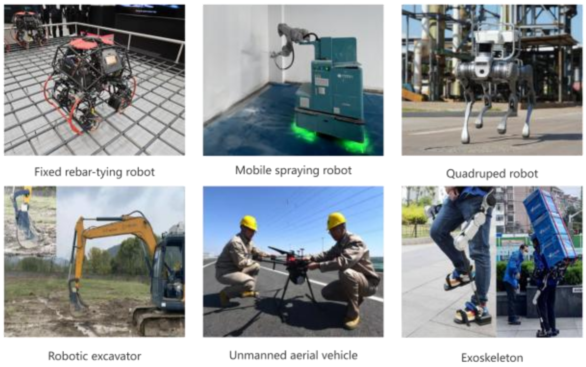

Figure 1. Typical construction robots

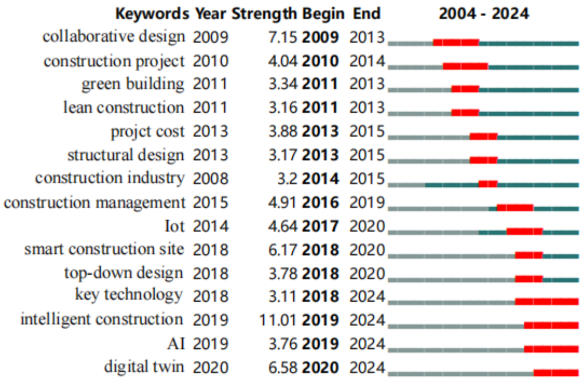

Figure 2. Top 15 Keywords with the Strongest Citation Bursts of BIM

II. LITERATURE REVIEW

A. Data Model and Standard

TABLE I. OVERVIEW OF STANDARD

#	Standard	Content	ref
1	IFC (Industry Foundation Classes)	IFC (Industry Foundation Classes) is an open and neutral BIM data exchange standard developed and maintained by the international organization buildingSMART. It facilitates cross-software and cross-organizational information sharing and collaboration throughout the entire lifecycle of architecture, engineering, construction, and operations (AECO).	[14]
2	IDM (Information Delivery Manual)	The Information Delivery Manual (IDM) standardizes the deliverable information content across project phases, delineates responsibilities and workflows of various stakeholders in information exchange, and operates in conjunction with IFC (Industry Foundation Classes) to ensure accurate information transmission to designated recipients at appropriate stages.	[15]
3	IFD (International Framework for Dictionaries)	The International Framework for Dictionaries (IFD) addresses ambiguities in terminology and conceptual definitions across languages, regions, and software systems by assigning a Globally Unique Identifier (GUID) to each concept, thereby ensuring semantic interoperability.	[16]
4	CityGML	CityGML serves as an open standard for the exchange of 3D urban model data, enabling city-scale spatial information modeling and can be interoperably utilized with IFC for integrated applications in architecture and urban planning.	[17]

5	URDF (Unified Robot Description Format)	Unified Robot Description Format (URDF) is an XML-based file format of a robot model and developed by the ROS (Robot Operating System) community to describe a robot's geometry, kinematic and inertia information as well as other physical parameters. As a "digital blueprint" of a robot, URDF files can be "read" by ROS for simulation, motion planning and animation. URDF files may use either the .urdf or .xml file extension.	[8]

B. Maturity evaluation system for BIM-related scenarios

1) NBIMS ICMM：Minimum BIM

In 2007, the U.S. National Building Information Modeling Standard (NBIMS) included an initial BIM maturity assessment tool as part of its national BIM standard. The tool for assessing maturity has been adapted for BIM and is derived from the Capability Maturity Model (CMM)[18,19]. As the standard was revised the tool in the third revision uses 11 assessment indicators with 10 intermediate levels to define a maturity level.Each evaluation indicator of each level is assessed by the evaluator in its own context and the corresponding level score is assigned. A weighted value is calculated to be the total score of this BIM maturity level. In the third version of the standard, the weightings of 11 evaluation indicators is assigned by the evaluator. Also, the standard sets a Minimum BIM that sets the total score of 40 points as the Minimum BIM requirement[20].

2) iBIM

The BIM maturity model in the United Kingdom classifies BIM maturity into four levels, ranging from Level 0 to Level 3. Level 0 represents the stage of 2D CAD application; Level 1 denotes the stage of 2D/3D CAD model application with object models; Level 2 signifies the stage of collaborative application achieved through 3D BIM technology; and Level 3 represents the stage where all data throughout the engineering lifecycle undergoes comprehensive integrated management and application. This stage - division theory intuitively reflects the depth and breadth of BIM technology application at different stages of construction projects[21].

3) IU BIM Proficiency Matrix

Indiana University created the IU BIM Capability Matrix, an Excel sheet with 8 categories: the degree to which models are accurate in depicting the physical state, the degree to which integrated product development is done using BIM, the degree to which a computational mindset is present, spatial awareness, innovation of content, construction data, as-built modeling, and richness of facility management data. The matrix has 32 dimensions that it evaluates against and five maturity levels. (Unlike NBIMS ICMM, not all of the matrix's dimensions have weights associated with them). To estimate BIM maturity, respondents answer each item on a scale from 0 to 1; the range 0 is the situation without using BIM, 1 is a complete function use of BIM. Finally, the sum of items gives the score of the total maturity of BIM with the range of scores indicating one of five stage "Pilot stage of BIM development", "Established stage of BIM" ,"Silver BIM", "Gold" BIM, "Ideal" BIM[22,23].

4) BIM Maturity Matrix

The BIM Maturity Matrix (BIM MM) created by Succar, 2009 is a mature evaluation model. It is based on available theory, which also tries to offer explanations to different metrics used to avoid lack of consistency in these metrics and opens up the evaluation out of the context of technological elements of BIM, including the matrix model comprises three areas: processes, technologies and policies.This consists of 12 review criteria for resources, processes, products, services, leadership, software, hardware, networks, benchmarks, contracts, and oversight. Each criterion is marked with a five-level scoring system. Then, the value of the BIM maturity level is simply the mean score of the individual indicator's mark values.[22,24].

5) BIM Quick Scan

The BIM Quick Scan tool was developed by TNO (Netherlands Organization for Applied Scientific Research). This instrument is structured into four primary components: Organization and Management, Mindset and Culture, Information Structure and Information Flow, as well as Tools and Applications. Each section encompasses a series of key performance indicators (KPIs) in the form of multiple-choice questionnaires, offering a range of potential responses. Each response option is assigned a specific score, and every KPI is associated with a corresponding weighting coefficient. The overall BIM performance score for an organization is derived from the aggregated scores of all sections, taking into account their respective weightings[25,26].

6) VDC Scorecard

VDC Scorecard in 2012 is Stanford University and it defines four fundamental domains: Planning, Adoption, Technology and Performance. The Planning involves goals, processes and planning; the Adoption reflects the organizational and processes issues; the Technology reflects the applications, coverage and integration; the Performance reflects quantifiable and non-quantifiable result respectively. There are 10 categories and 74 metrics in total. A unique function of the tool is ability to assure trustworthiness and examine the degree of objective integrity of data sources and to heighten the legitimacy of the assessments. Additionally, due to being a tool for benchmarking, the scores to the metrics are compared to industry norms and provided as percentiles ranked in five classes expressing the BIM implementation maturity level with regards to the other participants[27].

7) CIC Research Program's Owner Matrix

The revised BIM Project Execution Planning Guide for Facility Owners Version 2.0 was issued by BIM Consensus Standards Committee in 2013 to guide all project participants' effective planning of BIM implementation. The facility owners, namely project client in other words, is the main user of this version 2.0 guidance. The basic BIM planning contents including strategy, uses, process, information, infrastructure, personnel are explained in this guideline.The Strategy component, including the company's mission and goals, BIM mission and targets, the senior leadership support, the senior BIM leader's support, and the content of the BIM plan; the Uses component, including project uses, operational purposes, etc.; the Processes component, including project process and organizational process; the Information component, including the model element decomposition, the development process, as well as the property data of facilities, etc.The infrastructure element focuses on software, hardware, and physical space; the personnel element concentrates in roles and responsibilities, organizations structure, education, training, and readiness for change; and the guide includes brief descriptions of the maturity levels prescribed for each planning element.Every element is equipped with a 0-5 maturity grade, based on an ordinal 6-scale maturity level representing an organization's gradual degree of maturity for using the element (from not at all to 100%)[28].

8) Owner's BIMCAT

In 2013, Giel and Isaa jointly developed the Owner BIM Capability Assessment Tool (Owner BIM CAT), a framework specifically designed for project owners. This tool comprises three core assessment domains: operational capability, strategic capability, and administrative capability, which are further subdivided into 12 sub-domains. It contains BIM deliverable review; Project BIM, Technology, People Competency, Organizational BIM Implementation, Project Documenting, Project Standard, Readiness, Goals, Policy, Personnel and Procedures. The framework further contains 66 specific measures that basically covers all the concepts of BIM implementation from a life-cycle view.The Owner BIM CAT describes the key owner competence areas under three general categories: operational, strategic and administration. Each category is further delineated into six competency levels[29].

9) BIM Cloud Score

BIM Cloud Score has been created in 2014 as a specific tool to analyze BIM modeling technologies maturity and it consists of six main evaluation criteria and 19 numerical indicators. Main criteria are productivity, performance, model quality, precision, user friendliness, cost efficiency.The implementation of BIM Cloud Score requires accuracy in input data while with the support of hybrid computation and pre-programmed software, it can realize the entire workflow automation from data acquisition to grade evaluation and weighted composition. It can be self-adaptable and optimized by means of various mathematical test theories[30,31].

TABLE II. MATURITY MODEL USE ATTRIBUTES

Attribute Category	Attribute Name	Model								
		NBIMS CMM	iBIM	IU BIM Proficiency Matrix	BIM Maturity Maxtrix	BIM Quick Scan	VDC Scoredcard	CIC Research Program's Owner Matrix	Owner's BIMCAT	BIM Cloud Score
Method of application	Self-assessment	√	√	√	√	√	√	√	√	√
	Third-party assisted assessment	√	√	√	√	×	√	√	√	√
	Assessment by certified practitioners	√	×	√	√	×	√	√	×	×
Support of application	Software assessment tool	×	√	√	√	√	√	√	√	√
	Textual description or handbook	√	√	√	√	√	√	√	√	√
	Relevant explanatory materials	√	√	√	√	√	√	√	√	√
Practicality of evidence	Explicit recommendations	√	√	√	√	√	√	√	√	√

III. DISCUSSION

Despite their shared objectives, these models also exhibit distinctions and varying degrees of efficacy as table 2 shown. For instance, the Capability Maturity Model (CMM), developed by the Software Engineering Institute at Carnegie Mellon University in the United States, assesses an organization's software development capability maturity across five levels, ranging from initial to optimized[18]. NBIMS-US V3 incorporates the CMM concept to evaluate organizational BIM implementation processes, employing both Tabular CMM and Interactive CMM approaches[20]. In contrast, the UK's BIM Maturity Model (iBIM) categorizes BIM maturity into four levels, from Level 0 to Level 3, providing a clear representation of the depth and breadth of BIM technology application at different stages of construction projects[21]. Different models may vary in specific evaluation dimensions, indicator systems, and methodologies, making them suitable for diverse assessment purposes and contexts.

Based on a comprehensive comparison of the aforementioned data standards as table 1 and table 2 shown and evaluation models with indicator systems, a new evaluation model and indicator framework should encompass four fundamental dimensions: leveling, model composition, model application, and capability assessment.

A. Leveling

Although specific definitions of maturity levels may vary depending on evaluation criteria and frameworks, they generally follow a progression from low to high, simple to complex, and isolated to integrated, reflecting the developmental trajectory of an organization or project in terms of technological application, process management, collaboration, and related capabilities. To construct maturity levels for the scenario of construction robotics, it is essential to first identify key evaluation dimensions and indicators, such as the extent of technology adoption, data sharing and collaboration capabilities, and process standardization. Subsequently, distinct maturity tiers are delineated based on the degree to which these indicators are met, with clear characteristics and criteria defined for each level. During this process, industry-specific conditions and evolving trends must be thoroughly considered to ensure that each level exhibits clear differentiation and practical applicability.

B. Model composition

Model composition refers to the specific elements and structures incorporated within a maturity model, which collectively form a framework for evaluating and analyzing maturity. The model composition typically encompasses assessment dimensions, indicator systems, weight allocation, and evaluation methodologies[32,33]. Assessment dimensions, such as technology, process, personnel, and resources, constitute the core of the model, reflecting the key aspects of maturity evaluation; the indicator system further refines and quantifies each dimension to provide specific measures of maturity levels; weight allocation for dimensions and indicators should be determined through methods like expert scoring or data analysis. Weight allocation reflects the relative importance of each dimension or indicator in the maturity assessment. Finally, suitable evaluation methods, such as surveys, interviews, or case studies, must be selected to ensure the accuracy and reliability of assessment results.

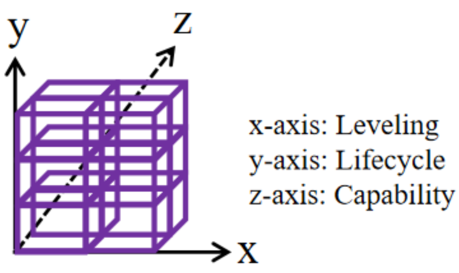

Figure 3. Model structure

C. Model application

Model application involves implementing a maturity model to assess, diagnose, and improve organizational or project maturity. It includes defining scope, gathering data, evaluating, analyzing results, and enacting improvements, fostering continuous development. Enterprises may self-assess information model maturity using relevant standards or tools, or engage third-party experts. These assessments identify strengths and weaknesses in construction robotics use, guiding targeted improvements. Clarify application scenarios, evaluation goals, and establish schedules, personnel, and survey strategies. Follow the evaluation framework to ensure data integrity. Analyze results to identify issues, report to stakeholders, design improvements, and monitor effectiveness, maintaining a closed-loop for sustained progress.

D. Capability framework

A capability framework provides a holistic view of the competencies required by an organization or project to successfully implement and utilize relevant technologies or management practices. It explains how capabilities interrelate and are hierarchically structured to guide capacity development. Within a maturity model, the capability framework systematizes the necessary competencies, offering direction and benchmarks for improvement. To build the framework for construction robotics, deriving capability domains and elements from construction best practices, standards, and project and organizational requirements. Analyzing relationships among elements, group and tierring them logically are considered to ensure scientific integrity and practical usability.

IV. CONCLUSION

Those aforementioned models have common features in one sense, because they all pursue the quantitative or qualitative assessment of the application scope and developmental level of BIM technology according to different dimensions. The development path of levels, the beginning level to the optimal level are considered as progressive development from the level, and various outstanding features and strength BIM technology at the stages should have been focused on. In addition, all these models are oriented to usability and efficiency with the goal of encouraging the establishment of an incremental evolution and refinement process of the construction robotic application technology through assessment, and also provide practical guidelines and references for evaluation method of data interoperability for construction robotics.

Furthermore, data interoperability for construction robots needs to take into account the integration of structured models and unstructured data in the construction scenario. First of all, the model layer should be extended from static geometry to construction semantics. It is recommended to consider a lightweight construction extension layer to achieve the two-way binding of the robot model and tasks. Secondly, formulate an industry-unified "Construction Robot URDF Document", standardize the coordinate system and sensor mounting points, and establish an open URDF library to reduce repeated modeling. Then, construct a 4D-URDF with real-time parameter updates driven by the BIM schedule. Next, unify the robot-environment data frame, preset coordinate alignment links and cascade multi-source measurements to address the deviation between the site and the drawings. At the same time, consider adopting methods such as edge-cloud collaboration to achieve lightweight model optimization. Finally, establish a data closed-loop, use the measured point cloud to reversely correct the URDF parameters and manage them in a versioned manner to achieve the convergence of the model and the site.

Through maturity models of application level for robotic technology in different projects, people can make systematic evaluation, thus identifying the advantages and disadvantages and make clear directions of future improvements. The models can also facilitate the normalized and standardized application of the construction robotics in the project, and promote the digital upgrade of the engineering domain.With the help of these models, the utility and popularity of information model application is greatly increased, which offers firm support and perfection for the whole life management of engineering works.

ACKNOWLEDGMENT

This research is supported by the National Key R&D Program of China (No. 2024YFC3809703) and National Natural Science Foundation of China (No. 52378306).

REFERENCES

[1] T. Wang, C. Mao, B. Sun, and Z. Li, "Genealogy of construction robotics," *Automation in Construction*, vol. 166, p. 105607, Oct. 2024, doi: 10.1016/j.autcon.2024.105607.

[2] X. Tan *et al.*, "Rebar-tying Robot based on machine vision and coverage path planning," *Robotics and Autonomous Systems*, vol. 182, p. 104826, Dec. 2024, doi: 10.1016/j.robot.2024.104826.

[3] C. Zhao *et al.*, "Dual-arm cooperative construction robots for wall repair with adaptive spraying and troweling," *Automation in Construction*, vol. 181, p. 106613, Jan. 2026, doi: 10.1016/j.autcon.2025.106613.

[4] J. Tuomisto, Y. Zheng, I. Chauhan, O. Seppänen, and J. Pajarinen, "Automating on-site object inspection with a quadruped robot and BIM," *Automation in Construction*, vol. 181, p. 106571, Jan. 2026, doi: 10.1016/j.autcon.2025.106571.

[5] "The World's First Fully Autonomous Trenching Solution — Built Robotics." Accessed: Oct. 17, 2025. [Online]. Available: https://www.builtrobotics.com/solutions/trenching

[6] J. G. Martinez, G. Albeaino, M. Gheisari, R. R. A. Issa, and L. F. Alarcón, "iSafeUAS: An unmanned aerial system for construction safety inspection," *Automation in Construction*, vol. 125, p. 103595, May 2021, doi: 10.1016/j.autcon.2021.103595.

[7] A. Ojha, S. Shayesteh, Y. Liu, H. Jebelli, and A. Akanmu, "Psychophysiological impacts of working with powered exoskeletons on construction sites," *Automation in Construction*, vol. 177, p. 106312, Sept. 2025, doi: 10.1016/j.autcon.2025.106312.

[8] D. Tola and P. Corke, *Understanding URDF: A Dataset and Analysis*. 2023. doi: 10.48550/arXiv.2308.00514.

[9] D. Prosper, "Application of Drone Technology in Overground Pipeline and Valve Inspection," Sept. 2025.

[10] W. Xingyu and X. Zining, "Control technology research of building wall spraying robot," *Scientific Reports*, vol. 15, Oct. 2025, doi: 10.1038/s41598-025-20252-x.

[11] R. Akhavian, M. Amani, J. Mootz, R. Ashe, and B. Beheshti, *Building Information Models to Robot-Ready Site Digital Twins (BIM2RDT): An Agentic AI Safety-First Framework*. 2025. doi: 10.48550/arXiv.2509.20705.

[12] L. Li, Z. L. Ma, H. G. Zhu, D. F. Li, and B. H. Zhou, "Review of Research on BIM Standards," Science Technology and Engineering, vol. 25, no. 20, pp. 8347–8363, 2025.

[13] D. Gachkar, S. Gachkar, E. Ghofrani, A. García Martínez, and C. Angulo Bahón, "Automating data integration for construction Life Cycle Assessment Using fuzzy matching and supervised learning," *Automation in Construction*, vol. 178, p. 106381, Oct. 2025, doi: 10.1016/j.autcon.2025.106381.

[14] M. Laakso and A. Kiviniemi, "The IFC Standard - A Review Of History, Development, And Standardization," p. 29.

[15] K. Jeon and G. Lee, *Information Delivery Manual (IDM) Configurator: Previous Efforts and Future Work*. 2018.

[16] F. Shayeganfar, A. Mahdavi, G. Suter, A. Anjomshoaa, A. Zarli, and R. Scherer, "Implementation of an IFD library using semantic web technologies: A case study," *Proc., ECPPM 2008 eWork and eBusiness in Architecture, Engineering and Construction*, pp. 539–544, Sept. 2008, doi: 10.1201/9780203883327.ch60.

[17] A. Malhotra, *Technical Report: Literature Review concerning IFC, gbXML and CityGML data models for Energy Performance Simulation*. 2019. doi: 10.18154/RWTH-2019-08837.

[18] I. Walhidayah and K. Surendro, "Development of an AI Governance Model for Higher Education Using the Capability Maturity Model Integration (CMMI)," *Jurnal Teknik Informatika (Jutif)*, vol. 6, pp. 2001–2018, Aug. 2025, doi: 10.52436/1.jutif.2025.6.4.4709.

[19] A. J. Arar, E. Poirier, and S. Staub-French, "A Capability Maturity Model for Integrated Project Delivery," *Buildings*, vol. 15, p. 1733, May 2025, doi: 10.3390/buildings15101733.

[20] "An Overview of the U. S. National building Information Model Standard (NBIMS)." Accessed: Oct. 22, 2025. [Online]. Available: https://ascelibrary.org/doi/epdf/10.1061/40937%28261%298

[21] J. Gabro, "iBIM – integrated Building Information Modeling. An Integrated BIM Team in the Design Phase.," 2014. Accessed: Oct. 22, 2025. [Online]. Available: https://www.semanticscholar.org/paper/iBIM-%E2%80%93-integrated-Building-Information-Modeling.-An-Gabro/7230d56b28609e3b8efe9ee67c8b7133621d9e9b

[22] M. P. Nepal, J. R. Jupp, and A. A. Aibinu, "Evaluations of BIM: Frameworks and Perspectives," in *Computing in Civil and Building Engineering (2014)*, Orlando, Florida, United States: American Society of Civil Engineers, June 2014, pp. 769–776. doi: 10.1061/9780784413616.096.

[23] B. Succar, W. Sher, and A. Williams, "Measuring BIM performance: Five metrics," *Architectural Engineering and Design Management*, vol. 8, no. 2, pp. 120–142, May 2012, doi: 10.1080/17452007.2012.659506.

[24] "(PDF) 301in BIM Maturity Matrix." Accessed: Oct. 22, 2025. [Online]. Available: https://www.academia.edu/26882284/301in_BIM_Maturity_Matrix

[25] L. van Berlo, T. Dijkmans, H. Hendriks, D. Spekkink, and W. Pel, "BIM QUICKSCAN: BENCHMARK OF BIM PERFORMANCE IN THE NETHERLANDS".

[26] R. Sebastian and L. van Berlo, "Tool for Benchmarking BIM Performance of Design, Engineering and Construction Firms in The Netherlands," *Architectural Engineering and Design Management*, vol. 6, Nov. 2010, doi: 10.3763/aedm.2010.IDDS3.

[27] C. Kam, M. H. Song, and D. Senaratna, "*VDC Scorecard* : Formulation, Application, and Validation," *J. Constr. Eng. Manage.*, vol. 143, no. 3, p. 04016100, Mar. 2017, doi: 10.1061/(ASCE)CO.1943-7862.0001233.

[28] "Using Building Information Modeling to Enhance Supply Chain Resilience in Prefabricated Buildings: A Conceptual Framework." Accessed: Oct. 22, 2025. [Online]. Available: https://www.mdpi.com/2076-3417/13/23/12694

[29] C. Wu, B. Xu, C. Mao, and X. Li, "OVERVIEW OF BIM MATURITY MEASUREMENT TOOLS".

[30] D. Gor, R. Patel, Dr. J. Pitroda, and C. Patel, *A CRITICAL LITERATURE REVIEW OF BIM CLOUD SCORE: BUILDING INFORMATION MODEL AND MODELING PERFORMANCE BENCHMARKING*. 2018.

[31] "BIM Cloud Score: Benchmarking BIM Performance | Journal of Construction Engineering and Management | Vol 140, No 11."

Accessed: Oct. 22, 2025. [Online]. Available: https://ascelibrary.org/doi/full/10.1061/%28ASCE%29CO.1943-7862.0000891
[32] "5068_Preskill_Chapter_5.pdf." Accessed: Oct. 24, 2025. [Online]. Available: https://us.sagepub.com/sites/default/files/upm-binaries/5068_Preskill_Chapter_5.pdf
[33] F. Pyrczak and M. Tcherni-Buzzeo, *Evaluating Research in Academic Journals: A Practical Guide to Realistic Evaluation*. 2018. doi: 10.4324/9781351260961.