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Building Information Modeling Technology Capabilities: Operationalizing the Multidimensional Construct

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Abstract: The identification and leverage of the Building Information Model (BIM) technology are at the core of the successful digital transformation of the construction industry. However, due to its ability to integrate with various digital technologies and platforms, facilitating the digital and sustainable construction of the entire lifecycle of a building, BIM technology cannot be simply defined and operationalized with a single dimension of the construct. Based on the importance of multidimensional structures called for in the viewpoint of existing research and the resource-based view, we develop a second-order construct model to measure BIM technology capabilities. We define and operationalize the BIM technology capabilities, based on theory, as a reflective–reflective higher-order construct by developing and validating a 17-item scale that captures three first-order constructs. The measurement model results show strong reliability, dimensionality of the first-order measurement model, convergent validity, and discriminant validity. The multidimensional structure and instrument provide researchers with an opportunity to test the theories about the antecedents and outcomes of BIM technology capabilities, as well as the process and conditions.

Keywords: BIM (Building Information Modeling) technology capabilities; scale development; multidimensional construct; construction industry

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1. Introduction

BIM has been attracting great interest from academics and practitioners for its critical role as an innovative resource that offers potential competitive advantages to construction organizations [1]. However, most studies are focused on the adoption, implementation, and capability maturity model of BIM technology [2–5], and construction companies are still struggling to fully leverage the pros of BIM to achieve an above-average return, as well as to implement their digital first strategy to transform the construction industry to achieve sustainability.

The gap between the seemingly prosperous literature and unresolved emerging new challenges to optimize the BIM technology resources can be largely attributed to the lack of understanding of the technology. Due to BIM technology's ability to integrate with various platforms and technologies, such as GIS, IoT, AI, 3D Scanning, and other technologies or platforms [6–9], the concept of BIM technology is often vague and prone to confusion. Thus, BIM technology cannot be simply defined and operationalized with a single dimension of the construct, and Law et al. (1998) [10], Polite et al. (2012) [11], and Wright et al. (2012) [12] emphasize the significance of the multidimensional construct in defining and measuring a complex technology like BIM. Law et al. [10] argue that the multidimensional structure can be conceptualized within an underlying theoretical framework and call for using this overarching framework to represent the complex structure of the dimensions. Thus, we employ the multidimensional construct to comprehend and define the complex BIM technology capabilities conceptually and operationally. This approach will provide a firm foundation for both researchers and practitioners to explore new theories and business opportunities.

Although the measurement methods are not completely consistent, there has been a considerable amount of research related to assessment frameworks and models associated with BIM maturity. Giel and McCuen (2014) [13] reported that there were more than a dozen measurement models for BIM maturity at the time, including those for internal organizational assessments and assessments of the extent and stages of BIM technology application. Wu et al. (2017) [14] compared nine mainstream measurement models and concluded that there was no universally applicable maturity measurement tool. Each tool had its own focus and advantages and disadvantages, with most having limited usability. Alankarage et al. (2022) [15] conducted a review of BIM maturity measurement models within organizations. They observed that while the number of maturity models was increasing, many of them were essentially repetitive. There was a lack of clear differentiation regarding which model is suitable for an organization or project, as well as the clarity in identifying potential application areas for these models. Adekunle et al. (2022) [16] also noted that BIM maturity models are typically developed based on independent research and, to date, most of them have not followed a rigorous approach.

Despite all of these efforts, the reason why the adoption and the implementation of BIM technology encounter various obstacles and challenges [17,18] is the perception that the economic benefits are often vague and intangible [5]. On one hand, the stagnation of theory development and empirical findings between BIM technology and firm performance can largely be attributed to the lack of a clear definition and operationalization of BIM technology; on the other hand, a new perspective on BIM technology as firm-wide IT capabilities is needed [19]. By integrating the resource-based view and institutional theory, Huang et al. (2014) conceptualized the IT capabilities as a multi-dimensional construct and empirically tested the mechanism and context for influencing the firm's performance [19]. Therefore, there is a need to develop multi-dimensional measurement instruments for assessing BIM technology capabilities instead of measuring BIM technology as fragmented IT assets.

In summary, the identification and leverage of the application of Building Information Model (BIM) technology are at the core of the successful digital transformation of the construction industry. However, due to its ability to integrate with various digital technologies and platforms, facilitating the digital and sustainable construction of the entire lifecycle of a building, BIM technology cannot be simply defined and operationalized with a single dimension of the construct. Based on seminal work by Olowa et al. (2022) [20], a resource-based view, and Law et al.'s (1998) [10] call for a multidimensional construct, we develop a second-order construct model to measure BIM technology capabilities. Based on a resource-based view, we follow the recommendations by Wright et al. (2012) [12] to define and operationalize the BIM technology capabilities as a reflective–reflective higher-order construct by developing and validating a 17-item scale that captures three first-order constructs.

2. BIM Technology Capabilities (BIMTC)

Regarding the definition of BIM technology capabilities, scholars have provided various definitions based on different BIM technology application scenarios and purposes. Building Information Modeling (BIM) is a technology based on three-dimensional visualization modeling that can store a large amount of drawings, documents, and parameter information [21] and connect various tools to create an information exchange platform for information retrieval and technical intervention throughout the entire construction process [2–4]. Ku and Mahabaleshwarkar (2011) [22], with the aim of constructing a virtual world based on BIM modeling for Second Life, introduced the concept of 'BiM' (Building Interactive Models). They defined it as a web-based virtual world that allows users with minimal software skills to participate in collective decision-making processes through role-playing scenarios, thus combining the virtual world with BIM. Building upon this, Olowa et al. (2022) [20] defined 'BLE' (BIM Learning Environment) as a web-based platform designed to facilitate education and training supported by BIM. This innovative teaching approach aims to meet the demands of students for new job skills and capabilities.

However, the focus of our research is on the practical application of BIM technology, with the ultimate goal of enhancing BIM technology capabilities to improve the competitiveness of teams and organizations. In the construction industry, BIM technology capabilities stand as the core driving force behind the industry's digital transformation, regarded as an innovative resource that offers potential competitive advantages to construction organizations [1]. Therefore, our conceptualization of BIM technology capabilities aligns closely with Bharadwaj et al. (1999) [23], who includes the concept of IT capabilities encompassing both technology and organizational aspects. Scholars consider IT capabilities as a company's ability to continually restructure resources based on information technology (IT) to maintain a competitive edge.

Over time, the strategic value of IT for organizations has captivated considerable attention from both scholars and practitioners [24–27]. In a similar vein, Bhatt and Grover (2005) [25] conducted an extensive review of the trajectory of IT research concerning competitive advantage, shedding light on classical, economic, complementary resources, and the Resource-Based View (RBV) perspectives. Likewise, BIM, classified as an enterprise-level information technology, has also attracted scholarly investigation by addressing its fundamental technological underpinnings [28,29], facets of economic value creation [30], and dimensions of competitiveness [31]. However, the uncertainties and ambiguities surrounding the returns on investment and the underexploited potential benefits of BIM technology have emerged as shared concerns within both the academic community and the industry, paralleling Carr's (2003) [32] argument concerning the diminished economic contribution of IT. Bhatt and Grover (2005) [25] advocated for the assessment of IT's significance through the lens of RBV, as IT underscores the capacity for leveraging capabilities rather than undifferentiated IT assets. Huang [19] and King [33] further argue that firms exhibit considerable disparities in their ability to cultivate IT capabilities, transcending the mere expenditure on disparate IT components.

Consequently, IT capabilities are constructed as a dynamic, organization-wide competence, going beyond a specific array of intricate technical functionalities to encompass an enterprise-wide competence characterized by combining the technological and organizational resources.

In line with the RBV perspective, we conceptually define BIM technology capabilities as the strategic competences that are applicable to teams and enterprises alike. BIM technology capabilities stand as a significant resource, and as competency is poised to empower teams and enterprises in achieving and sustaining a strategic competitive advantage, it should encompass multiple dimensions. Some researchers focus on BIM technology as an information technology's basic operational capabilities, emphasizing certain aspects, such as software interoperability [5,14], modeling issues [14], and so forth. Some researchers emphasize BIM technology's ability in coordination and collaboration, including conflict detection in design [34,35], BIM-based model checking [36], and the interaction between BIM technology and construction organization workflows [1]. There are also researchers who focus on BIM technology's expansion capabilities, where integration with various applications is necessary to facilitate cross-organizational, interdisciplinary, and project stage development [37]. For example, this includes BIM's ability in learning modules [38], integration with the Internet of Things [7], combination with AI [8], integration with 3D scanning [9], incorporation with VR and AR [39], and integration with GIS [6].

Based on the literature review, we conceptualize BIM technology capabilities into three complementary dimensions: the BIM infrastructure capabilities dimension (BIC), the BIM collaboration capabilities dimension (BCC), and the BIM expansion capabilities dimension (BEC), which are consistent with the multi-dimensional structure of IT capabilities developed by Huang et al. (2014) [19].

2.1. BIM Infrastructure Capabilities

BIM infrastructure capabilities primarily refer to the fundamental functionalities inherent in BIM technology, such as modeling, storage, linking, and visualization. These capabilities enhance the competitiveness of organizations or teams. BIM infrastructure capabilities serve as the prerequisite and foundation for improving the level of technological application within the industry. To fully harness the advantages of BIM infrastructure capabilities, it is essential to have comprehensive hardware and software support, systematic technical training, as well as well-structured task assignments and reward mechanisms [40–42].

2.2. BIM Collaboration Capabilities

BIM collaboration capabilities pertain to the ability of teams or organizations to enhance mutual collaboration and coordination through the use of BIM technology, thereby increasing the competitiveness of both teams and organizations. Coordination and collaboration have long been significant challenges in the construction industry, where traditional design coordination settings are known for their inefficiency and susceptibility to errors [43]. Building Information Modeling (BIM) has proven to be valuable, as it can improve satisfaction with the meeting process and reduce disputes over issues. Scholars have confirmed that conflict detection and resolution solutions based on BIM can lead to cost savings [35].

2.3. BIM Expansion Capabilities

BIM expansion capabilities refer to the abilities of teams or organizations to leverage BIM technology in combination with other technologies to expand their functional scope or venture into other domains, thereby enhancing competitiveness. Within this dimension, BIM expansion capabilities are regarded as an innovative resource that offers potential competitive advantages [1], enabling collaboration across multiple domains. In recent years, the capabilities for real-time connectivity to sensors deployed in the environment have given rise to the concept of the digital twin in the built environment [7]. BIM-AI integration plays a role in advancing intelligent construction management [8]. The creation of learning modules supported by BIM [38] and the deep integration of BIM with other technologies have facilitated the extensive development of BIM application areas.

After further developing the concept of BIM technology capabilities, our focus has shifted to constructing and preliminarily validating a scale to measure the three dimensions of BIM technology capabilities in our research. Study 1 concentrates on identifying the sources of BIM technology capabilities items and evaluates the adequacy of their content using a diverse sample. Study 2 utilizes samples from various organizations to verify the scale's reliability, validity, dimensions, and factor structure.

3. Research Methodology

3.1. Study 1: Project Generation and Content Adequacy Assessment

3.1.1. Item Generation

We employed both deductive and inductive methods to generate items [44]. Building upon the structural characteristics summarized for BIM Learning Environments from an adaptive structural perspective by Olowa et al. (2022) [20], we initially generated 33 items to assess BIM technology capabilities. These items representatively encompass the three dimensions theoretically constituting BIM technology capabilities.

Subsequently, we engaged in in-depth discussions and interviews with nine experts involved in BIM technology applications and management roles to further refine and identify projects suitable for representing the three dimensions. Through this iterative process, we compiled a total of 35 indicators for BIM technology capabilities in the Chinese context (Table 1).

Table 1. Indicators of BIM technology capabilities.

	Indicators of BIM Technology Capabilities	Derived from the Literature (Olowa et al., 2022) [20]	Derived from Interviews
1	BIM model viewing.	The ability to visually inspect components in the model.	-
2	Capabilities to input, access, and extract BIM model data.	Availability of input data in the model, accessible to users and easily extractable.	Data handling and data transmission.
3	BIM model sharing.	Capabilities to share the model for communication and collaboration purposes.	Enhancing communication effectiveness by adding annotation and navigation tools around the model. Adding view linking functionality around the model.
4	BIM model version management.	Ability to track and manage different versions of BIM models.	Software version compatibility; synchronization and interoperability among multiple forms of software.
5	BIM model editing.	Meaningful data input into the model is necessary.	Low modeling efficiency.
6	BIM model collaborative viewing and editing.	Collaborative viewing and editing of the model, ideally utilizing collaborative viewing and editing features in team collaboration.	Collaboration using a central file and work sets. Issues with assigning permissions for collaborative design.
7	Repository of example BIM models.	Capabilities to accommodate a repository or database for storing high-quality, consistent, and error-free models.	Product industry libraries. Cloud storage and local storage.
8	Common Data Environment (CDE) for project data/Multi-software Interoperability Environment.	Ability to host project data consistently and persistently. Project data are not limited to data incorporated into the BIM model. Therefore, a common data environment is a necessary attribute.	Data barriers among multiple forms of software; preserving information after importing software to ensure model continuity; data interfaces that can integrate multiple forms of software.
9	Simulation of the project development process (realistic BIM workflow, key stakeholder roles, etc.).	Ability to simulate real-life project development processes, serving the roles of relevant stakeholders and BIM-based workflows.	Clear milestones, complete documentation, explicit requirements, and comprehensive records in the collaborative process.
10	BIM model creating.	Capabilities to create BIM models.	Refining modeling to improve modeling efficiency.
11	BIM model checking.	Ability to perform process and model standard checks on BIM models.	Adding generic nodes and rule checks for automated model validation.
12	Capabilities to integrate other advanced technologies (extended reality, artificial intelligence, Internet of Things, etc.).	Integration of extended reality features: Augmented Reality (AR), Mixed Reality (MR), Virtual Reality (VR).	Integration of BIM with GIS; integration of BIM with AI; digital twin combining BIM and the Internet of Things (IoT).
13	BIM object creation and editing.	Creation and editing of BIM components.	Bringing together individuals with different specialties and backgrounds based on project requirements.
14	Group formation (Different majors and backgrounds).	Stakeholders can collaborate in creating group work.	Communication features integrating the functionality of WeChat documents.
15	Collaboration in groups (communication and cooperation within the team).	Capabilities to create and manage teams, enabling communication and collaboration within the team.	Face-to-face communication.

Table 1. *Cont.*

	Indicators of BIM Technology Capabilities	Derived from the Literature (Olowa et al., 2022) [20]	Derived from Interviews
16	Collaboration between groups (interaction and cooperation between teams).	Possibility for communication and interaction among the working or learning community, where stakeholders engage in interactions for project development.	Real-time collaboration, real-time updates, real-time visualization of results are required. Implementation of clash detection; communication challenges when dealing with a large number of people; real-time information sharing with high-quality data exchange; the need for quick file updates and iterations.
17	Instructor access and monitoring of groups and group work.	Capabilities to create teaching permissions for access and group work monitoring, where instructors interact with teams and individuals.	Permission issues in collaborative work sets; software permission problems.
18	Collaborative viewing and editing of documents and spreadsheets.	Collaborative viewing and editing of documents and spreadsheets (not just limited to BIM models) are crucial for executing learning tasks within a group.	-
19	Live interactions between users.	Ability to engage in real-time interactions with users, enhancing the convenience and time efficiency of teaching and group work.	Enhancement of interaction through features like WeChat voice calls; addition of view linking functionality; inclusion of annotation and navigation tools to directly locate model issues and improve communication effectiveness.
20	Capabilities to record group meetings and courses/Ability to record informal communication	Capabilities to record group meetings and courses.	Lack of archiving in communication processes.
21	Registration of users (learners/instructors).	Ability to register and unregister users.	Authentication of different stakeholders' identities.
22	Data security/password protection.	Capacity to protect user data and information, especially data and information related to registered users and their activities.	Concerns about the risk of damaging the shared master files.
23	Capabilities to host multiple courses or promote multiple projects simultaneously.	Capabilities to host multiple courses.	Platform's model hosting capacity, software's information hosting capabilities; capacity to handle and store information.
24	File upload, storage, download, sharing, editing.		File format conversion.
25	Video playback.	Ability to play course content videos and access external (video) materials.	-
26	Capabilities to link to additional learning materials or other professional information.	Capabilities to link to additional learning materials, including course content and access to various materials.	Ability to accommodate large amounts of data, extensive information; drawbacks of linking; digital assets.
27	Individual learners' storage for learning materials.	Ability to allow individual learners to store learning materials.	-
28	Capabilities to link various courses or projects together.	Ability to connect multiple courses to reinforce the outcomes of previous courses and track the impact on future course engagement.	Learning from completed projects or transferring knowledge to new projects.
29	Assessment/grading.	Capabilities to assess and grade learners—inputting scores for individuals/groups, grade book—for learning management, quality, and learner assessment purposes.	-

Table 1. *Cont.*

	Indicators of BIM Technology Capabilities	Derived from the Literature (Olowa et al., 2022) [20]	Derived from Interviews
30	Questionnaire creation, completion, submission.	Creation and analysis of questionnaires, quizzes, and surveys.	-
31	Student feedback.	Ability to gather feedback from users and learners for quality assurance and improvement purposes.	-
32	Gamification support.	Capabilities to integrate gamification features, combining elements of gaming. Enhancing competition as a way to motivate learners—high scores/leaderboards, etc.	-
33	Integration of platform with external systems/business.	Ability to integrate with external platforms—for example, integration with institutional research information systems.	Integration with enterprise management platform.
34	Capabilities of lightweight BIM operation.		Web-based lightweight platform; cloud-based platform.
35	Capabilities of conducting post-model generation sustainability analysis.		Green building analysis, cost analysis, carbon emissions, emergency evacuation simulation, etc.

"-" indicates not mentioned in the interview.

3.1.2. Content Adequacy Testing

Content adequacy testing was conducted using the quantitative method proposed by Schriesheim et al. (1993) [45], ensuring that the content of a measure encompasses a representative sample of the domains to be assessed.

Sample and Procedure

The sample comprised technical managers and educators involved in BIM technology applications in China, representing a diverse range of institutions, including consulting and training, enterprises, and universities. This broad sample scope aimed to cover various sectors of BIM application within the Chinese construction industry. The age distribution of the sample primarily ranged from 21 to 40 years, with 7.48% having 6–9 years of experience using BIM technology, 13.08% with 3–5 years, and 79.44% with 1–2 years, representing the main group of individuals who have learned and applied BIM technology.

Analysis and Results

In the preliminary survey, a questionnaire was created based on the first 33 indicators (items 1–33) of BIM technology capabilities. Respondents were asked to rate the level of importance of BIM technology capabilities in terms of their impact on practical work and learning using a 5-point Likert-type scale: "1—Not Important", "2—Slightly Important", "3—Moderately Important", "4—Very Important", and "5—Extremely Important".

A total of 107 questionnaires were collected. After excluding those with response times less than 55 s, a total of 95 valid questionnaires were retained. Exploratory factor analysis was conducted on the questionnaire data. The data were subjected to a KMO test and Bartlett's sphericity test using SPSS Statistics version 27. The analysis yielded a KMO value of 0.898 for the questionnaire data, and Bartlett's sphericity test was significant at the 0.01 level, indicating that the sample data in this study were suitable for exploratory factor analysis.

From the scree plot, it was observed that the inflection point appeared at position 3. The cumulative variance explained by the three common factors reached 66.7%. Principal component analysis was chosen, and the maximum variance rotation method was used to extract factors with specified eigenvalues set at 3. Items that loaded on two or three factors, had loadings exceeding 40%, and lacked clear discriminant validity were removed. This initial analysis resulted in a factor structure with three factors and 26 items, with factor loadings for each item ranging from 0.60 to 0.82.

Subsequently, factors with lower factor loadings were further eliminated, and two new items (34, 35) from the interviews were added. This led to a final factor structure with three factors and 19 items (Table 2).

Table 2. Dimensions and indicators of BIM technical capabilities.

	Sub-Dimension	Item Number	BIM Technology Capabilities Indicator	Factor Loading
BIM Technology Capabilities (BIMTC)	BIM Infrastructure Capabilities (BIC)	3#	Capabilities to share the model for communication and collaboration purposes	0.795
		4#	Capabilities to track and manage different versions of BIM models	0.772
		5#	Capacity to edit the BIM model	0.867
		6#	Capabilities for collaborative viewing and editing of models	0.785
		7#	Repository of example BIM models	0.819
		8#	Common Data Environment (CDE) for project data/Multi-software Interoperability Environment	0.811
	BIM Collaboration Capabilities (BCC)	14#	capabilities for Group formation	0.912
		15#	Ability to collaborate within a group	0.928
		16#	Ability to collaborate between groups	0.918
		17#	Instructor access and monitoring of groups and group work	0.857
		19#	Ability to engage in real-time interactions with users	0.833
		34# [1]	Capabilities of lightweight BIM operation	
	BIM Expansion Capabilities (BEC)	20#	Capabilities to record group meetings and courses /Ability to record informal communication	0.798
		23#	Capabilities to host multiple courses or promote multiple projects simultaneously	0.833
		26#	Capabilities to link to additional learning materials or other professional information	0.872
		27#	Ability to allow individual learners to store learning materials	0.826
		28#	Capabilities to link various courses or projects together	0.894
		29#	Ability to assess and grade learners	0.855
		35# [1]	Capabilities for conducting post-model generation sustainability analysis	

[1] 34# and 35# are the newly added items after the expert meeting and were not included in the pre-survey questionnaire.

3.2. Study 2: Reliability, Validity, Dimensions, and Factor Structure

3.2.1. Sample and Procedure

In Study 2, a structural validity test was conducted on the 19 items retained from Study 1. A survey was conducted to collect data from enterprises within the Chinese construction industry that use BIM technology. Questionnaires were distributed to experienced professionals familiar with and knowledgeable about BIM technology and BIM project management. From the statistical data, it was observed that 58.1% of respondents had more than 10 years of work experience, 25.7% had 6–9 years of experience, and the majority of respondents (40%) had been using BIM for 3–5 years, with 21.9% using it for 6–9 years and 14.3% for 10 years or more. Overall, the sample had rich work experience, ensuring the quality of the collected questionnaires.

The questionnaire content was based on the 19 indicators of BIM technology capabilities. A scale was constructed to measure BIM technology capabilities. Questions in the scale were framed as: "Compared to other companies in your industry in the past 3–5 years, how strong is your company's ability in BIM model version management?" Responses were recorded on a 7-point Likert scale, ranging from "1—Strongly Disagree" to "2—Disagree", "3—Somewhat Disagree", "4—Neutral", "5—Somewhat Agree", "6—Agree", and "7—Strongly Agree". A new scale was used for the second round of questionnaire surveys to validate the scale's reliability

In this round, a total of 90 questionnaires were collected. Two questionnaires with excessively short response times were excluded, leaving a total of 88 valid questionnaires, all of which had response times exceeding 82 s.

3.2.2. Analysis

The questionnaire data were analyzed using AMOS to construct a measurement model. The overall fit of the model was satisfactory. However, items 20# (bec1) and 29# (bec6) showed a strong correlation in both the BCC and BEC dimensions. Some individuals may perceive items related to recording group meetings (20#) and assessing learners' capabilities (29#) as necessary abilities during the collaboration process. Therefore, the two potentially confusing items, bec1 and bec6, were removed. The final measurement model fit indices are as follows (Table 3): CMIN/DF is 1.673, which is less than 3; TLI is 0.964 and CFI is 0.970, both of which are greater than 0.9; RMR is 0.064; and RESEM is 0.088. The overall fit of the model is good.

Table 3. Measurement model fit indices.

	CMIN/DF	**TLI**	**CFI**	**RMR**	**RESEM**
Actual Value	1.673	0.964	0.970	0.064	0.088
Fit Value	<3	≥ 0.9	≥ 0.9	<0.08	<0.1

An analysis of the reliability and validity of the BIM technology capabilities scale, consisting of the final 17 items, yielded the following results, as shown in Table 4. The standardized factor loadings for all items were above 0.86, indicating that the items could effectively explain the underlying constructs. The composite reliability (CR) values for each dimension were 0.979, 0.978, and 0.968, all exceeding 0.9, indicating good composite reliability. Convergent validity was examined using the Average Variance Extracted (AVE), where a higher AVE suggests that the measurement indicators better represent the variables. The analysis results (as shown in Table 4) revealed that the AVE values for BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities were 0.885, 0.882, and 0.859, respectively, all exceeding 0.7, indicating good convergent validity for the dimensions of the scale.

According to the Fornell and Larcker criteria [46], the square root of the Average Variance Extracted (AVE) should be higher than its bivariate correlation values with all other constructs [47]. The square root of the AVE values for each component (as shown in Table 5) exceeds 0.9 and is greater than their intercorrelations. This indicates that the discriminant validity of the three dimensions of BIM technology capabilities is also satisfactory.

Table 4. Reliability and validity analysis of the scale.

Potential Construction	Path	Items	Std.	*p*	CR	AVE
BIM Infrastructure Capabilities (BIC)	bic1←BIC	Capabilities to share the model for communication and collaboration purposes	0.938	***	0.979	0.885
	bic2←BIC	Capabilities to track and manage different versions of BIM models	0.951	***		
	bic3←BIC	Capacity to edit BIM model	0.944	***		
	bic4←BIC	Capabilities for collaborative viewing and editing of models	0.927	***		
	bic5←BIC	Repository of example BIM models	0.953	***		
	bic6←BIC	Common Data Environment (CDE) for project data/Multi-software Interoperability Environment	0.930	***		
BIM Collaboration Capabilities (BCC)	bcc1←BCC	Capabilities for Group formation	0.927	***	0.978	0.882
	bcc2←BCC	Ability to collaborate within a group	0.917	***		
	bcc3←BCC	Ability to collaborate between groups	0.940	***		
	bcc4←BCC	Instructor access and monitoring of groups and group work	0.925	***		
	bcc5←BCC	Ability to engage in real-time interactions with users	0.960	***		
	bcc6←BCC	Capabilities of lightweight BIM operation	0.965	***		
BIM Expansion Capabilities (BEC)	bec2←BEC	Capabilities to host multiple courses or promote multiple projects simultaneously	0.956	***	0.968	0.859
	bec3←BEC	Capabilities to link to additional learning materials or other professional information	0.863	***		
	bec4←BEC	Ability to allow individual learners to store learning materials	0.947	***		
	bec5←BEC	Capabilities to link various courses or projects together	0.939	***		
	bec7←BEC	Capabilities for conducting post-model generation sustainability analysis	0.926	***		

*** $p < 0.001$.

Table 5. Discriminant validity test table.

	BIC	BCC	BEC
BIC	**0.941**		
BCC	0.895	**0.939**	
BEC	0.780	0.883	**0.927**

The bold numbers on the diagonal represent the square root of AVE.

Based on the above, the final validated BIM technology capabilities scale with good reliability and validity is obtained. It is divided into three dimensions: BIM infrastructure capabilities, BIM collaboration capabilities, and BIM extension capabilities, consisting of a total of 17 measurement items.

3.2.3. Dimensions and Factor Structure

Types of Multidimensional Structures

BIM technology capabilities are a multidimensional structure consisting of three sub-dimensions: the BIM infrastructure capabilities dimension, the BIM collaboration capabilities dimension, and the BIM expansion capabilities dimension. Within the BIM infrastructure capabilities sub-dimension, there are six measurement indicators, while the BIM Collaboration capabilities sub-dimension comprises six measurement indicators, and the BIM expansion capabilities sub-dimension includes five measurement indicators. The relationships between indicators and sub-dimensions, as well as those between sub-dimensions and the BIM technology capabilities construct, were distinguished following the approach of Jarvis et al. (2003) [48] and Diamantopoulos A et al. [49]. This differentiation was based on the form and summary of questions and practical analysis. Scholars suggest assessing the form of the structure from multiple perspectives, including causal relationships, structural characteristics or manifestations, whether changes in indicators (items) and structural variables lead to changes in each other, the content of indicators with respect to the theme, the conceptual domain of the structure, expected antecedents, and consequences.

Firstly, an analysis was conducted to determine the relationships between lower-order indicators and sub-dimensions by assessing causal relationships. Measurement indicators reflect specific aspects of BIM technology capabilities within sub-dimensions, such as specific modeling editing capabilities, model sharing capabilities, etc. These measurement indicators are reflective indicators of BIM infrastructure capabilities. Additionally, a reduction or change in these indicators does not lead to a change in the first-order structure (BIM infrastructure capabilities); therefore, they are reflective in nature at the first-order level.

Following this, in accordance with the recommendations of Law et al. [10] and Poliet et al. [11], an analysis of the relationships between the multidimensional structure of BIM technology capabilities and their sub-dimensions was conducted. The three sub-dimensions (namely, BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities) collectively represent overall BIM technology capabilities. A reduction or change in any one sub-dimension of BIM technology capabilities may not necessarily affect the overall BIM technology capabilities. Focusing on the development of a specific dimension of BIM technology capabilities can also lead to strong competitiveness. Therefore, a higher-order structure exists at a deeper level than its dimensions [10], and relationships flow from this structure to its dimensions. Consequently, from a theoretical perspective, the structure of BIM technology capabilities is a multidimensional structure with reflective dimensions, meaning it is a higher-order latent structure with reflective–reflective characteristics.

Testing the Multidimensional Structure

Following the advantages of PLS and PLS-SEM for analyzing small-sample data and higher-order structures, as indicated by Chin et al. [50], Ringle et al. [51], and Sarstedt et al. [52], the PLS-SEM method was applied to test the reflective–reflective higher-order structure of BIM technology capabilities. The primary method employed was the repeated indicator approach. The measurement model of the higher-order construct was primarily assessed for its reliability, convergent validity, and discriminant validity between the lower-order indicators and sub-dimensions.

Contemporary methodologists recommend modeling multidimensional structures as second-order factor models. To achieve this, the higher-order construct was modeled as a second-order factor, with the dimensions being modeled as first-order factors and the dimension measures being modeled as observed variables [53,54].

First, using Smart PLS 4 software, a first-order measurement model was constructed using the repeated indicator method (Figure 1). The statistical data obtained are presented in the following table (Table 6). In accordance with the recommendations of Hair et al. [47], the internal consistency reliability, convergent validity (CV), and discriminant validity (DV) of the lower-order measurement model were assessed.

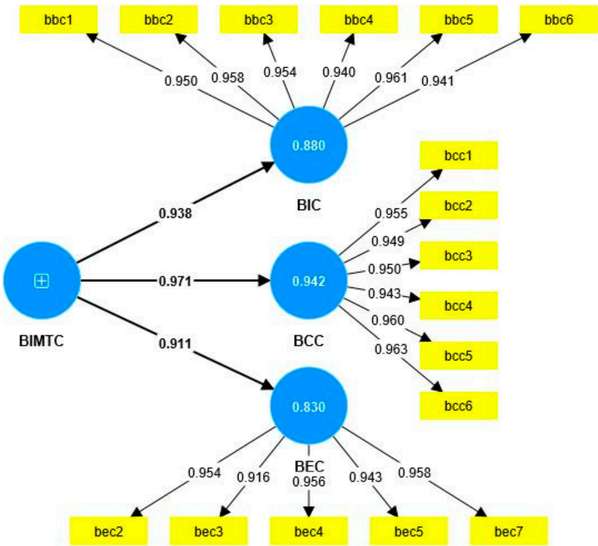

Figure 1. PLS high-order measurement model.

Table 6. Statistical table of measurement model parameters.

High-Order Construction	First-Order Construction	Form	Index	Factor Loading	Cronbach's α	CR	AVE
BIM Technology Capabilities		Reflective			0.986	0.987	0.796
	BIM Infrastructure Capabilities (BIC)	Reflective	bic1	0.950	0.979	0.983	0.904
			bic2	0.958			
			bic3	0.954			
			bic4	0.940			
			bic5	0.961			
			bic6	0.941			
	BIM Collaboration Capabilities (BCC)	Reflective	bcc1	0.955	0.980	0.984	0.909
			bcc2	0.949			
			bcc3	0.950			
			bcc4	0.943			
			bcc5	0.961			
			bcc6	0.963			
	BIM Expansion Capabilities (BEC)	Reflective	bec2	0.954	0.970	0.977	0.894
			bec3	0.916			
			bec4	0.956			
			bec5	0.943			
			bec7	0.958			

The Cronbach's α values for BIM technology capabilities as a whole and within each dimension are all greater than 0.95 (0.986, 0.979, 0.980, 0.970), indicating good internal consistency. The reliability coefficients for BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities are 0.983, 0.984, and 0.977, respectively, and the CR values for each dimension are all above the 0.80 standard (as shown in Table 6), indicating good construct reliability.

Further analysis of the results (as shown in Table 6) reveals that the Average Variance Extracted (AVE) values for the three factors of BIM infrastructure capabilities, BIM collaboration capabilities, and BIM expansion capabilities are 0.904, 0.909, and 0.894, respectively, all exceeding the threshold of 0.50. This indicates good convergent validity.

To examine the discriminant validity of the constructs, a measurement model cross-loading table (Table 7) is used. The factor loadings for each dimension are well-distributed and correspond well to their respective dimensions.

Table 7. Cross-loading table of the measurement model.

High-Order Construction	First-Order Construction	Index	BIMTC	BIC	BCC	BEC
BIM Technology Capabilities (BIMTC)	BIM Infrastructure Capabilities (BIC)	bic1	0.856	**0.950**	0.811	0.654
		bic2	0.886	**0.958**	0.845	0.700
		bic3	0.897	**0.954**	0.838	0.751
		bic4	0.881	**0.940**	0.839	0.722
		bic5	0.901	**0.961**	0.848	0.734
		bic6	0.877	**0.941**	0.820	0.719
	BIM Collaboration Capabilities (BCC)	bcc1	0.912	0.831	**0.955**	0.794
		bcc2	0.907	0.826	**0.949**	0.782
		bcc3	0.914	0.835	**0.950**	0.803
		bcc4	0.922	0.826	**0.943**	0.828
		bcc5	0.948	0.856	**0.961**	0.853
		bcc6	0.928	0.843	**0.963**	0.811
	BIM Expansion Capabilities (BEC)	bec2	0.905	0.747	0.847	**0.954**
		bec3	0.805	0.631	0.737	**0.916**
		bec4	0.894	0.730	0.828	**0.956**
		bec5	0.886	0.728	0.815	**0.943**
		bec7	0.871	0.706	0.794	**0.958**

According to Fornell and Larcker's criteria [46], the square root of AVE should be higher than its bivariate correlations with all other constructs [47]. The square root of AVE values for each component (Table 8) are all above 0.9 and greater than their intercorrelations. This indicates good discriminant validity among the three dimensions of BIM technological capabilities.

Table 8. Discriminant validity of first-order constructs.

	BIC	BCC	BEC
BIC	**0.951**		
BCC	0.895	**0.953**	
BEC	0.769	0.872	**0.946**

The bold numbers on the diagonal represent the square root of AVE.

When evaluating the second-order structural model, researchers should adhere to the heuristic method provided by Gefen et al. [55]. Subsequently, an overall assessment of the model is conducted. As shown in Table 9, the external weight values for the three indicators are 0.969, 0.910, and 0.874, with T-values of 105.949, 25.024, and 19.118, respectively, all of which are significant. Therefore, all three indicators are considered important and significant factors for the BIM technology capabilities construct. Additionally, the VIF (Variance Inflation Factor) values for the various dimensions of BIM technology capabilities are 4.330, 6.881, and 3.643, with both inner and outer VIFs exceeding 5. As shown in Table 7, the factor loadings indicate that the indicators load significantly on their respective dimensions, but the cross-loadings also exceed 0.7. These data suggest the possibility of multicollinearity among the indicators. In theory, it is acceptable for reflective–reflective multidimensional constructs.

Furthermore, Wright et al. (2012) argue that researchers should evaluate the model fit alongside alternative models [12]. The assessment of model fit should be supplemented by comparisons with other models [56] (Anderson and Gerbing, 1988). In this study, the model fit was compared between a single-factor model that combines all three dimensions, a two-factor model that combines any two dimensions, and a three-factor model. Their model fit was compared (see Table 10), and the results in the table below indicate that the three-factor model exhibits the best fit.

Table 9. Assessment of the structural model.

High-Order Construction	First-Order Construction	Factor Loading	T-Value	Confidence Intervals (Bias Corrected)		R-Square	Sig.
				2.50%	97.50%		
BIMTC	BIC	0.938	28.103	0.847	0.977	0.880	0.000
	BCC	0.971	104.726	0.947	0.985	0.942	0.000
	BEC	0.911	26.936	0.814	0.955	0.830	0.000

Table 10. Model fit indices.

	CMIN/DF	TLI	CFI	RMR	RESEM
Single-Factor Model	4.813	0.798	0.828	0.174	0.209
Two-Factor Model	3.155	0.886	0.904	0.151	0.157
Two-Factor Model	4.032	0.840	0.865	0.210	0.187
Two-Factor Model	2.921	0.898	0.914	0.118	0.149
Three-Factor Model	1.673	0.964	0.970	0.064	0.088

Therefore, it can be further concluded that BIM technical capabilities have been validated as a reflective–reflective higher-order multidimensional structure.

4. Discussion

4.1. Key Findings and Contributions

This study offers several key theoretical and practical contributions.

First and foremost, we offer a validated multi-dimensional structure and measurement scale of BIM technology capabilities by drawing upon existing theories. The inherent ambiguity that has encumbered research and theory development calls for both theoretical and operational understanding of this concept. To advance the field, we have integrated insights from works by Law et al. (1998) [10], Bharadwaj et al. (1999) [23], Olowa et al. (2022) [20], Polite et al. (2012) [11], Huang et al. (2014) [19], Bhatt and Grover (2005) [25], and King (2003) [33]. Consequently, we decided to use the notion of BIM technology capabilities to further develop the measurement scale. Thus, drawing upon the resource-based view (RBV) framework, we conceptualize BIM technical capability as a strategic competency that aids teams and enterprises in attaining and preserving a sustainable competitive advantage. Our proposition posits BIM technology capabilities as a reflective–reflective multidimensional structure comprising three distinct dimensions: (1) BIM infrastructure capabilities, (2) BIM collaborative capabilities, and (3) BIM expansion capabilities. These dimensions synergize, laying the foundation for a comprehensive grasp of BIM technology capabilities between and among subdimensions. Furthermore, this offers researchers and practitioners a robust framework to explore novel theories and business prospects in this domain, which can profoundly impact the effectiveness and efficiency of the whole construction industry.

Secondly, we have rigorously identified and validated the theoretically grounded BIM technology capabilities scale. The 17 measurement items retained, following two rounds of validation, exhibit commendable reliability and validity. This multidimensional structure and measurement instrument not only furnishes researchers with the means to develop new theories pertaining to the antecedents and consequences of BIM technology capabilities but also offers insights into the inherent mechanisms and contextual conditions. This holds particular significance for quantitative research within the construction industry's BIM technology applications. It aids in addressing pivotal questions concerning the nexus between BIM technology capabilities and organizational performance, demonstrates the mechanisms through which it leads to sustained competitive advantages, and underscores the factors that catalyze digital transformation and sustainability within the construction sector. The empirical outcomes of future quantitative research are poised to facilitate grassroots advocacy for the widespread adoption of BIM technology, thus assuming equal importance in propelling BIM technology applications and steering the construction industry's digital transformation.

Lastly, we responded to the call by Olowa et al. (2022) [20] by externally validating and extending the analysis of 33 features, primarily conducted with European samples, to regions beyond Europe—notably, emerging economies, such as China. The generalization of the measurement in the context of the Chinese construction industry will contribute to savings in both resources and costs while championing the digitization and sustainability of the entire construction lifecycle, because this expansion engenders a more comprehensive perspective of the constituents of BIM technology capabilities. It also ensures content fidelity while amplifying the scope of applicability of BIM technical capabilities in diverse contexts.

4.2. Limitations and Future Research

This study has several limitations.

Firstly, the sampling methodology employed in this research was non-random, focusing exclusively on firms engaged in proactive utilization of BIM technology within their operational framework. While this non-random approach may potentially circumscribe the extent of generalizability of our findings, it is important to note that this strategic selection affords a more laser-focused and pragmatic vantage point, notably enriching the depth and pertinence of insights gleaned for the construction and validation of the BIM technology capabilities scale.

Secondly, while there is a reasonable presumption that BIM technology capabilities exert an influence on organizational performance outcomes, further inquiry is warranted to meticulously explicate the specific mechanisms by which they precipitate performance enhancements. Simultaneously, it becomes imperative to discern the nuances of the contextual factors that may moderate the relationship. These prospective research endeavors hold the potential to furnish a more profound comprehension of the multifaceted relationships intertwined with BIM technology capabilities and their impact on organizational performance.

5. Conclusions

Drawing from the existing body of research, we constructed a second-order structural model to assess the construct of BIM technology capabilities. Subsequently, we meticulously developed and validated a measurement scale encompassing three dimensions and comprising a total of 17 items. This comprehensive scale affords us the capability to conduct a more granular investigation into the procedural mechanisms governing the application of BIM technology. Furthermore, we have deliberately delineated the interrelationships between BIM technology capabilities and their constituent sub-dimensions, ensuring the alignment of conceptualization with operationalization.

It is worth noting that the process of scale development is inherently iterative in nature. Although we employed a two-step validation process in this study to craft and initially validate the BIM technology capabilities scale, it is imperative to underscore that these findings necessitate further validation and corroboration. We extend a cordial invitation to scholars with an interest in BIM technology capabilities to incorporate our scale into their research surveys, and, concurrently, we encourage them to embark on the task of refining and empirically validating the BIM technology capabilities model. We anticipate that this collective effort will provide a firm foundation that will promote further insights and in-depth scholarly investigations into this pivotal research domain.

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