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BIM-CAREM: Assessing the BIM capabilities of design, construction and facilities management processes in the construction industry

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ABSTRACT

BIM adoption has accelerated worldwide since it is an important enabling technology for digitalisation in the construction industry. Adopting BIM requires transforming the traditional building life cycle stages (planning, design, construction and facilities management) into BIM-integrated project deliveries. Assessing the BIM capabilities of these stages helps organisations to identify gaps in their BIM uses and improve them. There is a lack of a comprehensive model in the literature for assessing the BIM capabilities of individual building life cycle stages and their processes. Existing assessment models focus on assessing the BIM maturity of construction projects and organisations which do not inform the required BIM improvements for individual stages and their processes. Hence, we iteratively developed the Building Information Modelling (BIM) Capability Assessment REference Model (BIM-CAREM) and demonstrated its usability through multiple explanatory case studies performed with two international design and engineering companies and two general contractors in Turkey. We assessed the BIM capabilities of design, construction and facility management processes of various buildings i.e. residential, stadiums, hospitals and airports. The results showed that the BIM capability levels of design, construction and facility management processes vary within and across the companies.

1. Introduction

The Architecture, Engineering, Construction and Facility Management (AEC/FM) industry has a highly fragmented structure. Various stakeholders with different expertise, such as owners, engineers and contractors, need to collaborate throughout the facility life cycle, which consists of seven stages i.e. perceived needs, conceptual planning and feasibility study, design and engineering, procurement and construction, handover, operation and maintenance (O&M), and disposal of a facility (Hendrickson, 2008). Due to its various benefits, such as enhancing collaboration, BIM adoption rates have increased in the construction industry worldwide (Anon, 2021; Anon, 2021), and its adoption in the manufacturing industry was also considered recently (Alvanchi et al., 2021). BIM adoption needs a significant change in the construction organisations such as hiring. BIM-savvy workforce (Klein et al., 2022); hence, even after adopting BIM, the AEC/FM organisations need to evaluate the effectiveness of their BIM implementations to enable BIM improvements (Wu et al., 2017). Several BIM maturity models were developed to help organisations to evaluate the BIM maturity of AEC/FM companies and projects. However, most of the BIM maturity models in the AEC/FM industry lack three critical aspects, which already exist in the commonly used two software engineering capability maturity models; namely Capability Maturity Model Integration (CMMI)(SEI, 2010) and ISO/IEC 330xx family of standards (ISO/IEC, 2015a).

First, the BIM maturity models existing in the literature do not include separated components, namely process and capability dimensions, as in the ISO/IEC 330xx family of standards (Yilmaz et al., 2019). Having separated parts allows users to select one AEC/FM process from the process dimension and measure its BIM capability using key parameter indicators defined in the capability dimension. Secondly, BIM maturity and capability models used in the AEC/FM industry mostly do not mention why the maturity and capability models were developed and how different maturity and capability are from each other. On the other hand, similarities and differences between maturity and capability assessment models are explained in detail in both the Capability Maturity Model Integration (CMMI) and ISO/IEC 330xx family of standards. While maturity models identify the process sets

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Nomenclature

AEC/FM	Architecture, Engineering, Construction and Facility Management.
ARCH D	Architectural Design.
BS D	Building Services Design.
BIM	Building Information Modeling.
BIM-CAREM	Building Information Modeling Capability Assessment REference Model.
BIM A	Building Information Modeling Attribute.
BIM PRM	Building Information Modeling Process Reference Model.
BIM MF	Building Information Modeling Measurement Framework.
C	Construction.
CMMI	Capability Maturity Model Integration.
GEO D	Geotechnical Design.
HVAC	Heating, Ventilation and Air Conditioning.
FM	Facility Management.
MEP	Mechanical, Electrical and Plumbing.
STR D	Structural Design.

associated with the levels in a specified scale of organisational process maturity, process capability assessment models are used for assessing the specified process quality characteristics of processes defined within a process reference model (ISO/IEC 33001, 2015a). While a maturity level consists of specific and generic practices for a defined set of organisational processes, a process's capability level is satisfied when generic practices of a process are achieved (SEI, 2010). Although capability and maturity models provide ways to improve processes to achieve organisational goals, the approach to process improvement is different. In other words, while capability levels are used to evaluate individual processes within an organisation, maturity levels are used for organisational and project-based evaluations based on a set of processes divided into maturity levels.

Laslty, most of the BIM maturity models are missing to highlight the validation strategies, which was also highlighted as a significant concern in Tarhan et al. (Tarhan et al., 2016) for the capability maturity models developed based on the CMMI and ISO/IEC 15504 Software Process Improvement and Capability dEtermination (SPICE) (Anon, 2000). As there is a lack of a comprehensive model enabling the BIM capability assessments of AEC/FM processes within the facility life cycle phases, we developed the BIM Capability Assessment REference Model (BIM-CAREM) iteratively. BIM-CAREM was developed in conformance with the ISO/IEC 330xx standards and revised iteratively through expert reviews and an explanatory case study (Yilmaz et al., 2019). The usability of the BIM-CAREM was tested through multiple explanatory case studies, which is the main focus of this paper, including four international construction companies building various structures residential buildings, stadiums, hospitals and airports (see Fig. 1).

2. BIM capability and maturity models

We compared the nine different BIM capability and maturity assessment models included in the research of Yilmaz et al. (2017) based on the assessment purpose and scoring, and validation strategies of the models (see Table 1). The analysis showed that each model focuses to fulfil a specific BIM assessment purpose, such as assessing the BIM performance of construction projects and the BIM maturity levels of organisations (see Table 1).

Additionally, validation strategies of half of the models, which is the main focus of this work, were not completed or stated clearly in the literature (see Table 1). Capability Maturity Model of the National Institute of Building Sciences (NBIMS CMM) was tested by six NBIMS testing team members by evaluating nine award-winning models selected by the American Institute of Architects. The test focused on achieving similar scores for the same models by different individual evaluators. The results showed a 1% difference when the same models were evaluated using CMM (NBIMS, 2015c). Although the validation strategy of the BIM Maturity Matrix was not stated in Succar (Succar, 2010) explicitly, it can be inferred that the model's applicability was tested through BIM Excellence (Anon, 2013). BIM QuickScan (Anon, 2009) was validated by comparing scores found by conducting self-scans using free online assessment tools and results identified via scans performed by certified consultants. The results showed that scores found via self-scans aligned with the results identified by certified consultants (van Berlo and Hendriks, 2012). Virtual Design and Construction (VDC) Scorecard (2009; Gao, 2011) was implemented in 108 pilot projects of 11 facility types in 13 countries. Detailed statistical analysis was conducted using the data collected to confirm the results since empirical data were unavailable by the experts. Results reported that VDC Scorecard is a holistic, practical, quantitative, and adaptive method (Kam et al., 2013; Kam et al., 2014). BIM Application Maturity Model (BIM-AMM) is tested through one project evaluated by five different project staff, including the project manager and BIM manager (Sun et al., 2021). Although we have looked at different sources of evidence to identify if the models were tested or not, validation strategies of BIM Proficiency Matrix (Anon, 2009), Organizational BIM Assessment Profile (AP) (Anon, 2012), VICO BIM Scorecard (2011), and Multifunctional BIM Maturity Model (MM) (Liang et al., 2016), were not clearly explained in the literature.

Due to the lack of a model facilitating BIM capability assessments of individual building life cycle stages, we used the well-established structure of the ISO/IEC 3300xx family of standards of the software engineering domain for developing the BIM-CAREM (Yilmaz et al., 2019). We defined and differentiated the BIM maturity and capability to clarify the usage of these two terms in the construction industry. While BIM maturity is implementing a set of BIM processes within a defined scope that contributes to achieving the BIM needs of organisations, BIM capability is the characterisation of the ability of a BIM process to deliver its defined BIM outcomes and BIM attribute outcomes (ISO/IEC, 2015a).

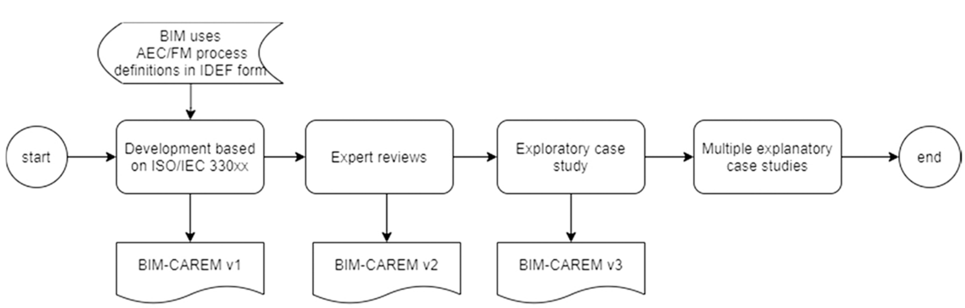

Fig. 1. Development flow of BIM-CAREM.

Table 1
Comparison of Existing BIM Capability and Maturity Models in AEC/FM Domain.

Name	Purpose and Scoring	Validation
NBIMS CMM	Rates performance of projects Weighted sum of 11 areas of interests, 10 levels of maturity with ordinal scale	Six assessors measured nine models and deviation of measurement result was 1%
BIM Proficiency Matrix	Scores BIM services performances of organizations for selecting subcontractors Sum of 32 measures grouped under 8 areas of interests, 5 levels of maturity with ordinal scale	Not clear
BIM Maturity Matrix	BIM competency of individuals, organizational capability & maturity and BIM performance of a project Total points subdivided by the number of competencies plus one capability stage and one organizational scale, 5 metrics (BIM competencey sets, organizational scale, granularity level, BIM capability stages, BIM maturtiy levels), 3 levels of capability and 5 levels of maturity with ordinal scale	Tested via BIM Excellence community platform
BIM QuickScan	Provides insight about BIM strengths and weaknesses of the organization Weighted sum of 50 multiple questions grouped under 4 categories, 6 levels with ordinal scale	Self-scans conducted using free online assessment tools and resulting scores compared
VDC Scorecard	Measures the project performance against an industry benchmark Weighted sum of 74 individual measures with quantitative and qualitative questions clustered into 4 key areas and 10 divisions, 5 levels with ratio scale	Implemented in 108 pilot projects of 11 facility types in 13 countries
Organizational BIM AP	Evaluates the organization's maturity of BIM planning elements Sum of 20 sub elements clustered into 6 main planning elements, 6 maturity levels with ordinal scale	Not clear
VICO BIM Scorecard	Scores the BIM performance of specific BIM uses such as coordination and cost estimation in organizations Weighted sum of 27 questions clustered into 7 categories with 3 three columns, 4 capability levels with ordinal scale	Not clear
Multifunctional BIM MM	Evaluates BIM maturity in projects, companies with a portfolio of projects, and the industry as a whole Sum of 21 subdomains clustered into 3 domains, 4 levels of maturity with ordinal scale	Not clear
BIM-AMM	Evaluates the BIM maturity of projects Sum of 10 sub-factors which are grouped under 3 index factors divided by the number or evaluators, 4 levels of maturity with ordinal scale	One project assessed by five staff

The BIM capability assessment model addresses specific BIM quality characteristics. The BIM maturity models are derived from one or more BIM assessment models identifying BIM process sets associated with the defined BIM maturity levels (ISO/IEC, 2015a). ISO/IEC 33004 and ISO/IEC 33003 provide requirements for developing the process and capability dimensions, respectively. The process dimension is represented by a process reference model that contains a set of processes that support the organisational goals in a specific domain and a unique description of each process (ISO/IEC, 2015c). The capability dimension is represented by a process measurement framework that should address measuring a single process quality characteristic by including multidimensional attributes (ISO/IEC, 2015b).

3. Development methodology of BIM-CAREM

Two staged qualitative research study was conducted to develop BIM-CAREM (Fig. 1). In the first stage, we developed BIM CAREM based on the meta-model of the ISO/IEC 3300xx family of standards due to its well-established structure and high adaption rate into other domains. We revised it iteratively via expert reviews and an exploratory case study explained in detail in Yilmaz et al. (2019). The second stage tests its usability, presented in Section 3, through multiple explanatory case studies conducted with four international design and engineering companies and general contractors in Turkey. We assessed the BIM capabilities of individual building life cycle stages (design, construction, and facility management) and their processes included in different construction projects are residential buildings, stadiums, hospitals and airports.

BIM-CAREM is a reference model for systematically assessing the BIM capabilities of AEC/FM processes and has two parts: the BIM process (ISO/IEC, 2015c) and BIM capability dimensions. The process dimension of BIM-CAREM includes two process reference models, the Building Process Reference Model (PRM) and BIM PRM, which define the AEC/FM processes based on the purpose, outcomes, and work products of the processes. The BIM capability dimension has a BIM Measurement Framework (MF), which is the schema for characterising the BIM capability of an implemented AEC/FM process. The Building PRM and BIM PRM include the same set of AEC/FM processes classified into the facility life cycle stages, which are conceptual planning (P), architectural design (ARCH D), structural design (STR D), building services design (BS D), geotechnical design (GEO D), construction (C), and facility management (FM). They define each process based on the purpose, outcomes, and work products of the processes (Table 3). BIM PRM (defines 26 AEC/FM processes) is a subset of Building PRM (defines 32 AEC/FM processes), which means six processes were excluded from Building PRM as they were not related to BIM. For example, the P1-Assign planning team in Table 3 is not related to BIM; hence, it does not have any BIM outcomes and was not included in the BIM PRM. The resultant 26 AEC/FM processes related to BIM are included in BIM PRM. As presented in Table 3, each process is defined based on the BIM outcomes, which are BIM-related observable evidence of the achievement of the process purpose by performing base practices of an AEC/FM process. BIM outcomes of these 26 AEC/FM processes were determined based on the BIM uses identified from various resources in the literature (Yilmaz et al., 2019).

The BIM MF consists of four levels of BIM capability, Level 0 Incomplete BIM, Level 1 Performed BIM, Level 2 Integrated BIM, and Level 3 Optimized BIM, indicating an organisation's BIM leverage capability in their AEC/FM processes (Table 2). In Level 1, the BIM is not implemented or partially implemented and fails to achieve the BIM outcomes. Level 2 capability level means that BIM is integrated to enable collaboration between the project stakeholders and data exchange throughout the facility life cycle phases and the processes. At Level 3, BIM is used at the enterprise level and continuously improved to support organisations' business goals.

Except for Level 0, each level is characterised by two BIM attributes

Table 2
BIM capability levels and the required BIM attribute ratings for their achievement.

BIM Capability Levels	BIM Attributes BIM A1.1 Performing BIM	BIM A1.2 BIM Skills	BIM A2.1 BIM Collaboration	BIM A2.2 Interoperability	BIM A3.1 Corporate-wide BIM Deployment	BIM A3.2 Continuous BIM Improvement
L3 Optimized	F	F	F	F	L / F	L / F
L2 Integrated	F	F	L / F	L / F	-	-
L1 Performed	L / F	L / F	-	-	-	-
L0 Incomplete	-	-	-	-	-	-

L / F: BIM attribute is required to be achieved Largely or Fully F: BIM attribute is required to be achieved Fully
Not Achieved (N): 0 Partially Achieved (P): 1 Largely Achieved (L): 2 Fully Achieved (F): 3
Not Available (N/A): insufficient observable evidence

and their BIM attribute outcomes. BIM attribute is a performance indicator for identifying the BIM capability level of a process. BIM attributes are rated based on the observable evidence, namely BIM outcomes and attribute outcomes presented in Tables 3 and 4, after their achievement. Performing BIM measures the extent to which the defined BIM outcomes are achieved. BIM Skills measures the extent to which the organisation prefers to work with BIM-trained and experienced employees. Having a BIM skilled team was mentioned as a significant enabler for generating and managing BIM information (BSI Standards Publication, 2018b). BIM Collaboration measures the extent to which the BIM is used to support the collaboration and information exchange between the processes. ISO 19650–1 (BSI Standards Publication, 2018a) defines collaboration and describes creating a framework to manage BIM information consisting of exchanging, recording, versioning, and organizing for all BIM stakeholders. ISO 19650–2 (BSI Standards Publication, 2018b) focuses specifically on project delivery, where the most graphical data, non-graphical data and documents, known collectively as the project information model, are accumulated from design and construction activities. Interoperability measures the extent to which interoperability and flexible data exchange between BIM tools and software applications are supported. The interoperable formats are defined in ISO 16739 (Anon, 2013) open international standard for BIM data which consists of the data schema, represented as an EXPRESS schema specification (Anon, 2004), and reference data, represented as definitions of properties and quantities (NBIMS, 2015b, 2015a). Corporate-wide BIM Deployment measures the extent to which BIM is diffused to each process and embraced by all team members. BIM uses are various such as 3D coordination, cost estimation and phase planning and are clustered into two: essential and enhanced (Anon, 2017). Implementing BIM in different AEC/FM processes are dependent on each other; for example, for 3D coordination, BIM models for different design disciplines need to be generated. Hence, BIM deployment across the facility life cycle can be established by implementing BIM at the individual stages of the facility life cycle and connecting them via sharing and exchanging BIM data and collaborating on BIM models. For example, implementing BIM for plant systems such as Air Conditioning (HVAC) (Marini et al., 2018) and Mechanical, Electrical and Plumbing (MEP) enables automatic clash detection by including data item identification in design coordination (Leite et al., 2009) which increases the collaboration within and between the organisations. Continuous BIM Improvement measures the extent to which BIM changes are planned based on the BIM usage variations and improvements (Yilmaz et al., 2019). BIM uses evolves in parallel to emerging technologies such as integrating BIM with Construction 4.0 for analysing the as-is condition of HVAC systems by collecting data through sensors (Akinci, 2014) and facilitating BIM for prefabrication to improve quality and working conditions (Bataglin et al., 2019).

Formal BIM capability assessment of AEC/FM processes in an organisation begins with selecting the process from BIM PRM, such as ARCH D3-Make global design in Table 3. Assessors look for observable evidence within the organisation to identify the achievement level of the BIM outcomes, and BIM attribute outcomes of the process given in Table 3. A four-point ordinal rating scale, which is Fully Achieved (F), Largely Archived (L), Partially Achieved (P) and Not Achieved (N), is used to give single scores to BIM outcomes and BIM attribute outcomes as defined in Table 2 (ISO/IEC, 2015d). Not Available (N/A) value is used when there is not enough evidence to score. The single ratings of the BIM outcomes and BIM attribute outcomes are aggregated based on the principles explained in ISO/IEC 33020 (2015d) to have a composite rating for the BIM attributes. Later, the BIM capability level of the assessed AEC/FM processes is identified based on the ratings of all BIM attributes, which should be rated either with L or F for the assessed process. To achieve one level higher BIM capability, BIM attributes of the latter level should be rated as F (Table 2).

4. Multiple explanatory case studies

Multiple case studies with four different AEC/FM organisations were designed and implemented by considering four components of the case study research: company selection strategy, data collection methods, validation strategy, and data analysis methods (Yin, 2003). The four staged case study flow and techniques used to eliminate the validity threats in each stage are represented in Fig. 2.

4.1. Company selection strategy

We selected four AEC/FM organisations, demographics are introduced in Table 5, based on these five criteria: 1) organisations that are using BIM for performing AEC/FM processes, but it is not necessary to have BIM as a contract requirement, 2) different types of organisations such as designers and constructors with different size, 3) different facility types such as hospitals, stadiums, and airports and different structural frame types such as steel and reinforced concrete, 4) at least one company for each facility life cycle stage, 5) BIM usage at different BIM capability levels (Yilmaz, and Yilmaz et al., 2019, 2017).

4.2. Data collection and analysis methods

According to Yin (2003), the collected data is analysed and examined to address the research problem. Hence, its quality is established through data collection techniques which are multiple sources of evidence, a case study database, and a chain of evidence including documents, archival records, interviews, direct observation, participant observation, and physical artefacts. During the case studies, primary data was collected by conducting formal assessments through semi-structured interviews using an excel-based assessment sheet consisting of pre-defined interview questions. Secondary data was collected through direct observations using a checklist which includes BIM work products, generic BIM work products and generic resources. The primary and secondary data were summarised as assessment reports for each company and used as objective evidence to give scores for the BIM outcomes and attribute outcomes which were aggregated into single scores of BIM attributes. The final BIM capability levels of the AEC/FM processes and facility life cycle stages were identified based on the BIM attributes scores with respect to the rules given in Table 2.

Table 3
BIM A 1.1 Performing BIM with BIM outcomes for AEC/FM processes

BIM A1.1	BIM Outcomes
P1-Assign planning team	There are no available BIM outcomes since process is not related to BIM
P2-Study/define needs	P2–1. User needs and requirements are defined regarding BIM usage in Design, Construction and FM phases P2–2. Existing conditions modelling is conducted for a site/facility on site/a specific area within a facility
P3-Study feasibility	P3–1. Feasibility information (Economic, environmental, and technical) is studied
P4-Develop program	There are no available BIM outcomes since process is not related to BIM
P5-Develop project execution plan	P5–1. Define BIM as part of project delivery strategy and identify required BIM services P5–2. BIM Execution Plan is created
P6-Select and acquire site	P6–1. Site analysis: Site analysis is conducted to determine the most optimal site location
ARCH D1-Draw up brief	There are no available BIM outcomes since process is not related to BIM
ARCH D2-Draw up program	ARCH D2–1. Draw up space program and requirements are developed (areas, volumes and etc.). ARCH D2–2. Programming: Design performance is assessed in terms of spatial requirements.
ARCH D3-Make global design	ARCH D3–1. Design authoring: Architectural design alternatives are created. ARCH D3–2. Design authoring: General layout design is developed. ARCH D3–3. Design authoring: Architectural scheme is created. ARCH D3–4. Coordination: 3D coordination is conducted between architectural model and models from all disciplines (STR, BS and GEO). ARCH D3–5. Code validation is performed. ARCH D3–6. Design authoring: ARCH global model is developed. ARCH D3–7. An application for a building permit is submitted.
ARCH D4-Make detail design	ARCH D4–1. Design review: Design review is conducted for the global model created. ARCH D4–2. Design authoring: Detailed architectural model is authored. ARCH D4–3. Coordination: 3D coordination is conducted between detailed architectural model and all other detailed models (STR, BS, GEO). ARCH D4–4. Design authoring: Architectural detail model is updated further for construction. ARCH D4–5. Cost estimating: 5D cost estimating is created via quantity take off from the model. ARCH D4–6. Phase and 4D planning: 4D planning is prepared to plan construction sequence effectively. ARCH D4–7. Engineering analysis: Energy analysis is conducted based on the model to assess building energy performance. ARCH D4–8. Engineering analysis: Sustainability (LEED) evaluation is done based on the model. ARCH D4–9. Tender documents including BIM protocols are created.
ARCH D5-Do design tasks during construction	ARCH D5–1. Record modelling: As-Built model is created for use in facility management.
STR/BS D1-Draw up brief	There are no available BIM outcomes since process is not related to BIM
STR/BS D2-Draw up program	There are no available BIM outcomes since process is not related to BIM
STR D3-Make global design	STR D3–1. Design authoring: Alternative structural frames are developed based on structural possibilities STR D3–2. Coordination: 3D Coordination of BS designs and bearing structures, and 3D coordination of STR design alternatives and proposed design solutions for all disciplines (ARCH, BS, GEO) are checked and one STR solution is proposed. STR D3–3. Coordination: 3D coordination is conducted between chosen STR model and models from all disciplines (ARCH, BS and GEO) STR D3–4. Design authoring: STR model is further authored to create structural global model
STR D4-Make detail design	STR D4–1. Design authoring: Detailed STR model is created based on structural calculations STR D4–2. Engineering analysis: Structural analysis is conducted STR D4–3. Cost estimating: 5D cost estimation is prepared via quantity take off from model STR D4–4. Phase and 4D planning: Phase and 4D planning is developed
STR D5-Do design tasks during construction	STR D5–1. Record modelling: As-Built model is created for use in facility management
BS D3-Make global design	BS D3–1. Design authoring: Proposed BS models (HVAC, AUT, TEL, ELE) are created. BS D3–2. Coordination: 3D coordination is conducted between proposed BS models (HVAC, AUT, TEL, ELE) and proposed models from all disciplines (ARCH, STR, GEO). BS D3–3. Coordination: 3D coordination is conducted for BS models (HVAC, AUT, TEL, ELE) and BS design solutions are chosen and approved. BS D3–4. Desing authoring: BS schemes are created and BS global designs are approved.
BS D4-Make detail design	BS D4–1. Design authoring: Detailed BS models (HVAC, AUT, TEL, ELE) are developed. BS D4–2. Coordination: 3D coordination is conducted between BS detail models (HVAC, AUT, TEL, ELE). BS D4–3. Cost estimating: 5D cost estimation is prepared via quantity take off from model. BS D4–4. Phase and 4D planning: 4D planning is prepared. BS D4–5. Engineering analysis: Energy analyses (heating energy consumption, cooling energy consumption, electricity consumption, water consumption, lightening analysis, etc.) are carried.
BS D5-Do design tasks during construction	BS D5–1. Record modelling: As-Built model is created for use in facility management.
C1-Acquire construction services	C1–1. Qualified parties with BIM capability who will be invited to bid on a work package are identified C1–2. Proposals for bid including BIM costs are prepared by qualified parties C1–3. Proposals are reviewed and BIM using constructor/subcontractors are selected based on the criteria set by the staffing plan C1–4. Contracts including BIM clauses are formalized
C2-Plan and control the work	C2–1. Phase and 4D planning: Construction sequencing is created C2–2. Site utilization planning: BIM is used to graphically represent facilities on site which can include labor resources, materials with associated deliveries, and equipment location C2–3. 5D cost estimating is used for developing the budget C2–4. Shop drawings are created using BIM C2–5. Status/progress monitoring is visualized from site data
C3-Provide resources	C3–1. Resources are acquired and inventory is managed in accordance with inventory information gathered from integrated ERP and BIM tools C3–2. Digital fabrication: Digital fabrication is facilitated C3–3. The distribution priorities are determined based on 4D plan
C4-Build facility	C4–1. Daily work is executed based on 4D plan C4–2. 3D location identification: Physical locations of elements on site are pinpointed for construction layout C4–3. Facility is constructed by using BIM C4–4. Quality assurance is conducted C4–5. Operation data is handed over to the owner with BIM
FM1-Plan/control facility	FM1–1. Asset management: Financial decision making, short term and long term planning and generating work orders schedules are assisted via

(continued on next page)

Table 3 (*continued*)

BIM A1.1	BIM Outcomes
	integrating record models with asset management systems. FM1–2. Space management: Scape distribution, management and tracking is utilized by integrating record models and spatial tracking software. FM1–3. Disaster planning and management: Critical building information is made available to the responders by integrating record models and BMS which allows clear display of emergency locations.
FM2-Manage operations	FM2–1. Physical performance information and operations historical data reviewed via integrating record models and facility management systems. FM2–2. O&M scheduling is planned by integrating record models and facility management systems suhc as BAS and CMMS.
FM3-Monitor facility conditions and systems	FM3–1. Facility points/areas are selected for collecting operations data through sensors. FM3–2. Operations data, which is collected through sensors, is stored, classified, or simplified in record model integrated with BAS in order to be used by other functions.
FM4-Evaluate conditions and detect problems	FM4–1. Monitoring information for identifying problem area is compared with critical or expected performance values which are attached to models.
FM5-Develop solutions	FM5–1. Root-cause analysis is performed by using the model to understand the problem. FM5–2. Technical solution for the problem is designed by using the model. FM5–3. Implications of the problem solving plan are analyzed by using the model.
FM6-Select plan of action	FM6–1. Decisions for selecting problem solution plan are made via integrating models and facility management tools/asset management tools. FM6–2. Services and resources for implementing the plan are allocated by integrating models and facility management tools.
FM7-Implement plan	FM7–1. Performed O&M tasks are reflected to the model.

Table 4
BIM attributes and their BIM attribute outcomes of BIM capability levels 2 and 3.

BIM Attribute	BIM Attribute Outcomes
BIM A1.2 BIM Skills	BIM A1.2–1 Staff with BIM trainings are hired BIM A1.2–2 BIM trainings are supported within the company BIM A1.2–3 BIM related process are assigned to BIM chiefs/managers
BIM A2.1 BIM Collaboration	BIM A2.1–1 Strategies for BIM collaboration are defined BIM A2.1–2 Strategies for exchanging models and facility information are defined BIM A2.1–3 BIM collaboration strategies are implemented BIM A2.1–4 Model exchanging strategies are implemented
BIM A2.2 Interoperability	BIM A2.2–1 Interoperable formats are made available and used to support data exchange between BIM software and other construction software applications
BIM A3.1 Corporate-wide BIM Deployment	BIM A3.1–1 Model is used for all processes and embraced by all team members BIM A3.1–2 Required facility information for different processes are extracted from the model and provided for the use of all team members BIM A3.1–3 Change management and synchronization of the model are established and the model updates are tracked BIM A3.1–4 BIM objects and facility information are reused on future projects
BIM A3.2 Continuous BIM Improvement	BIM A3.2–1 A feedback mechanism is created to identify common causes of variations in BIM usage BIM A3.2–2 Improvement opportunities, which are derived from feedback mechanism and from new BIM technology trends and best practices, are identified BIM A3.2–3 An implementation strategy is established to achieve BIM improvement objectives

4.3. Actions taken to eliminate validity threats

The four threats, which are construct validity, internal validity, external validity, and reliability, need to be addressed to increase the validity in case studies (Yin, 2003). The validity denotes to what extent the case study results are accurate (Wohlin et al., 2012). As presented in Fig. 3, we used various techniques to address the validity threats in the case study design. Construct validity ensures correct operational measures for the concepts being studied and it was addressed through data triangulation (Yin, 2003). Data triangulation ensured us to collect data from different sources i.e., primary and secondary data through various approaches (interviews, direct observations, questionnaires, voice records, and checklists) and to analyse these data using different techniques (Fellows and Liu, 2015). Internal validity may arise from the investigator's inferences based on the interview (Yin, 2003). To address this threat, we used respondent validation (Fellows and Liu, 2015). Informal checks were performed by sharing the understandings with the interviewees to clarify the findings identified for each case study. External validity ensures that the findings of a case study are generalisable, and a single case study is poor for generalizability (Yin, 2003). Generalizability is the ability to transfer results from a particular group to a larger group (Fellows and Liu, 2015). To eliminate generalizability threats, different companies were selected based on the five selection criteria (see Table 3). The reliability of a case study aims to reach the same findings and conclusions after following the same procedures described by an investigator who has conducted the case study (Yin, 2003). To increase the reliability, replication, which is described as observations of the case studies under identical treatments (Fellows and Liu, 2015), was facilitated for one of the case studies. Two weeks after conducting the case study in Company A, we spent four hours in the company to ask the essential interview questions again. Even though we did not conduct a new assessment from scratch, previously identified case study findings were observed again, and the results were verified.

4.4. Findings and results of the multiple case studies

This section introduces the assessment results found for Companies A to D. For each company we collected objective evidence with respect to the BIM capability levels and their BIM attributes that are BIM A1.1 Performing BIM, BIM A1.2 BIM Skills, BIM A2.1 BIM Collaboration, BIM A2.2 Interoperability, BIM A3.1 Corporate-wide BIM Deployment, and BIM A3.2 Continuous BIM Improvement. Objective evidence from each company were presented in Tables 6–8 and used for giving scores to BIM outcomes and BIM attribute outcomes of the BIM attributes. Individual scores for BIM outcomes and BIM attribute outcomes are presented by using the colour coding: Fully Achieved (F), Largely Archived (L), Partially Achieved (P) and Not Achieved (N) are represented by 'Green', 'Blue', 'Yellow', and 'Red', respectively, Not Available (N/A) is presented with the colour 'Grey'. The same colour coding is used for representing all results presented in this work.

Table 6 presents the findings with respect to the BIM outcomes of the BIM A1.1 Performing BIM to determine to what extent companies are using BIM in the facility life cycle stages (architectural, structural, and building services design, construction and facility management) and their sub-processes. We performed BIM capability assessment across all facility life cycle stages in only Company D. The rest of the assessments performed for architectural design, structural design and construction were completed in companies B, A and C, respectively. Table 7 presents the findings with respect to the key performance indicator of BIM A1.2 BIM Skill which helped us to understand to what extent companies A to D employed BIM-skilled people and assigned them to the facility life cycle stages and their sub-processes.

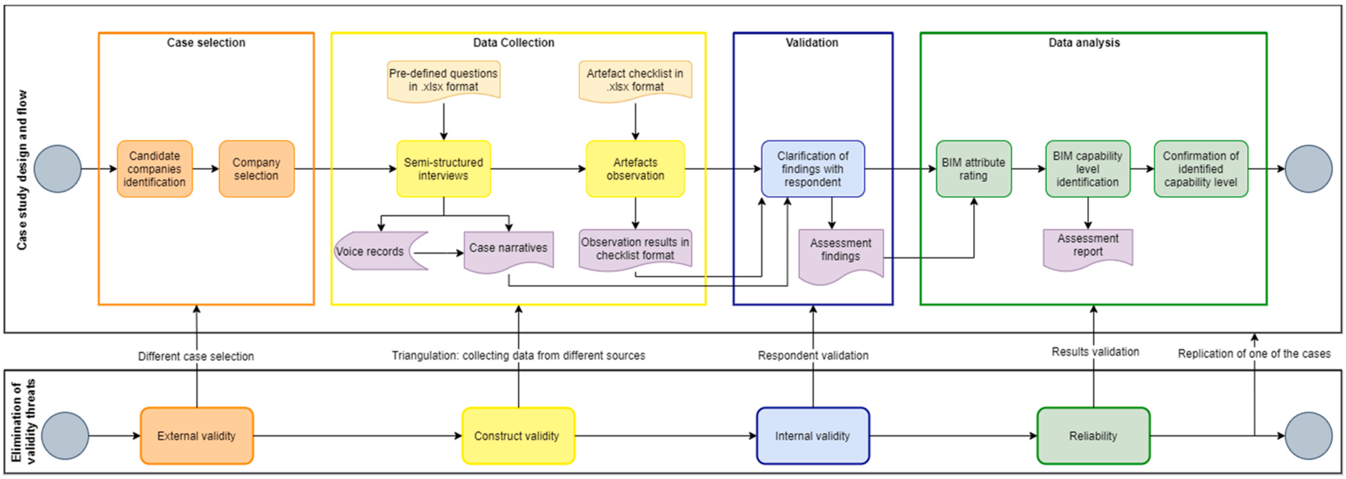

Fig. 2. Multiple case study design and actions to eliminate validity threats.

Table 5
Demographic information of AEC/FM organizations included in the multiple case studies.

Companies	Company A	Company B	Company C	Company D
Type and Size	Structural design firm with less than 50 employees (small)	Architectural design firm with less than 10 employees (small)	International constructor with more than 200 employees (medium)	International constructor with more than 2500 employees (large)
Evaluated Project Type	Sports facilities such as stadiums with steel frames and buildings with concrete frames	Buildings such as hotels and residential buildings	Health complexes and hospitals	Airports
Evaluated Frame Type	Steel and reinforced concrete	Reinforced concrete	Reinforced concrete	Steel and Reinforced concrete
Evaluated phases and processes	Structural design and its all sub-processes given in Table 3	Architectural design and its all sub-processes given in Table 3	Construction and its all sub-processes given in Table	All design stages, construction and facility mangement and their all sub-processes given in Table 3
BIM Contract Req. (Y/N)	Y	N	Y	Y
Applied Criteria	1–6	1,2,4–6	1,2,3,5,6	1,3–6
Company's BIM Experience	5 + years	5 + years	5 + years	5 + years
Interviewees and their roles	Civil engineer, the founder of the company, the lead structural designer, and technician	Architect and co-founder	Architect and BIM supervisor	Director of engineering and design team, and BIM chief

Table 8 presents the findings with respect to the key performance indicators of Level 2 (BIM A2.1 BIM Collaboration, and BIM A2.2 Interoperability) and Level 3 (BIM A3.1 Corporate-wide BIM Deployment and BIM A3.2 Continuous BIM Improvement) across the facility life cycle stages and their sub-processes in companies A to D. BIM Collaboration and Interoperability measured to what extent companies used BIM for collaboration and exchanged model information using interoperable formats within and between the processes. Corporate-wide BIM Deployment and Continuous BIM Improvement measured to what extent companies deployed BIM internally and externally and followed emerging standards and technologies to optimise BIM uses.

Findings given in Tables 6–8 were first used to give ratings for individual BIM outcomes and BIM attribute outcomes ratings based on the four-point ordinal rating scale defined in Section 3. Individual scores for BIM outcomes and BIM attribute outcomes are presented in Figs. 3 and 4 by using the same colour coding introduced for Tables 6–8. Later, these individual scores of BIM outcomes and BIM attribute outcomes were aggregated using the BIM MF aggregation procedures defined in Section 3. The aggregation of these scores into single scores of the BIM attributes with respect to Companies A, B, C and D are presented in Figs. 3 and 4.

BIM attributes of Level 1 (Perfomed BIM) and Level 2 (Integrated BIM) were fully achieved by most companies. Company A did not fully achieve Performing BIM, since it is a medium-sized enterprise with limited budget to invest in using BIM for collaboration internally and externally. Level 3 (Optimized BIM) were not fully achieved by most companies due to the challenges in deploying BIM at the enterprise level for internal and external stakeholders with a continuous improvement owing to the fragmented structure of the construction industry (Fig. 5).

Company A used BIM to perform the structural design processes and had the required BIM-skilled employees. Company A also used BIM to integrate different processes for steel and concrete frame projects. Despite the differences in ratings of BIM A3.1 for the structural design of steel and that of concrete frames, both were found at BIM Capability Level 2-Integrated (Fig. 6). The architectural design of Company B was found at BIM Capability Level 1-Performed since BIM was used to create 3D models rather than integrating different processes/phases (Fig. 6). Company C has been implementing BIM in most of their construction practices by achieving the expected BIM outcomes and have the required BIM skilled employees. BIM was used to integrate different processes/ phases by facilitating BIM collaboration, and interoperable formats have been used. Company C has also been using BIM at the enterprise level. Based on the findings, explained above, the BIM capability level of the construction phase in Company C was found at BIM Capability Level 3-Optimized, presented in Fig. 6. Company D used BIM in most of the design and construction practices. However, they have limited usage of BIM in their facility management practices. Employees of Company D

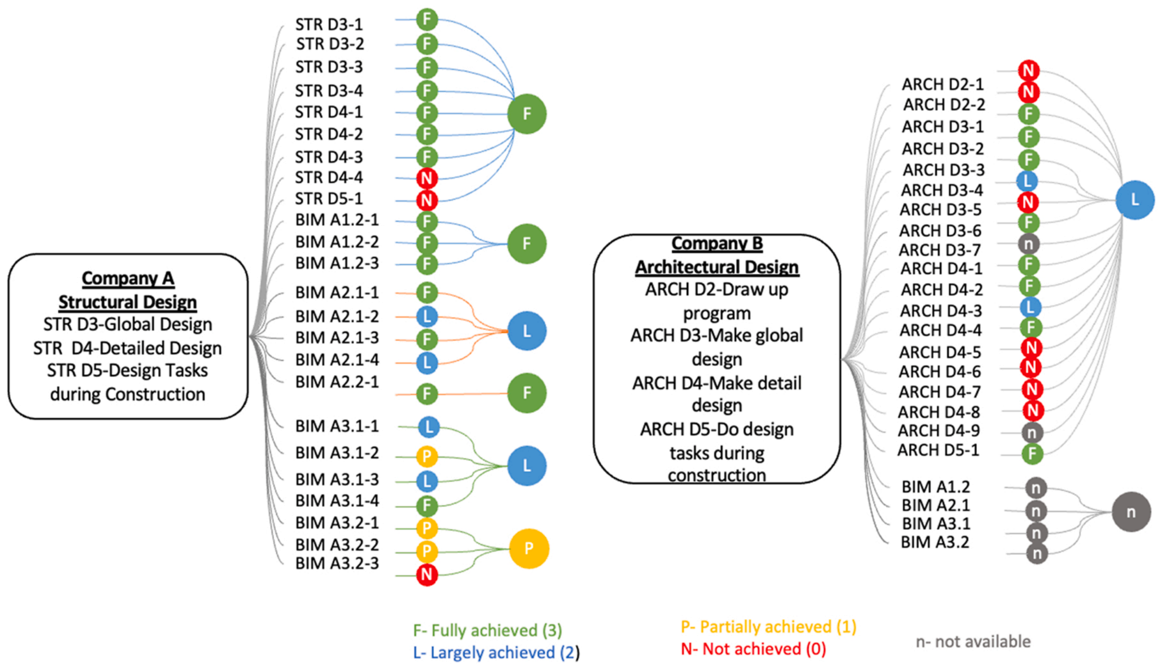

Fig. 3. Aggregation of the BIM outcomes and BIM attribute outcomes' ratings into single scores of BIM attributes for Company A and B.

have BIM skills. BIM was used to integrate different processes and phases by enabling BIM collaboration and the usage of interoperable formats. Company D also used BIM at the enterprise level for design and construction, but they do not use BIM at the enterprise level for facility management. ARCH D, STR D, BS D, and C phases of Company D were found at BIM Capability Level 3-Optimized, and the FM phase was found at BIM Capability Level 1- Performed, as presented in Fig. 6.

5. Discussions

During the multiple case studies, we did not observe any significant difficulties in applying BIM-CAREM to identify the BIM capabilities of various facility life cycle stages and AEC/FM processes. Apart from the exceptional situations such as companies did not perform a specific process due to the contractual constraints, assessment of BIM A1.1 Performing BIM in design, construction and facility management were practical due to the clearly defined BIM outcomes for each stage in Table 3. It is very easy for assessor to identify which evidence they need to look for within a company during the formal assessments and how to trace these evidence for scoring to identify the BIM capabilities. We observed that the assessment of both BIM A1.2 BIM Skills and BIM A3.1 Continuous BIM Improvement were repetitive when different processes were assessed. To eliminate repititions, BIM skills and continuous BIM improvement can either be measured at the organisation level instead of the project level, or more detailed assessment questions can be developed to evaluate differences in applications in individual processes. Measuring BIM A2.1 BIM Collaboration in design was easier than construction and facility management. We did not face difficulty measuring BIM A2.2 Interoperability since, in most of the facility life cycle phases, interoperable formats were used. We identified differences in the evaluation of BIM A3.2 Corporate-wide BIM Deployment in engineering and design firms compared to general contractors. Models originated in the design phases are used in the further phases of construction and facility management. BIM usage at the enterprise level is more traceable and visible if all of the phases (design, construction and facility management processes) are evaluated at the same time, which is similar to the case study conducted in Company D. Architecture, engineering and design firms, which are Company A and Company B, only have design and engineering processes but not construction and facility management processes; hence, it was more challenging to assess the enterprise-level BIM usage in these firms.

5.1. BIM capabilities across the facility life-cycle stages

The architectural design phase was evaluated in Company B and Company D. There are differences between BIM usage in the architectural design phase of these two companies. Because architects in Company B have created standalone models only for benefits brought by having 3D models such as visualisation, BIM A1.1 was found as 'L', and the rest of the BIM attributes were rated as 'N/A' for Company B (see Fig. 7). On the other hand, Company D has been using BIM in the architectural design phase for integrating all architectural design processes; hence, for Company D majority of the BIM attributes were rated as 'F' and only BIM A3.2 as 'L' (Fig. 7).

The structural design phase was evaluated in both companies A and D. Although there are slight differences between BIM usage in the structural design of steel frames and that of concrete frames, Company B has been using BIM at the enterprise level both in the structural design of steel frames, and that of concrete frames. These different BIM practices caused different ratings given to the BIM A3, which are 'L' and 'P' for steel and concrete frames, respectively (Fig. 7). In Company D, most of the structural design process includes BIM and these processes are integrated through BIM practices; hence, majority of the BIM attributes were rated as 'F' and only BIM A3.2 was rated as 'L' for the structural design phase of the Company D (Fig. 7). Building services design was evaluated only in Company D; similar to the assessment results of the other design phases found for Company D, BIM was being used at the enterprise level in building services design processes. Only BIM A3.2 was rated as 'L', and the ratings of the rest of the BIM attributes were found as 'F' (Fig. 7).

Construction was evaluated in companies C and D, and both were integrating the construction processes via BIM, which means that companies C and D have been using BIM at the corporate level. According to these top-level BIM usages in the construction processes of both companies, only the rating of the BIM A3.2 was found as 'L', and the rest of the BIM attributes were rated as 'F' (Fig. 8). **Facility management was assessed** only in Company D. Its radar diagram is given in Fig. 8. BIM was being used for only performing facility management processes,

Table 6
Assessment Findings for Level 1 (BIM A1.1 Performing BIM in Design, Construction and Facility Management) in Companies A to D.

BIM Outcomes	Indicators collected from Companies		Ratings	
ARCH D	**Company B**	**Company D**	**B**	**D**
ARCH D2–1	No models for space program	No models for space program	N	N
ARCH D2–2	No performance assessment based on models	Spatial design performance calculations generated using BIM, models used for looking at the foundation locations and the possible effects on the metro line	N	F
ARCH D3–1	BIM models created using Autodesk Revit	Models created using Autodesk Revit	F	F
ARCH D3–2	BIM models created using Autodesk Revit	Models created using Autodesk Revit	F	F
ARCH D3–3	BIM models created using Autodesk Revit	Models created using Autodesk Revit	F	F
ARCH D3–4	3D coordination with STR and BS designs	3D coordination of architectural design using Navisworks in design phases	L	F
ARCH D3–5	No code and compliance checking based on BIM models	Code and compliance checking using Dynamo	N	F
ARCH D3–6	Models created using Autodesk Revit	Models created using Autodesk Revit	F	F
ARCH D3–7	No evidence as governmental bodies do not request models	No evidence of application for a building permit since they are completed by clients	N/A	N/A
ARCH D4–1	BIM models created using Autodesk Revit	Design reviews via model updates using Autodesk Revit	F	F
ARCH D4–2	BIM models created using Autodesk Revit	Models created using Autodesk Revit	F	F
ARCH D4–3	3D coordination of STR and BS designs using BIM	3D coordination of architectural design using Navisworks in design phases	L	F
ARCH D4–4	Design reviews using Autodesk Revit	Design reviews via model updates using Autodesk Revit	F	F
ARCH D4–5	No model-based quantity take-offs	Quantity take-offs created using Revit, Dynamo and cost calculations based on facilities' systems	N	F
ARCH D4–6	No model-based construction schedules	Construction work schedules created using MS project and Primavera, construction simulations generated by integrating these schedules with models using Navisworks	N	F
ARCH D4–7	No model-based engineering analyses	Engineering analyses conducted using a plug-in into Autodesk Revit, conducted pedestrian comfort analysis in an airport using 3D models	N	F
ARCH D4–8	No model-based engineering analyses	Energy and LEED analyses for two airport projects by integrating a plug-in into Autodesk Revit	N	L
ARCH D4–9	Did not create tender documents as a sub-contractor	Tender documents including BIM protocols	N/A	F
ARCH D5–1	As-built models using Autodesk Revit	As-built models using Autodesk Revit	L	F
STR D	**Company A**	**Company D**	**A**	**D**
STR D3–1	Structural models designed using Allplan and Tekla Structures	Models created using Autodesk Revit	F	F
STR D3–2	3D coordination reports generated using Allplan and Tekla	3D coordination of structural design using Navisworks in design phases	F	F
STR D3–3	3D coordination reports generated using Allplan and Tekla	3D coordination of structural design using Navisworks in design phases	F	F
STR D3–4	Structural models designed using Allplan and Tekla Structures	Structural models created using Autodesk Revit	F	F
STR D4–1	Structural models designed using Allplan and Tekla Structures	Structural models created using Autodesk Revit	F	F
STR D4–2	Structural analysis reports completed using Sap 2000 and ETABS	Engineering analyses, decreased the amount of sunlight coming inside the airport by arranging a facade ratio according to the BIM-based analysis	F	F
STR D4–3	Quantity take-off reports based on BIM models and cost estimations based on take-offs	Quantity take-offs created using Revit, Dynamo and cost calculations based on facilities' systems	F	F
STR D4–4	No BIM models for 4D phase planning	Construction work schedules created using MS project and Primavera, construction simulations generated by integrating these schedules with models using Navisworks	N	F
STR D5–1	No BIM models for creating as-built models	As-built models via Autodesk Revit	N	F
BS D	**Company D**		**D**	
BS D3–1	Models created using Autodesk Revit and Bentley		F	
BS D3–2	3D coordination using Navisworks in the construction phase since 3D building services models are too complex to handle in design		F	
BS D3–3	3D coordination using Navisworks in the construction phase since 3D building services models are too complex to handle in design		F	
BS D3–4	Models created using Autodesk Revit and Bentley		F	
BS D4–1	Models created using Autodesk Revit and Bentley		F	
BS D4–2	3D coordination using Navisworks in the construction phase since 3D building services models are too complex to handle in design		F	
BS D4–3	Quantity take-offs created using Revit, Dynamo and cost calculations based on facilities' systems		F	
BS D4–4	Construction work schedules created using MS project and Primavera, construction simulations generated by integrating these schedules with models using Navisworks		F	
BS D4–5	Sustainability, energy and LEED analyses for two airport projects by integrating a plug-in into Autodesk Revit		F	
BS D5–1	As-built models using Autodesk Revit and Bentley		F	
C	**Company C**	**Company D**	**C**	**D**
C1–1	Designers and subcontractors with BIM qualifications	Sub-contractors using BIM	F	F
C1–2	Bidding proposals including BIM costs	Contracts including BIM related costs	F	F
C1–3	Designers and subcontractors with BIM qualifications	Sub-contractors using BIM	F	F
C1–4	Contracts with BIM clauses	Contracts including BIM clauses	F	F
C2–1	Primavera for creating work schedules and Navisworks for 4D simulation of construction	4D simulations of construction work	F	F

(continued on next page)

Table 6 (*continued*)

BIM Outcomes	Indicators collected from Companies		Ratings	
	progress, construction date of each facility element included in the 3D models			
C2–2	Workforce plan created from BIM models but not site utilization plan	Site utilization plans i.e. crane locations	P	F
C2–3	Cost estimations based on quantity take-offs extracted from BIM models	Cost estimations based on quantity take-offs	F	F
C2–4	Shop drawings in the form of BIM models using Allplan based on the change requests from the site and design offices	Show drawings created using Autodesk Revit	F	F
C2–5	360-degree views taken from site combined with models for status/progress monitoring	Status monitoring through Viewpoint, Aconex Field, Autodesk Field	F	F
C3–1	No BIM integration with ERP tools	No BIM integration with ERP tools	N	N
C3–2	No digital fabrication based on models	A few steel elements fabricated via models	P	L
C3–3	No logistics planning using models	Logistics of material/elements based on model-based construction schedules	N	F
C4–1	ID numbers of model elements and each element assigned to specific subcontractors and daily works are traced from model	Daily works plan based on construction schedules	F	F
C4–2	No pinpoints of elements for construction layout	3D locations of elements i.e. crane locations	N	F
C4–3	Access to models and 4D simulations from site through handheld devices using BIMplus during construction, comments on the models for technical office to review using Allplan	Construction works based on models	F	F
C4–4	No quality assurance based on models	Point cloud collected through laser scanning compared to the model	N	F
C4–5	Handover information as a package including models to their clients	Handover information including models	F	F
FM	**Company D**		**D**	
FM1–1	Linked asset data to models		F	
FM1–2	Space plans attached to models		F	
FM1–3	No model-based disaster planning		N	
FM2–1	Tracking models through tablets using Autodesk 360 for facility quality control		F	
FM2–2	Work orders linked to the models through integrating Ecodomus and GIS		F	
FM3–1	No connection between BAS and models		N	
FM3–2	No connection between BAS and models		N	
FM4–1	No performance indicators attached to models		N	
FM5–1	Root cause analysis by integration between CMMS and models		F	
FM5–2	A few examples of model usage for technical solutions to O&M problems		L	
FM5–3	A few examples of model usage for implications of the technical solutions		L	
FM6–1	No model-based O&M related decision making		N	
FM6–2	No services/resources allocation related to models		N	
FM7–1	O&M works reflected to models		F	

processes have not been integrated BIM A1.1, BIM A2.2 and BIM A3.2 attributes were rated as 'L', and the ratings of the rest of the BIM were found as 'F' (Fig. 8).

5.2. Views from the industry

At the end of the assessment in each company, we asked interviewees to give ratings from 1 to 5 to confirm if the identified BIM capability level is like the ones they had in their mind before the assessment (see Fig. 9). None of the companies have experienced a similar BIM capability and maturity assessments before; only Company D came across and used pre-tender assessment models which aim to achieve a performance assessment of a company for a specific construction project. In general, all companies thought that BIM-CAREM is easy to use and was able to capture their existing BIM capability levels of the facility life cycle stages and AEC/FM processes. BIM-CAREM found to be useful for companies who are beginners and want to increase the capabilities of their BIM uses. This is possible through formal BIM capability assessments using BIM-CAREM which result in objective BIM capabilities of their specific processes.

One of the strongest properties of BIM-CAREM mentioned is the model's applicability to all AEC/FM processes defined in the BIM PRM. BIM-CAREM was found powerful in identifying relationships of BIM usage between different processes. Conducting an assessment based on each process and presenting BIM issues related to individual processes were important, especially for large-scale organisations. Large-scale organisations usually do not prefer to define their BIM protocols, while working with clients who do not have knowledge about BIM uses at the enterprise level. Assessment findings were found meaningful and helpful in prioritising and solving the BIM-related problems in their AEC/FM processes.

6. Conclusions

The primary contributions of this research are clustered into four main points: 1) having a well-established assessment approach enabling process-based BIM capability assessments including BIM uses, 2) combining qualitative and quantitative evaluation approaches, 3) validating the suitability of BIM-CAREM for identifying BIM capabilities of AEC/FM processes, and 4) enabling benchmarking support.

BIM-CAREM is a comprehensive and holistic approach which consists of two different parts which are Building and BIM PRMs, and BIM MF, since it was developed based on ISO/IEC 330xx family of standards, which is a well-known and established assessment framework in software engineering (Yilmaz et al., 2019) and (Yilmaz, 2017). Compared to other models in the literature, which mainly focus on BIM performance measurements of projects or organisations, BIM-CAREM enables BIM capability assessments of AEC/FM processes. Moreover, defining BIM outcomes, BIM work products, BIM attributes and generic resources based on the identified BIM uses created a common understanding for BIM users. We also enabled the combination of qualitative and quantitative approaches in BIM-CAREM. We collected assessment data via semi-structured interviews and direct observations, supported by pre-defined assessment questions and a checklist including BIM performance and capability indicators. Later we gave ratings to BIM outcomes and BIM attribute outcomes using a common rating scale (see Table 2).

BIM-CAREM is tested through multiple case studies conducted in four AEC/FM organisations. While one of them was an engineering and design firm specialising in structural design, one of them was an architectural design firm, and two of the companies were international constructors. This enabled us to assess the BIM capability of the entire AEC/FM process of the whole lifecycle. Additionally, various structures were included in the case studies. While Company A is a structural design and engineering company dealing with the design and engineering of sports and industrial facilities, Company B is doing the architectural design of residential buildings. Companies C and D are general contractors working internationally with expertise in building hospitals and airports. We also included different sizes of organisations which enabled us to generalise the findings of the multiple case studies.

According to the results of the multiple case studies, there were no

Table 7
Assessment Findings for Level 1 (BIM A1.2 BIM Skills) in Companies A, B, C and D.

BIM A Outcome	Indicators Collected from Companies				Ratings				
	A	B	C	D	A	B	C	D1	D2
BIM A1.2–1	BIM certificates of employees	N/A	Existence of BIM-experienced engineers and architects	Existence of engineers, architects with BIM skills	F	N/A	F	F	F
BIM A1.2–2	Tekla workshops, BIM trainings and peer BIM learning	N/A	Internal BIM trainings, delivering BIM trainings to their sub-contractors as need to work with local companies due to hospital projects in 12 cities in Turkey	Peer learning within the company, attendance to external BIM trainings	F	N/A	F	F	F
BIM A1.2–3	Peer learning support to assign BIM related task to these employees	N/A	Allplan trainings for using BIM in a wide range of processes, BIM manager role for BIM related processes	BIM manager role for BIM related processes	F	N/A	F	P	P

D1: Company D's ratings for Design and Construction. D2: Company D's ratings for Facility Management.

Table 8
Assessment Findings for Level 2 (BIM A2.1 BIM Collaboration and BIM A2.2 Interoperability) and Level 3 (BIM. A3.1 Corporate-wide BIM Deployment and BIM A3.2 Continuous BIM Improvement) in Companies A, B, C and D.

BIM A Outcome	Indicators Collected from Companies				Ratings				
	A	B	C	D	A	B	C	D1	D2
BIM A2.1–1	Internal collaboration strategy document	N/A	Internal BIM guide, including collaboration strategies such as instructions about creating models in conformance with their standards to get accurate quantity take-offs and monitor progress on-site, roles and responsibilities of the BIM team	Defined BIM collaboration procedures	F	N/A	F	F	F
BIM A2.1–2	Ad-hoc external collaboration strategies based on contractors' requirements	N/A	Internal BIM guide including information sharing strategies	Defined BEP workflows	L	N/A	F	F	F
BIM A2.1–3	Implementing the internal collaboration strategies	N/A	BIMplus and Autodesk 360 for model-based collaboration, Opentext for enterprise information management	Aconex for collaboration based on models	F	N/A	F	F	F
BIM A2.1–4	Sharing BIM information via e-mails with external stakeholders	N/A	Shared servers within the organization and cloud-based common data environments which were used by their subcontractors, weekly meetings for BIM collaboration including their employees and subcontractors	Hybrid system: cloud and desktop server to exchange models, Basecamp as a project management tool	L	N/A	F	F	F
BIM A2.2–1	BIM models in IFC, NC formats	N/A	IFC for exporting and importing models between design authoring tools, other BIM tools, and other construction software applications using direct proprietary links	File formats such as IFC and BFC	F	N/A	F	F	F
BIM A3.1–1	Digital fabrication based on BIM models NC formats but no digital fabrication for concrete frames	N/A	Tracing construction progress and calculating progress payment based on models	Utilization of models fully in design, construction but partially in Facility Management (FM)	L	N/A	L	F	L
BIM A3.1–2	Models used for only specific tasks by specific employees not by the whole team	N/A	Model information filtered according to the requirements of different employees, comments in BIM plus accessed by the whole team in real time	Utilization of models fully in C but partially in FM	P	N/A	F	F	L
BIM A3.1–3	Latest versions of BIM models were available, but lack of change management	N/A	Change management procedures for 3D models and version control and archiving system to store different versions of the models	Version control, change management and existence of track sheets for C but non-existence for FM	L	N/A	F	F	L
BIM A3.1–4	Library of model elements for reusability	N/A	3D object libraries, a collection of building elements such as walls, doors, and windows	BIM objects library	F	N/A	F	F	F
BIM A3.2–1	Ad-hoc model usage, no feedback about the existing BIM use	N/A	No procedures for identifying BIM-related problems	Ad-hoc mechanism to solve issues in BIM uses	P	N/A	L	L	L
BIM A3.2–2	Ad-hoc BIM improvement tasks	N/A	Weekly innovation meetings and BIM related goals based on trends such as implementing LEED and VR	Following new BIM trends for BIM use improvement	P	N/A	L	F	F
BIM A3.2–3	Lack of BIM improvement and implementation strategies	N/A	Ad-hoc implementations for identified BIM improvements	Ad-hoc mechanism for BIM improvements	N	N/A	L	L	L

D1: Company D's ratings for Design and Construction. D2: Company D's ratings for Facility Management.

missing and redundant processes in Building PRM and BIM PRM. Therefore, we concluded that the Building PRM and BIM PRM include key AEC/FM processes and their definitions for covering all the facility lifecycle phases. Defining BIM outcomes based on the identified BIM uses in the literature created a common understanding for the users who already know BIM. We also clarified which BIM outcomes are achieved by performing which specific processes. This clarification created awareness for the users who do not have deep knowledge about BIM. BIM capability levels and associated BIM attributes were neither insufficient nor overlapped for identifying BIM capabilities; hence, we concluded that BIM capability levels and BIM attributes of BIM-CAREM were complete and suitable for assessing the BIM capabilities of different AEC/FM processes. We met the demand of different users' specific assessment purposes by developing Building and BIM PRM as a separate part from BIM MF. Users can select processes from the reference models and perform assessments using BIM MF for the selected processes. Being able to assess the BIM capability of individual AEC/FM processes supports benchmarking by enabling multiple evaluations of the same AEC/FM processes using BIM MF. This allows users to compare the BIM capability of specific processes within and across the organisations and to create BIM improvement paths in terms of their priorities.

Four main limitations of BIM-CAREM were observed during the multiple case studies. First, BIM-CAREM was developed by focusing on the first-tier suppliers in the construction supply chain, including

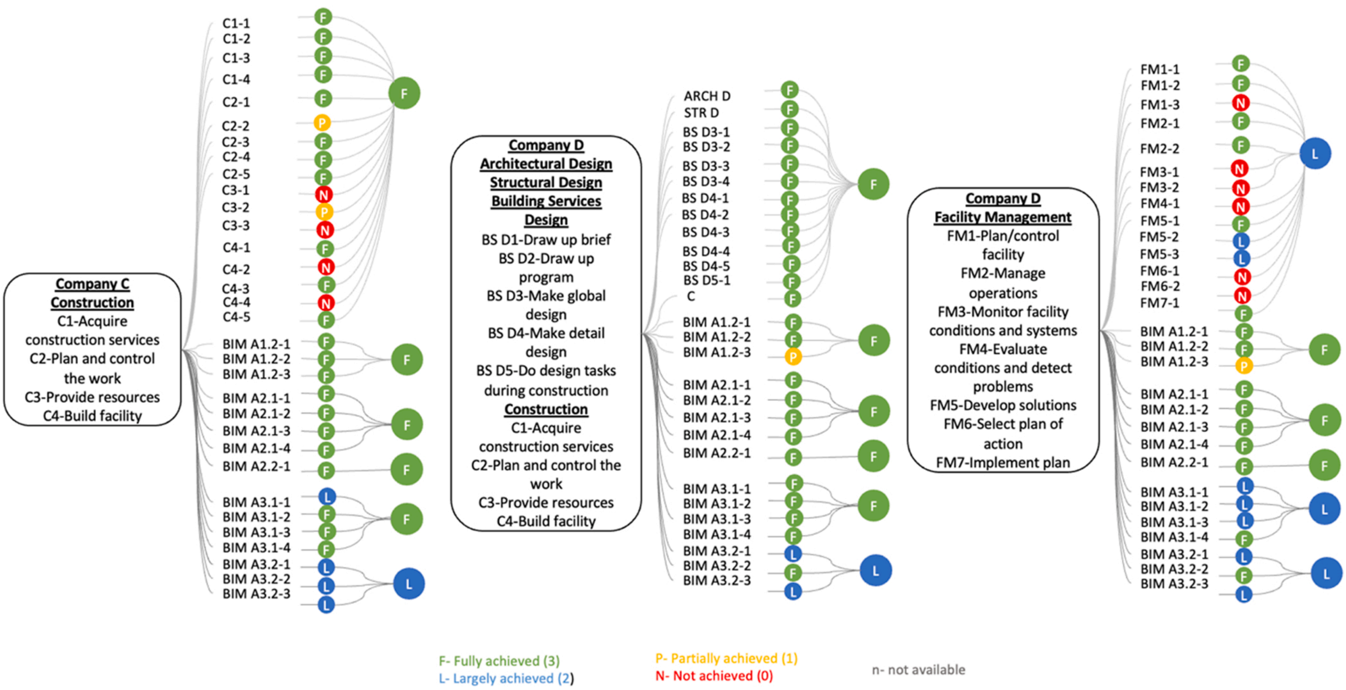

Fig. 4. Aggregation of the BIM outcomes and BIM attribute outcomes' ratings into single scores of BIM attributes for Company C and D.

Evaluated Phase in Companies		Level 1-Performed BIM		Level 2-Integrated BIM		Level 3-Optimized BIM	
		BIM A1.1	BIM A1.2	BIM A2.1	BIM A2.2	BIM A3.1	BIM A3.2
Comp. B	ARCH D	L	N/A	N/A	N/A	N/A	N/A
Comp. D	ARCH D	F	F	F	F	F	L
Comp. A	STR D of steel frames	F	F	L	F	L	P
Comp. A	STR D of concrete frames	F	F	L	F	P	P
Comp. D	STR D	F	F	F	F	F	L
Comp. D	BS D	F	F	F	F	F	L
Comp. C	C	F	F	F	F	F	L
Comp. D	C	F	F	F	F	F	L
Comp. D	FM	L	F	F	F	L	L

Fig. 5. Ratings of BIM attributes for facility life cycle phases in each company.

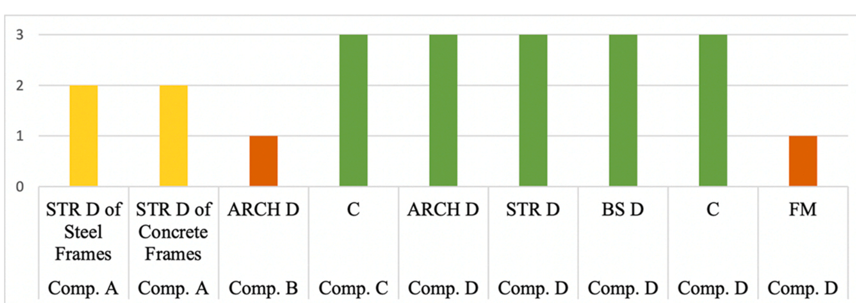

Fig. 6. BIM capability levels of the facility life cycle phases across the companies.

general contractors, and design and engineering firms. It does not include BIM uses and requirements of the second-tier suppliers, including sub-contractors, material suppliers, fabricators, and the owners such as municipalities, which could affect the effectiveness of the BIM capability assessments when BIM-CAREM is used for evaluation of their processes. Secondly, the model does not consider the flexibility requirements of organisations while evaluating the BIM capabilities of AEC/FM processes. An architectural design company could use BIM at different capability levels in the architectural design processes according to the various regulations applied in the different countries' construction industries. Thirdly, some of the processes in BIM PRM and the BIM attributes in BIM MF need to be defined in more detail. The asset management, space management and disaster planning processes in facility management could be divided into different sub-processes by defining them in more detail. The ownership of the BIM model such as models may not be shared with other stakeholders due to privacy issues should be considered while assessing 'BIM Collaboration'; ownership issues should not indicate a lack of collaboration. Finally, the weights of BIM outcomes and BIM attribute outcomes in the existing model were taken equally but some might not affect the overall rating equally. Based

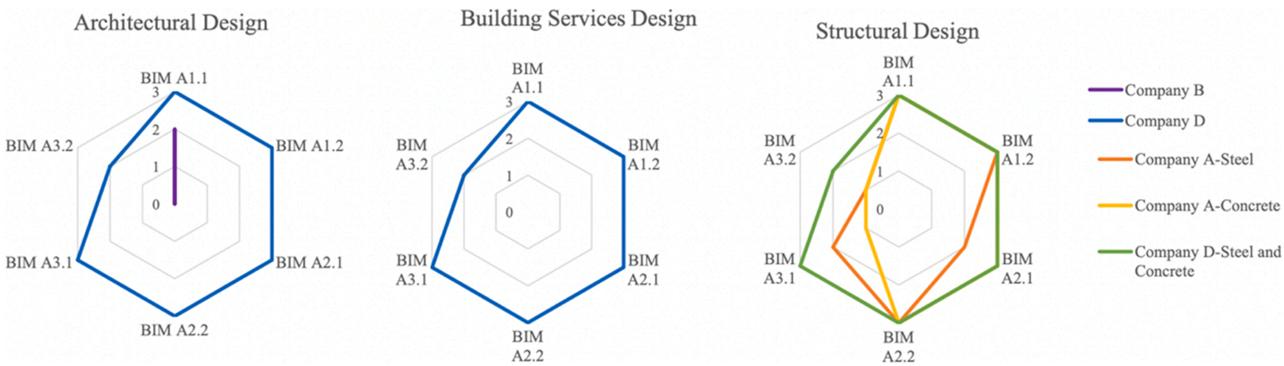

Fig. 7. Ratings of BIM attributes given for design phases in Companies A, B and D.

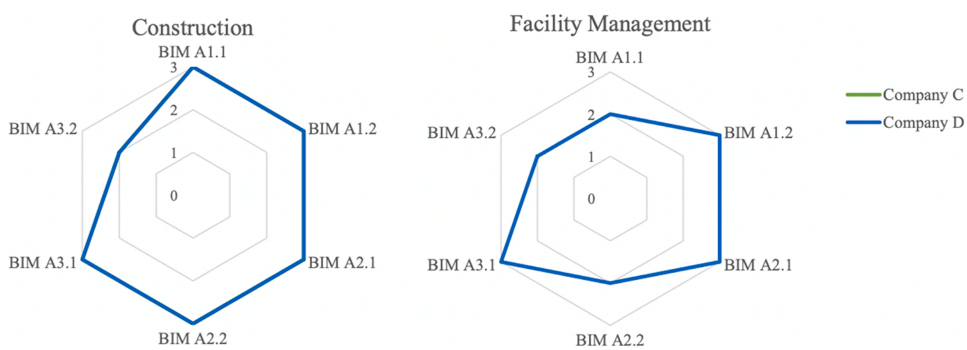

Fig. 8. Ratings of BIM attributes given for construction in Companies C and D and facility management in Company D.

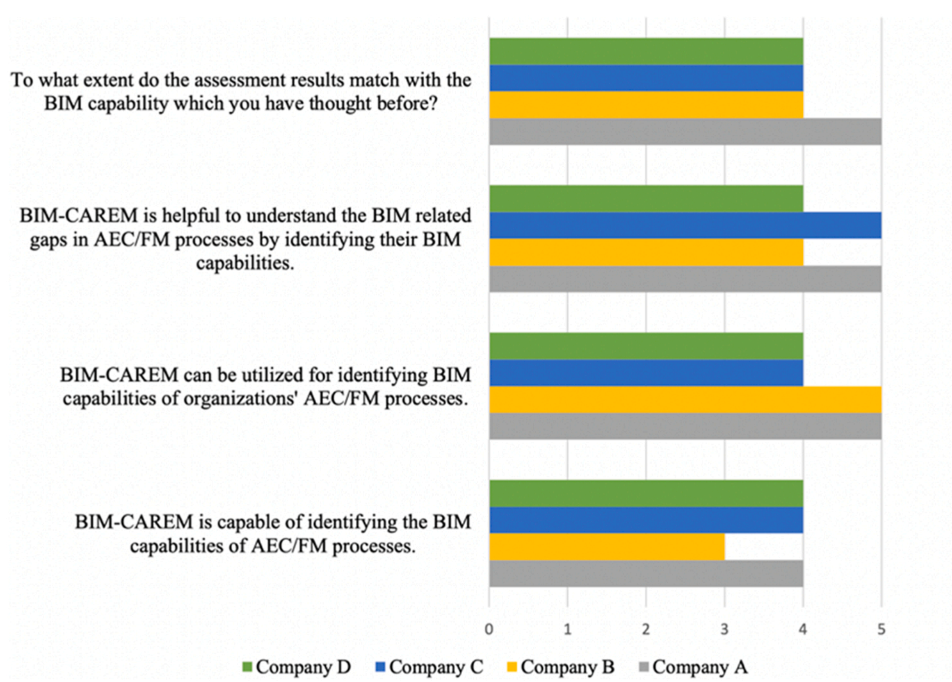

Fig. 9. Validation of the assessment results found using BIM-CAREM.

on these, we identified several tasks for future work. To address the first limitation, the model requires further categorisation regarding organisation types such as sub-contractors and owners. The BIM uses of the second-tier suppliers and the owners in the construction supply chain should be included in the model. Secondly, the variety in BIM uses according to the different construction regulations in different countries need to be added to the model to increase its usability across construction organisations worldwide. Thirdly, the asset management, space management, and disaster management processes should be divided into different sub-processes and defined in more detail in BIM PRM. As the fourth improvement point, the weights of the BIM outcomes and BIM attribute outcomes can be adjusted while calculating the overall rating to determine the BIM capability. Lastly, new and more case studies should be performed to gather more results from BIM-CAREM's application in real-life. Significantly, new case studies with sub-contractors are required to be carried out to evaluate the model's applicability for assessing their processes.

CRediT authorship contribution statement

Gokcen Yilmaz: Conceptualization, Methodology, Investigation, Data curation, Visualization, Formal analysis, Writing - original draft, Writing - review & editing. **Asli Akcamete:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Onur Demirors:** Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

References

Akinci, B., 2014. Situational awareness in construction and facility management. Front. Eng. Manag. 1 (3), 283. https://doi.org/10.15302/j-fem-2014037.

Alvanchi, A., TohidiFar, A., Mousavi, M., Azad, R., Rokooei, S., 2021. A critical study of the existing issues in manufacturing maintenance systems: can BIM fill the gap?. In: Computers in Industry, Vol. 131 Elsevier B.V. https://doi.org/10.1016/j.compind.2021.103484.

AnonISO/IEC, 2000. The ISO/IEC 15504 – 1 Information technology - Process assessment - Part 1: Concepts and Vocabulary.

AnonISO 10303–11, 2004. Industrial automation systems and integration - Product data representation and exchange - Part 11: description methods: The EXPRESS Language Reference Manual. International Standards Organisation. ⟨https://www.iso.org/standard/57620.html⟩.

AnonBIM Supporters B.V, 2009. BIM QuickScan Tool. ⟨https://app.bimsupporters.com/quickscan/⟩.

AnonIU Arhictect's Office, 2009. BIM Proficiency Matrix. ⟨http://www.iu.edu/~vpcpf/consultant-contractor/standards/bim-standards.shtml⟩.

AnonPennState CIC, 2012. Organizational BIM Assessment Profile. ⟨http://bim.psu.edu/resources/owner/bim_planning_guide_for_facility_owners-version_2.0.pdf⟩.

AnonBIM Excellence, 2013. BIMe. ⟨http://bimexcellence.com/⟩.

AnonISO 16739:2013, 2013. Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries. International Standards Organization. ⟨https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/⟩.

AnonNBIMS, 2017. National BIM Guide for Owners. ⟨https://www.nibs.org/?nbgo⟩.

AnonUKBIMA, 2021. State of the Nation Survey 2021.

AnonThe NBS, 2021. Digital Construction Report.

Bataglin, F.S., Viana, D.D., Formoso, C.T., Bulhões, I.R., 2019. Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: exploring synergies between Lean and BIM. Can. J. Civ. Eng. https://doi.org/10.1139/cjce-2018-0462.

van Berlo, L., Hendriks, H., 2012. BIM Quickscan: Benchmark of BIM Performance in The Netherlands. *Proceedings of the 29th International Conference* CIB W78 2012, 17–19.

BSI Standards Publication, 2018a. BS EN ISO 19650–1 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling - Concepts and principles.

BSI Standards Publication, 2018b. BS EN ISO 19650–2 Organization and digitization of information about buildings and civil engineering works, including building information modelling – Information management using building information modelling: Delivery phase of the assets.

Fellows, R., Liu, A., 2015. Research Methods for Construction. Wiley.

Gao, J., 2011. A characterization framework to document and compare BIM implementations on construction projects. Dep. Civ. Environ. Eng. (Issue September) https://doi.org/10.1097/EJA.0b013e328347dfd4.

2009 CIFE. (2009). VDC Scorecard. Retrieved April 4, 2018, from ⟨https://vdcscorecard.stanford.edu/survey-input-forms⟩.

Hendrickson, C. , 2008. *Project Management in Construction.*

ISO/IEC, 2015a. ISO/IEC 33001 Information technology — Process assessment — Concepts and terminology. ⟨https://www.iso.org/obp/ui/#iso:std:iso-iec:33001:ed-1:v1:en⟩.

ISO/IEC, 2015b. ISO/IEC 33003 Information technology — Process assessment — Requirements for process measurement frameworks. ⟨https://www.iso.org/obp/ui/#iso:std:iso-iec:33003:ed-1:v1:en⟩.

ISO/IEC, 2015c. ISO/IEC 33004 Information technology — Process assessment — Requirements for process reference, process assessment and maturity models. ⟨https://www.iso.org/obp/ui/#iso:std:iso-iec:33004:ed-1:v2:en⟩.

ISO/IEC, 2015d. ISO/IEC 33020 Information technology — Process assessment — Process measurement framework for assessment of process capability. ⟨https://www.iso.org/obp/ui/#iso:std:iso-iec:33020:ed-1:v1:en⟩.

Kam, C., Senaratna, D., Xiao, Y., McKinney, B., 2013. The VDC Scorecard: Evaluation of AEC Projects and Industry Trends. CIFE Working Paper #WP136. ⟨https://stacks.stanford.edu/file/druid:st437wr3978/WP136.pdf⟩.

Kam, C., Senaratna, D., Mckinney, B., Xiao, Y., 2014. The VDC Scorecard: Formulation and Validation. CIFE Working Paper. ⟨https://stacks.stanford.edu/file/druid:xd249sp3509/WP135.pdf⟩.

Klein, H.C., Stelter, A., Oschinsky, F.M., Niehaves, B., 2022. A status quo bias perspective on user resistance in building information modeling adoption – Towards a taxonomy. Comput. Ind. 143. https://doi.org/10.1016/j.compind.2022.103760.

Leite, F., Akinci, B., Garrett, J. , 2009. IDENTIFICATION OF DATA ITEMS NEEDED FOR AUTOMATIC CLASH DETECTION IN MEP DESIGN COORDINATION. ASCE Construction Research Congress.

Liang, C., Lu, W., Rowlinson, S., Zhang, X., 2016. Development of a Multifunctional BIM Maturity Model. J. Constr. Eng. Manag. 142 (11), 06016003 https://doi.org/10.1061/(ASCE)CO.1943-7862.0001186.

Marini, M., Mastino, C.C., Baccoli, R., & Frattolillo, A., 2018. BIM AND PLANT SYSTEMS: A SPECIFIC ASSESSMENT. Energy Procedia, 148, 623–630. https://doi.org/10.1016/j.egypro.2018.08.150.

NBIMS, 2015a. National BIM Standard - United States ® Version 3 Introduction to Information Exchange Standards. ⟨https://www.nationalbimstandard.org/⟩.

NBIMS, 2015b. National BIM Standard - United States ® Version 3 Introduction to Practice Documents. ⟨https://www.nationalbimstandard.org/⟩.

NBIMS, 2015c. National BIM Standard United States ® Version 3 - Minimum BIM. ⟨https://www.nationalbimstandard.org⟩.

SEI, S.E.I., 2010. CMMI for Development, Version 1.3. In Pittsburgh, PA. (Issue November). ⟨www.sei.cmu.edu/reports/10tr033.pdf⟩.

Succar, B., 2010. Building Information Modelling Maturity Matrix. In Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies (pp. 65–103). https://doi.org/10.4018/978–1-60566–928-1.ch004.

Sun, C., Xu, H., Wan, D., Li, Y., 2021. Building Information Modeling Application Maturity Model (BIM-AMM) from the viewpoint of construction project. Adv. Civ. Eng. 2021, 1–12. https://doi.org/10.1155/2021/6684031.

Tarhan, A., Turetken, O., Reijers, H.A., 2016. Business process maturity models: a systematic literature review. Inf. Softw. Technol. 75, 122–134. https://doi.org/10.1016/j.infsof.2016.01.010.

2011 VICO Software. (2011). VICO BIM Scorecard Survey. Retrieved August 25, 2017, from ⟨https://www.surveymonkey.com/r/9YCHVXC⟩.

Wohlin, C., Runeson, P., Höst, M., Ohlsson, M.C., Regnell, B., Wesslen, A. (2012). Experimentation in Software Engineering.

Wu, C., Estate, R., Xu, B., Estate, R., Mao, C., Estate, R., Li, X., 2017. Overview of BIM maturity measurement tools. J. Inf. Technol. Constr. 22 (March 2016), 34–62.

Yilmaz, G., 2017. BIM-CAREM: A Reference Model for Building Information Modelling Capability Assessment. ⟨http://library.metu.edu.tr/search/?searchtype=X&searcharg=BIM-CAREM&searchscope=15⟩.

Yilmaz, G., Akcamete-Gungor, A., Demirors, O., 2017. A Review on Capability and Maturity Models of Building Information Modelling. Lean and Computing in Construction Congress - Volume 1: Proceedings of the Joint Conference on Computing in Construction, 627–636. https://doi.org/10.24928/JC3–2017/0309.

Yilmaz, G., Akcamete, A., Demirors, O., 2019. A reference model for BIM capability assessments. Autom. Constr. 101 (December 2018), 245–263. https://doi.org/10.1016/j.autcon.2018.10.022.

Yin, R.K., 2003. Case Study Research: Design and Methods. SAGE Publications.