Automation in Construction 101 (2019) 245–263

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

A reference model for BIM capability assessments

Gokcen Yilmaz[a,*], Asli Akcamete[b], Onur Demirors[c,d]

[a] Informatics Institute, Middle East Technical University, Ankara, Turkey
[b] Department of Civil Engineering, Middle East Technical University, Ankara, Turkey
[c] Department of Computer Engineering, Izmir Institute of Technology, Izmir, Turkey
[d] Department of Computer Science and Engineering, UNSW, Sydney, Australia

ARTICLE INFO

Keywords:
Building information modeling
BIM
Capability and maturity model
BIM capability assessment
BIM capability

ABSTRACT

Various BIM capability and maturity models have been developed to assist architecture, engineering, construction and facilities management (AEC/FM) organizations in measuring the performance of their BIM utilizations. Due to differences in applicability and focus of these models, they are able to meet the demands of different BIM users. In this study, eight BIM capability and maturity models identified in the literature are compared based on several different criteria. The results show that there is no holistic model that includes process definitions that cover the facility life-cycle and contains measures for assessing all of these AEC/FM processes. A reference model for assessing BIM capability of AEC/FM processes was developed. It was grounded on the meta-model of ISO/IEC 330xx family of standards and developed iteratively via expert reviews and an exploratory case study. It includes AEC/FM processes which were evaluated using the BIM capability levels, their associated BIM attributes, and a four-point rating scale. BIM-CAREM was evaluated by conducting four explanatory case studies. The results showed that BIM-CAREM was capable of identifying BIM capabilities of different AEC/FM processes.

1. Introduction

There has been a shift toward BIM adoption in architecture, engineering, construction and facilities management (AEC/FM) industries around the world. BIM standardization and policy development initiatives have been undertaken by various countries, such as the USA, the UK, Finland, Singapore, Australia, and Norway during the last decade [1–6]. In these countries, various resources, such as BIM guidelines and standards have been developed to offer guidance to AEC/FM organizations in adopting BIM. For example, the National BIM Standard [7], BS/PAS 1192 series of standards [8–12], COBIM [13], Singapore BIM Guide [14], and the NATSPEC National BIM Guide [15], and Statsbygg BIM Manual [16] have been developed to help local industries within these countries.

According to a survey by McGraw-Hill Construction [17], which presents the percentages of industry-wide BIM adoption in North America, BIM adoption has increased from 28% in 2007 to 71% in 2012. In Europe, only 36% of the AEC/FM firms adopted BIM in 2010 [18], in South Korea, BIM adoption by AEC/FM firms was 58% in 2012 [19], and in New Zealand and Australia 51% of all users were engaged with BIM on more than 30% of their projects in 2014 [20]. According to a recent National BIM report, which highlights the BIM adoption and usage rates within the UK, 54% of the respondents including architects, project managers, and BIM managers were actively using BIM, 42% were familiar with BIM, and only 4% did not know BIM at all [21].

After adopting BIM, AEC/FM organizations need to gauge the effectiveness of their BIM implementations in order to measure the performance of their BIM utilizations and enable continuous BIM improvements. In order to meet the different BIM assessment purposes of BIM users, various BIM capability and maturity models, such as the Capability Maturity Model of the National Institute of Building Sciences (NBIMS CMM) [22] and the BIM Maturity Matrix (MM) [23] have been developed. We identified six models via the literature review [24], and later extended this review by also including two other recently developed models and analyzing these eight models based on five selected criteria [25]. Below are the identified limitations of these eight models followed by detailed explanation of each model:

- Some models only focus on specific assessment purposes, which makes the model selection process time-consuming for users,
- The models are not widely used and commonly accepted since they are not created on the basis of established standards,
- Most models do not cover BIM uses performed in the AEC/FM industry.

* Corresponding author.
E-mail addresses: gokceny@pau.edu.tr (G. Yilmaz), akcamete@metu.edu.tr (A. Akcamete), onurdemirors@iyte.edu.tr (O. Demirors).

https://doi.org/10.1016/j.autcon.2018.10.022
Received 1 January 2018; Received in revised form 28 October 2018; Accepted 31 October 2018
Available online 31 December 2018
0926-5805/

There are differences in the applicability and focus of these models. For example, the BIM Proficiency Matrix (PM) [26] was designed by Indiana University to score the performance of BIM services of designers and contractors in the selection of candidates for campus projects. When selecting an assessment model for a BIM performance assessment, users need to analyze the models in detail, which creates an extra time-consuming workload for the users.

Due to the highly-fragmented structure of the AEC/FM industry, the creation, collection, sharing and usage of information are performed by different stakeholders/organizations in the facility life-cycle phases. For example, while designer companies pay attention to use BIM effectively in their design processes, general contractors may need to assess the performance of BIM usage in multiple facility life-cycle processes. Therefore, AEC/FM organizations need to assess their own BIM capability for each specific process; however, the models in the literature do not enable process-based BIM capability assessments.

Although the existing models have a varying number of measures classified under different numbers of layers, common concepts have been used for the development of these measures. Similarly, a previous review paper has classified measures under the five categories of process, technology, organization, standards, and human (stakeholders) [27]. This shows that models are not based on established standards but inspired by each other. Hence, a commonly accepted and broadly used model does not exist [27].

According to the plan of work created by the Royal Institute of British Architects (RIBA) [28], the facility life-cycle phases are preparation and brief, concept design, developed design, technical design, construction, handover and close out, and in use. Even though some of the models have included a number of BIM uses performed in these facility life-cycle phases as their measures, most BIM uses performed by AEC/FM organizations are not covered within the context of these models. For example, defined measures in the process category are not comprehensive in most models. Due to these limitations, a holistic model enabling BIM capability assessments of AEC/FM processes is necessary. A model, which is based on the established standards, is required to meet different assessment purposes of BIM users.

This paper presents the iterative development process of a BIM capability assessment reference model (CAREM), as well as the structure of BIM-CAREM and definitions of its components. This model was developed to enable formal BIM capability assessments of the AEC/FM processes of the facility life-cycle phases. The development of BIM-CAREM conforms to the ISO/IEC 330xx family of standards employing the BIM uses identified in the literature. The model was updated iteratively via expert reviews and one exploratory case study. Lastly, BIM-CAREM was evaluated through explanatory case studies conducted in four different AEC/FM companies. The evaluation results are summarized in this paper with full details of the explanatory case studies being available in the PhD dissertation of Yilmaz [25].

2. Background

Eight BIM capability and maturity models were included in the context of this study. These eight models were analyzed to identify if the models met the selected criteria. This critical analysis is presented in Section 2.1, and was used to determine the requirements for developing BIM-CAREM. Moreover, one well-known process assessment standard in software engineering, the ISO/IEC 330xx family of standards, was taken as basis for the development of BIM-CAREM, and it is presented in Section 2.2.

2.1. BIM capability and maturity assessment models

The eight models selected were; NBIMS CMM [22], BIM PM created by Indiana University Architect's Office [26], BIM QuickScan from the Netherlands [29], VDC Scorecard developed by Stanford University Center for Integrated Facility Engineering [30], Organizational BIM Assessment Profile (AP) created by Pennsylvania State University Computer Integrated Construction (CIC) Research Program [31], VICO BIM Scorecard by Trimble [32], BIM MM [23], and Multifunctional BIM MM [33]. In this study, we analyzed each model and compared them based on five criteria, namely extent of measurement scope and purpose, coverage of metrics, extent of evaluation approaches, availability of open source guidelines and tools, and variety in validation methods. These criteria are given as important points for developing new BIM performance assessment models in the recent literature review paper by Wu et al. [27]. The analysis results and comparison findings are presented below.

Extent of measurement scope and purpose: Previous research studies have clustered the BIM capability and maturity assessment models into two categories as project evaluation and organization evaluation [34]. For example, while NBIMS MM and VDC Scorecard focus on evaluating BIM maturity of construction projects, BIM PM, BIM QuickScan, Organizational BIM AP, VICO BIM Scorecard, BIM MM, and Multifunctional BIM MM assess the BIM maturity of organizations. Hence, there is no model which facilitates process-based BIM capability and maturity assessment of AEC/FM organizations.

Each of the existing models was developed to achieve a specific BIM assessment purpose. For example, the first model, NBIMS CMM, was designed for assessing the BIM maturity of business practices of building/infrastructure projects, but it is more suitable to assess the BIM maturity of design practices since four of its 11 measures, which are data richness, graphical information, spatial capability and information accuracy, are related to design. BIM PM has a very specific assessment purpose. It was designed to score the performance of BIM services of designers and contractors for the selection of candidates on campus projects. BIM MM provides BIM assessments of organizations, projects, teams, and individuals by incorporating an online platform called BIM Excellence [35]. BIM QuickScan provides insight into the strengths and weaknesses of BIM usage in an organization. VDC Scorecard measures the project performance against an industry benchmark. Organizational BIM AP was developed to evaluate the organization's maturity of BIM planning elements. VICO BIM Scorecard focuses on evaluating performance of specific BIM uses, such as coordination and production planning in an organization. Therefore, it can be more useful for assessing BIM performances of designer firms. Multifunctional BIM MM evaluates BIM maturity in projects, organizations, and industry as a whole. Due to the variation in the applicability and focus of these models, users need to examine the models in detail to be able to choose the appropriate model according to their evaluation purposes [27]. Therefore, there is no commonly accepted and broadly used model that can meet the requirements of users working in different facility life-cycle phases.

Coverage of measures: A varying number of metrics and classification layers are defined in different models. NBIMS CMM includes 11 measures classified under one layer and six maturity levels. Since these measures are classified under a single layer, it does not have high level of coverage in terms of BIM aspects. On the other hand, the model has some level of flexibility since the weights of its measures are different and it is practical in performing an assessment due to its simple structure. BIM PM is composed of a total of 32 measures and five levels of maturity. Although its measures are grouped under two classification layers, it does not cover most BIM uses in the AEC/FM industry. The number of questions in BIM MM varies according to the granularity level of the assessment, which may be organization, team, or individual assessments; hence, it has a high level of flexibility with most BIM uses being included. Moreover, most BIM uses are included in the model due to having two classification layers. BIM QuickScan consists of 44 questions classified under four categories. Due to its two classification layers and high number of questions, most BIM uses are covered. VDC Scorecard comprises four major areas, 10 divisions, and 74 measures. Its coverage of BIM aspects is high since it has three classification layers of measures. Organizational BIM AP is composed of 20 measures and six maturity levels; however, it does not cover most BIM uses in AEC/FM industry. VICO BIM Scorecard has 27 questions in total and five capability levels. It has some BIM aspects coverage, since it was designed specifically for assessing performance of BIM uses in an organization. Multifunctional BIM MM has 21 measures and four maturity levels, but it does not cover most BIM uses in AEC/FM industry.

Only VDC Scorecard has three classification layers for the measures; the remainder of the models have two layers of classification for their metrics. NBIMS CMM has the simplest structure among all the tools; thus, it is easy to use, but criticized for having a single evaluation method [27] since having at least two or three layers increases the coverage of BIM aspects. Although each model has a different number of measures clustered into different numbers of layers, common concepts have been selected to define the metrics. In most models their measures are classified into common categories, which are process, stakeholder/personnel, standard, software, hardware, and data. Similarly, a previous paper categorized the model metrics into six categories, namely planning, technical, personnel, managerial, process, and BIM requirements [36]. Some example measures for the process category of Multifunctional BIM MM are "clash analysis process", "cross disciplinary model coordination", and "management support" [33]. The measures of the process category are not comprehensive since there are many AEC/FM processes in different facility life-cycle phases. For example, according to two technical reports, namely an integrated building process model created by CIC [37] and construction process model by Technical Research Center of Finland (VTT) [38], the architectural and structural detail design of the design phase and the build facility of the construction phase are a few examples of AEC/FM processes. In contrast, the process measures of some of the models are defined too broadly. For example, "activities/workflows" and "leadership/management" are too broad to be used as measures. The technology category is composed of measures related to technical infrastructure of AEC/FM organizations, such as "software adequacy" and "hardware adequacy" of VDC Scorecard. The organization category includes measures related to BIM skills of professionals, such "VDC training frequency" of VDC Scorecard and BIM visions, such as "BIM vision and objectives" of the Organizational BIM AP. Some of the example measures of the standard category are "VDC guidelines" of VDC Scorecard and "Contracts and agreements" of BIM MM. The human category contains metrics, such as "roles and responsibilities" and "change readiness" of the Organizational BIM AP. Moreover, even though some models have included a number of BIM uses in their measures, most BIM uses performed by AEC/FM organizations were not covered. For example, "quantity take-offs", "coordination modeling", "as-built modeling", and "asset management" are defined as measures of the BIM PM. In Multifunctional BIM-MM, "clash analysis process" and "cross disciplinary model coordination" are defined as measures of the process category. However, defined BIM uses are not comprehensive in most models.

Extent of evaluation approaches: Wu et al. suggested that new BIM capability and maturity models which combine qualitative and quantitative evaluation approaches should be designed [27]. NBIMS CMM, BIM PM, BIM MM, Organizational BIM AP, and Multifunctional BIM MM adopt a qualitative rating approach with an ordinal rating scale. BIM QuickScan and VICO BIM Scorecard take a quantitative evaluation approach with multiple choice questions, and they usually have five or ten levels in the rating scale. The overall score of most models is calculated by the weighted sum of measures. VDC Scorecard has both quantitative and qualitative evaluation methods with multiple choice and open-ended questions. The rating scale of VDC Scorecard is a ratio since it assesses performances of BIM projects against the industry benchmark.

Availability of open source guidelines and tools: Only four models, BIM PM, BIM QuickScan, VDC Scorecard, and Multi-Functional BIM MM, provide benchmarking functions. Guidelines are only created for Organizational BIM AP. To perform an evaluation with NBIMS BIM CMM, users can use an Excel workbook. BIM PM and Organizational BIM AP also have an online excel workbook to conduct an evaluation. BIM MM has a free online questionnaire only for individual assessments under umbrella of BIM Excellence [35]; however, team and organizational evaluations are a premium service. A free web-based questionnaire is available to perform an assessment via BIM QuickScan. For VDC Scorecard, survey input forms are available, but, there is no online assessment tool which should be provided since VDC Scorecard assesses project performances with respect to the industry benchmark. Assessments for BIM uses can be performed via an online questionnaire of VICO BIM Scorecard, but Multifunctional BIM MM does not have an available tool for evaluation.

Variety in validation methods: VDC Scorecard has been applied to 150 pilot projects so its applicability has been tested within different AEC/FM companies. Most models have been validated through qualitative methods. NBIMS BIM CMM has been validated through pilot projects, expert user interviews, and expert reviews [27]. Although BIM MM is a widely used model, empirical studies are lacking for its validation [27]. BIM QuickScan has been validated trough pilot projects, user interviews, expert reviews, and statistical tests. VDC Scorecard has been validated through pilot projects, expert reviews, and statistical tests. The validation methods of BIM PM, Organizational BIM PM, VICO BIM Scorecard, and Multifunctional BIM MM are not clearly defined.

For an easy comparison of the measuring aspects, we used the table presented by Wu et al. [27] (Appendix A), in which the measuring aspects are marked as Yes/No according to their existence in each of the six models (NBIMS CMM, BIM PM, BIM QuickScan, VDC Scorecard, Organizational BIM AP BIM MM). We added VICO BIM Scorecard, Multifunctional BIM MM, and BIM-CAREM as numbers 6, 8, and 9, respectively. The measures of the added three models were collated in an Excel sheet, with each of the measuring aspect being marked as "Yes" if the measuring aspect exists in the model or "No" if the model does not contain the measuring aspect. The measuring aspects are classified under the five categories of process, technical, organizational, human, and BIM standards. We also examined the definition of these aspects to eliminate any misunderstanding. According to this comparison, BIM-CAREM covers 37 measuring aspects out of 48 aspects in total. The measuring aspects not covered by BIM-CAREM are mostly related to the benefits gained by utilizing BIM. For example, BIM-CAREM could not measure the following aspects in the process category; "knowledge sharing processes", "documentations of actually gained benefits or impacts on working processes through applying BIM", "records of actual performance and the contribution of BIM related processes to objectives compliances", and "target BIM relating processes and developments of plans of transitions toward the targets". Only "actual impacts of BIM on organizations" in the organization aspect, and "change readiness among employees/stakeholders" in the human aspect cannot be measured using BIM-CAREM. The gained benefits by means of BIM usage are not measures of BIM-CAREM, but they are the results of assessments conducted via BIM-CAREM.

2.2. ISO/IEC 330xx family of standards

We developed BIM-CAREM based on the ISO/IEC 330xx family of standards, which is a well-known process assessment model. It has been widely used to conduct process capability assessments for process improvements. Our examination of ISO/IEC 330xx family of standards in detail revealed that it has a well-defined structure composed of the following four essential parts; process reference model, process measurement framework, procedures for conducting process assessments, and process improvement method. Each part serves a different purpose, but they need to be used together. For the process reference models, a list of key processes is given and a definition for each process is provided. In process measurement framework, a schema for utilization in assessing process quality characteristics of a process is presented for the process measurement framework. The procedures of conducting systematic and formal appraisals are explained in a separate part. Lastly, the process improvement method includes principles for creating process improvement strategies based on the assessments.

Separating these components creates value for assessors. For example, the process reference model offers users the opportunity of selecting processes and defining priorities for software process assessment. Similarly, the measurement framework allows users to acknowledge the dependencies among the outcomes of a process. A comparison of the structure of the existing models identified in AEC/FM industry with the structure of the ISO/IEC 330xx family of standards shows that the models in AEC/FM industry do not include a process reference model or a measurement framework. This separation has the potential to allow organizations to perform BIM capability assessments of specific processes.

Due to having a well-established structure, the ISO/IEC 330xx family of standards has been recently adapted into various other domains, such as automotive (Automotive SPICE) [39], space (SPICE4Space) [40], and medical device (MDevSPICE) [41] industries. Moreover, Part 52 of the family includes the process reference model for information security management [42], Part 63 is the process assessment model for software testing [43], and Parts 71 [44] and 72 [45] introduce an information security management process assessment model and an integrated process assessment model for enterprise processes, respectively.

We utilized the necessities defined in the ISO/IEC 33004 requirements for process reference, process assessment, and maturity [46] in the development of the Building/BIM process reference models (Building/BIM PRM). We also gained inspiration from the ISO/IEC 24774 systems and software engineering–life-cycle management–guidelines for process description [47] when generating the process descriptions. We used the principles and requirements explained in the ISO/IEC 33003 requirements for process measurement frameworks [48] to create the BIM measurement framework (BIM MF). We also used the ISO/IEC 33020 process measurement framework for assessment of process capability [49] and ISO/IEC 15504-5 an exemplar process assessment model [50], to analyze the process descriptions and the process capability levels. Furthermore, we employed the ISO/IEC 33002 requirements for performing process assessment without any change to conduct the systematic and formal assessments.

3. Methodology for development of BIM-CAREM

To address the limitations in previous assessment models, we aimed to create a holistic model which enables systematic and formal BIM capability assessments of the facility life-cycle processes. To achieve this goal, we created two main research questions and their sub-questions given below.

RQ1: How can BIM processes of an AEC/FM organization be formally assessed?
- RQ1.1: What key processes should be assessed to cover all facility life-cycle phases?
- RQ1.2: What BIM practices and outcomes are needed for each process of facility life-cycle?

RQ2: How general can a formalized assessment approach be to assess the BIM capabilities of AEC/FM processes?
- RQ2.1: What are the necessary assessment levels of BIM capability and BIM attributes for gauging/evaluating the BIM capability of AEC/FM organizations' processes?

We conducted qualitative research on three research activities to develop BIM-CAREM as presented in Fig. 1. From the answers to RQ1 and its sub-questions, we developed the Building PRM and BIM PRM. The larger light blue boxes in the diagram in Fig. 1 show the tasks conducted to develop Building PRM and BIM PRM. After the identification of the key AEC/FM processes, we defined each of them in terms of process purpose and process outcomes. Later, we determined the BIM related processes and defined them in terms of BIM outcomes instead of process outcomes. While Building PRM contains all of the key AEC/FM processes and their definitions with process outcomes, BIM PRM consists of only BIM-related AEC/FM processes and their definitions with BIM outcomes. This difference is clarified in Section 4.

We developed BIM MF as the answer to RQ2 and its sub-question. The larger green boxes in Fig. 1 present the tasks followed for development of the BIM MF. First, we identified the recurring keywords in BIM uses identified in the surveys, BIM guidelines, and articles. Later,

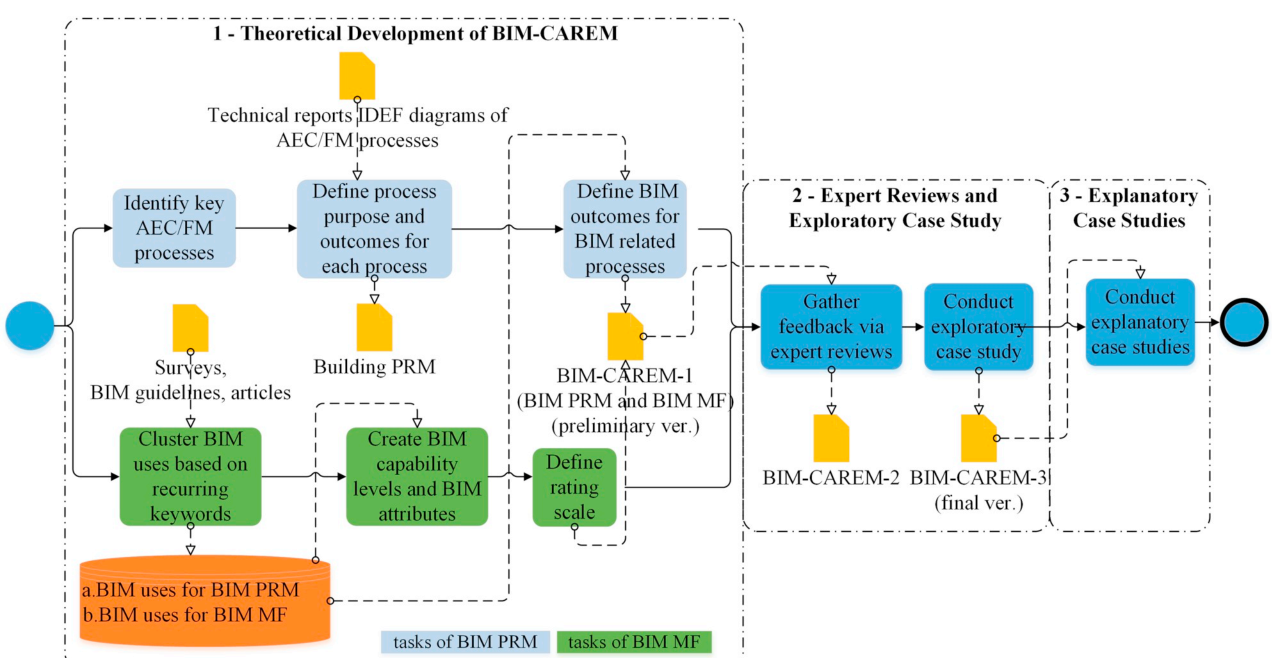

Fig. 1. Research tasks performed for the development of BIM-CAREM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

we clustered these BIM uses under these recurring keywords and utilized these clustered uses to create the BIM capability levels, their related BIM attributes, and the assessment indicators. The preliminary version of BIM-CAREM was grounded on the ISO/IEC 330xx family of standards and was updated iteratively based on the expert reviews and an exploratory case study. Discussion on how ISO/IEC 330xx was used to create BIM-CAREM can be found in Yilmaz et al. [51]. After the approval of BIM-CAREM, it was evaluated through explanatory case studies, which can be seen in the PhD dissertation [25].

3.1. Development of building PRM and BIM PRM

As shown in Fig. 1, Building PRM was created before BIM PRM. Building PRM consists of all AEC/FM process and the BIM-related processes are included in BIM PRM. According to ISO/IEC 33004 [46], a well-defined process reference model has a list of key processes within the related domain, and these processes are defined in terms of process purpose and process outcomes. The development of Building PRM began with identifying AEC/FM processes to cover all facility life-cycle phases. To achieve this, the facility life-cycle phases were identified based on the RIBA Plan of Work [28]. The facility life-cycle phases covered in this research were; conceptual planning, design (architectural, structural, building services, and geotechnical), construction, and facility management. Later, two technical reports, which are an integrated building process model [37] and construction process model [38], were examined to identify and define the key building processes of each facility life-cycle phase. Both technical reports cover all facility life-cycle phases and contain a list of key processes of each phase. However, the VTT technical report focuses more on the processes of the design disciplines of architectural, structural, building services and geotechnical designs. From the detailed descriptions of each design discipline in the technical report of VTT, the design processes were defined. Conceptual planning, construction, and facility management processes were selected and described based on the CIC technical report.

A process definition template is required to define each process systematically and have the same format for all AEC/FM process definitions. Table 1 presents the process definition template that was created conforming to ISO/IEC 33004 [46]. We were also inspired by ISO/IEC 24774 [47] when creating the process descriptions. Each AEC/FM process in Building PRM and BIM PRM has an ID, name, and purpose; however, the processes included in BIM PRM have BIM outcomes instead of process outcomes.

Both technical reports include descriptions of each AEC/FM process in terms of detailed explanations and integrated definition method (IDEF0) diagrams. Process purpose is created based on the text included in the technical reports. As depicted in the IDEF0 diagram of the Make Architectural Detail Design in Fig. 2, there are five components which are; function, input, output, control, and mechanism. The main component is function, which is an activity and described by an active verb shown in a box. Base practices in BIM-CAREM are created based on the functions. The outputs of the IDEF0 diagrams are utilized to develop the process outcomes of the related processes.

The functions of the IDEF0 diagram of the Make Architectural Detail Design in Fig. 2 are evaluate global design, make detail designs, check compatibility of detail designs, do additional tasks, and design for production, which are defined as the base practices. A review of global design, detailed design, description of compatibility, tenders, and designs for production were used to create the process outcomes of the Make Architectural Detail Design.

Since these two technical reports are not recent publications, they do not contain the BIM aspect. Therefore, we needed to include this aspect within the definitions of the BIM-related AEC/FM processes. To solve this problem, we interviewed a number of AEC/FM professionals resulting in our realization that AEC/FM processes and their base practices remain the same in traditional building/infrastructure projects in construction industry. However, the way of working has changed into BIM integrated project deliveries. In consideration of these issues, we marked the BIM-related AEC/FM processes first and then defined BIM outcomes of each process. Twenty-eight processes, marked as BIM-related processes, are shown in Table 5.

Instead of the process outcomes in Building PRM, BIM outcomes are defined for each BIM-related process in BIM PRM. BIM outcomes are generated based on the BIM uses clustered under the recurring keywords found as a result of Natural Language Analysis (NLA) [53,54] performed on BIM reports and guides from literature. Details of NLA are given in Section 3.2. On completion of the NLA, the recurring keywords are divided into two groups; the first group (see Table 2) was used for the development of BIM outcomes of the BIM-related AEC/FM processes of BIM PRM.

After the BIM outcomes were created, they were mapped to base practices. Moreover, they were also tagged with one of the two values, namely essential BIM use and enhanced BIM use as defined in the National BIM Guide for Owners published by NBIMS [55]. Essential BIM uses are the fundamental BIM uses, which are prerequisite to implement enhanced BIM uses. Some example essential BIM uses are design authoring and coordination. Enhanced BIM uses are the advanced BIM practices, such as cost estimation, and phase and 4D planning. However, we were not able to tag some of the BIM outcomes, since these BIM uses are not included in the National BIM Guide for Owners.

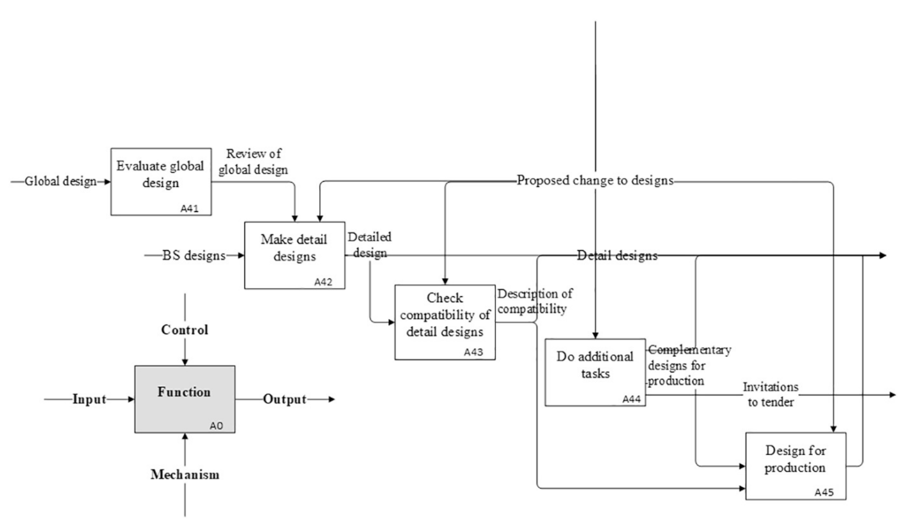

Fig. 2. IDEF0 diagram of the Make Architectural Detail Design Process [38].

Very well-known BIM uses, such as design authoring, engineering analysis, and asset management are defined in this report [55]. We planned to use this clustering a baseline for creating weight coefficients for calculating the overall rating of the BIM capabilities of the processes. However, since some of the BIM outcomes do not have tags, we could not use them as classifiers.

3.2. Development of BIM MF

To develop the second part of BIM-CAREM; i.e., BIM MF, principles and requirements defined in ISO/IEC 33003 [48] were followed. A well-defined model should possess a schema in which capability levels, attributes, and the observable indicators are defined to facilitate formal capability assessments [48]. First, it was necessary to decide how many capability levels should be defined to cover the different levels of BIM utilization in the AEC/FM industry. Various multi-stage models have been proposed for BIM maturity in the literature. For example, six levels of BIM maturity for NBIMS BIM CMM and BIM QuickScan; five levels of BIM maturity for Organizational BIM AP, BIM PM, and BIM MM; four levels of BIM maturity for VDC Scorecard, VICO BIM Scorecard, Multifunctional BIM MM, and the UK BIM Maturity Levels [56] have been defined. However, it has been observed that four stage models have been proposed and tested more frequently [57]. Additionally, we found that four levels of BIM capability appear to be sufficient without omitting any significant type of BIM utilization in the AEC/FM industry. Therefore, in the context of BIM-CAREM, we created four levels of BIM capability starting from Level 0 and finishing at Level 3.

BIM capability levels and associated BIM attributes were created simultaneously, and later they were improved iteratively. More resources related to the AEC/FM industry were required to create the BIM capability levels and BIM attributes without missing any significant BIM usages in the AEC/FM industry. Hence, we identified BIM uses from various resources which are surveys of McGraw Hill Construction [58–63] the UK's National BIM reports [21,64], the Project Execution Planning Guide of CIC [65], and an article [66]. After collecting the identified BIM uses in an Excel workbook, the duplicates were eliminated. The total number of BIM uses was 268. Although we eliminated the syntactically same BIM uses, the semantically same BIM uses remained in the list.

In order to select candidate BIM capability levels or BIM attributes within these BIM uses, we determined the recurring nouns and verbs using the NLA [53] [54] technique, which is an intuitive set of heuristics for generating a list of initial candidate objects, attributes, and associations from short descriptions and requirements specifications. RapidMiner [67] was used to find the frequent nouns and verbs, and the semantically same BIM uses were listed under these nouns and verbs. Later, the recurring nouns and verbs were divided into two groups. The first group (see Table 2) was used for development of BIM outcomes of the BIM-related AEC/FM processes of BIM PRM. The second group (see Tables 3 and 4) was utilized for the development of BIM capability levels, BIM attributes, generic BIM work products, and generic resources of BIM MF.

BIM capability levels 0 and 1 are defined as incomplete and performed, respectively based on ISO/IEC 33020 [49]. For Level 0, no BIM attributes are defined since BIM was not implemented or partially implemented in a AEC/FM organization at this level. For Level 1, two BIM attributes are defined; one is performing BIM which is given as a requirement in the ISO/IEC 33003 standard [48], and the second is BIM training since the "training" keyword was found to be a frequent keyword in BIM uses (Table 3), and it is another important criterion for using BIM effectively in construction organizations. BIM capability level 2 is defined as integrated, since BIM collaboration between different stakeholders and data exchange between different processes by using BIM are accepted as higher level of BIM uses by experts. As a result of NLA on BIM uses, "collaboration" and "interoperability" seem to be two important criteria for integrating facility life-cycle processes. Therefore, BIM collaboration and interoperability are defined as BIM attributes of BIM capability level 2. Lastly, BIM capability level 3 is defined as optimized, since BIM uses needed to be continuously improved in the facility life-cycle processes. One of the BIM attributes of Level 3 is corporate-wide BIM deployment, which was created as a result of expert reviews. The second BIM attribute is continuous BIM improvement created based on the keyword "customization" in Table 3.

To enable the operationalization of BIM capability assessments, users and assessors need to observe achievement of BIM attributes through objective evidence [49]. Therefore, after determination of BIM capability levels and BIM attributes, the observable measures of generic practices, BIM attribute outcomes, generic BIM work products, and generic resources were developed. Generic practices and BIM attribute outcomes were created based on ISO/IEC 15504-5 [50]. For the development of generic BIM work products and generic resources, the recurring keywords (see Table 4) identified via NLA, BIM handbook [68], and various BIM guidelines [1,13,14,16,69–76] were used.

For BIM Attribute 1.1 (performing BIM), generic BIM work products, such as 3D models and quantity take-offs are defined as assessment indicators which show that process is being performed using BIM. Additionally, generic resources, such as BIM authoring tools (Autodesk Revit [77] and Tekla Structures [78], etc.) were defined. For BIM Attribute 1.2 (BIM skills), generic BIM work products; e.g., BIM training budgets and certifications of employees, and generic resources, such as BIM consultancy were defined as evidence of achievement of BIM skills.

To rate the achievement of BIM Attribute 2.1 (BIM collaboration), generic BIM work products; e.g., BIM execution plans and customized standards, and generic resources, such as collaboration tools (Autodesk Vault [79]) and usage of common data environments were defined. For BIM Attribute 2.2 (interoperability), generic BIM work products and generic resources for interoperable formats, such as Industry Foundation Classes (IFC) and XML were defined as indicators of achievement of Interoperability.

For BIM Attribute 3.1 (corporate-wide BIM deployment), generic BIM work products; e.g., using model in construction site, and synchronization of model and libraries of custom BIM objects, and generic resources, such as devices (tablets, sensors, etc.) and international standards (Model View Definitions, and etc.) were defined as assessment indicators. For BIM Attribute 3.2 (continuous BIM improvement), generic BIM work products; e.g., strategies for BIM improvement and innovation meetings, and generic resources, such as project management tools were defined as evidence of achievement of continuous BIM improvement.

3.3. Iterations of BIM-CAREM

The preliminary version of BIM-CAREM, BIM-CAREM-1, provided a point of departure for further modifications of BIM-CAREM. The first version of BIM-CAREM was reviewed by Expert 1 (E1), the director of engineering and design team of an airport construction and operation company. According to the feedback from E1, we added two BIM attributes, namely "BIM skills" and "corporate-wide BIM deployment" to BIM capability level 1- performed BIM and to BIM capability level 2- integrated BIM, respectively. The first iteration included these updates, as well as the clarification of terminology. On completion of the first iteration, the second version of BIM-CAREM was developed.

BIM-CAREM-2 was reviewed by two experts. Expert 2 (E2) is an architect and BIM consultant to renowned Turkish design companies. Expert 3 (E3) is a mechanical engineer and BIM consultant to Turkish and Canadian companies. Based on the feedback of E2, BIM outcomes in BIM PRM were grouped under two categories; "essential use" and "enhanced use" (see Fig. 5). According to the feedback from E3, two BIM attribute outcomes of "corporate-wide BIM deployment" were updated, and the third version of BIM-CAREM was created. In the approval phase, BIM-CAREM-3 was approved by experts, E1 and Expert 4 (E4). E4 is a civil engineer, studied and worked as a consultant in the

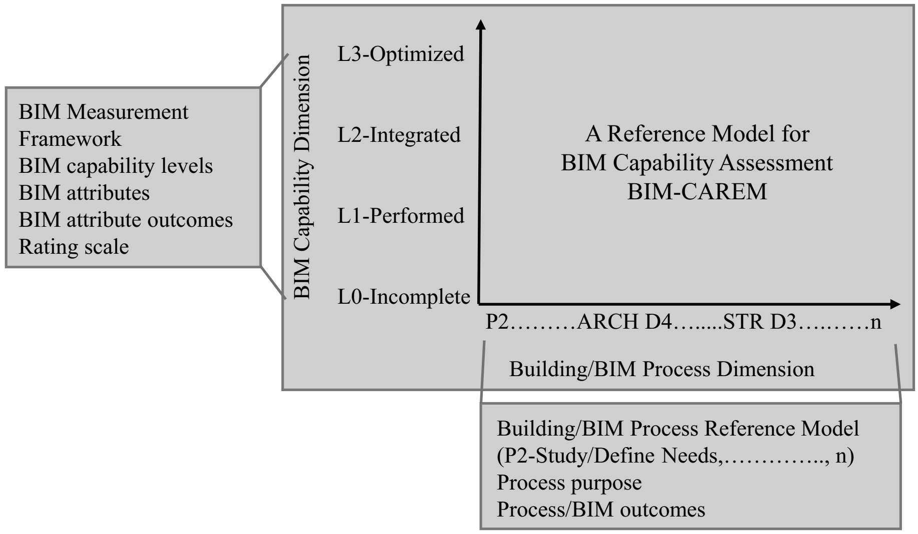

Fig. 3. The parts of BIM-CAREM.
(Adapted from Fig. 1 in [46].)

UK. Most of the feedback of E1 and E4 has been previously covered; therefore, no significant changes were made to BIM-CAREM-3 at this point. BIM-CAREM-3 is the final version and was tested via explanatory case studies which are explained in detail in Yilmaz [25].

4. BIM-CAREM

BIM-CAREM is a reference model for assessing the BIM capabilities of AEC/FM processes. Assessments using BIM-CAREM enable organizations to understand the BIM capabilities levels of their existing AEC/FM processes. The assessment results provide baseline for improvements in BIM usages and create awareness for risk mitigation. It allows users to undertake multiple evaluations for the same process and facilitates formal appraisals and benchmarking. As presented in Fig. 3, BIM-CAREM has the two dimensions of BIM process and BIM capability.

BIM process dimension is composed of a set of process elements related to BIM and represented by two process reference models, namely Building PRM and BIM PRM. BIM capability dimension is composed of a set of BIM capability levels and their associated attributes and represented by the measurement framework of BIM MF.

4.1. Building and BIM process reference models

The domain of the process reference models is the AEC/FM industry. The facility life-cycle phases covered in both process reference models are conceptual planning, design (architectural, structural, building services and geotechnical), construction, and facility management. The key AEC/FM processes of the facility life-cycle phases are listed, and their relation to BIM are identified and marked as Yes (Y)/No (N) in Table 5. While all the AEC/FM processes are included in Building PRM, only the processes marked with "Y" were collected in BIM PRM.

There are 37 AEC/FM processes in Building PRM in total, but only 28 processes are BIM-related and included in BIM PRM. In other words, BIM PRM is a subset of Building PRM as presented in Fig. 4.

Building PRM is composed of AEC/FM processes' definitions in terms of process ID and name, process purpose, base practices, and process outcomes as presented in Fig. 5. BIM PRM comprises definitions of the BIM-related AEC/FM process in terms of process purpose and BIM outcomes instead of process outcomes. Process outcomes and BIM outcomes are gathered as a result of base practices. A definition of each element is presented in Table 1 in Section 3.1. If those base practices given in Building PRM are performed using BIM instead of following traditional work tasks, BIM outcomes are achieved. BIM outcomes are

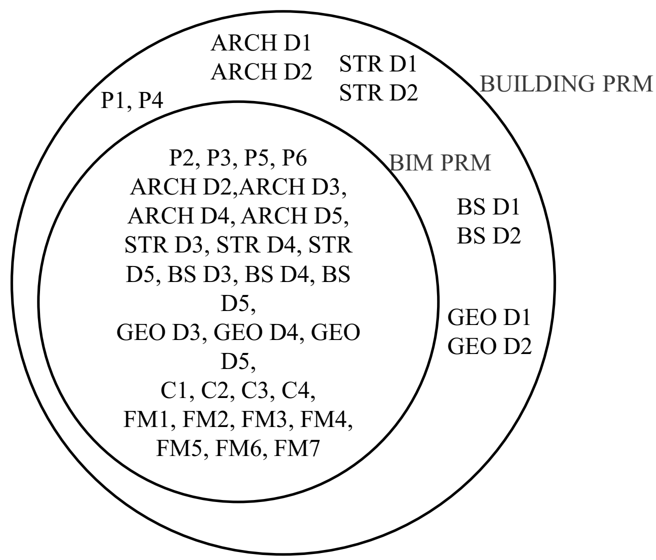

Fig. 4. Relationship between Building PRM and BIM PRM.

important since they are observed during the formal assessments to give rating for Performing BIM, which is one of the BIM attributes of BIM capability level 1. Definitions of processes in BIM PRM would have been incomplete, if we had developed BIM PRM without considering the traditional AEC/FM processes. As an example, the definitions of ARCH D4-Make Architectural Design in Building PRM and BIM PRM are presented in Fig. 5.

ARCH D4 consists of the process outcomes of the review of global design, detailed ARCH design, coordination, tenders, and detail designs for production. The same process ARCH D4 in BIM PRM consists of BIM outcomes, namely design review, design authoring, coordination, cost estimation, phase and 4D planning, and energy analysis. BIM outcomes have tags with one of the two values; essential BIM use and enhanced BIM use [55]. Essential BIM uses are the fundamental BIM uses, such as design authoring and coordination, and enhanced BIM uses are the advanced BIM practices; e.g., cost estimation, and phase and 4D planning [55]. We planned to use this clustering as a baseline to create the weight coefficients to be used in calculating the overall rating of the BIM capabilities of processes. However, since some BIM outcomes do not have tags, such as the ninth BIM outcome in Fig. 5, we could not use

Process ID	ARCH D4
Process name	Make Detail Design (Detail Design & Construction Documents)
Process purpose	The purpose of the Make Detail Design is to create detail designs for tendering.
Process outcomes	As a result of successful implementation of Make Detail Design: 1. Global design is reviewed. 2. Detailed ARCH design is developed. 3. Coordination is conducted with all design disciplines. 4. Tenders are created. 5. Detail designs for construction are prepared.
Base practices	1. Evaluate global design: Evaluate global design solutions. (Outcome 1) **(BIMout 1)** 2. Make detail designs: Design architectural detailed design such as facades, spaces, basements, and roof structures. (Outcome 2) **(BIMout 2)** 3. Check compatibility of detail designs: Check coordination with all disciplines. (Outcome 3) **(BIMout 3)** 4. Do additional tasks: Create invitations to tender. (Outcome 4) **(BIMout 5,6,9)** 5. Architectural detail design for construction: Create architectural detail design for construction. (Outcome 5) **(BIMout 4,7,8)**
Process ID	ARCH D4
Process name	Make Detail Design (Detail Design & Construction Documents)
Process purpose	The purpose of the Make Detail Design is to develop the model in detail for production and tenders.
BIM outcomes	As a result of successful implementation of Make Detail Design: 1. Design review: Design review is conducted for ARCH global model. (Essential BIM Use) 2. Design authoring: Detailed architectural model is authored. (Essential BIM Use) 3. Coordination: 3D coordination is conducted between detailed architectural model and all other detailed models (STR, BS, GEO). (Essential BIM Use) 4. Design authoring: Architectural detail model is updated further for construction. (Essential BIM Use) 5. Cost estimating: 5D cost estimating is created via quantity take off from the model. (Enhanced BIM Use) 6. Phase and 4D planning: 4D planning is prepared to plan construction sequence effectively. (Enhanced BIM Use) 7. Engineering analysis: Energy analysis is conducted based on the model to asses building energy performance. (Enhanced BIM Use) 8. Sustainability analysis: Sustainability/LEED evaluation is performed based on the model. (Enhanced BIM Use) 9. Tender documents including BIM protocols are created.

Fig. 5. Process description of the Make Architectural Detail Design in Building PRM and BIM PRM.

Table 1
Building/BIM PRM process definition template.

Name of the element	Definition of the element
Process ID	The ID of a process
Process name	The title of a process
Process purpose	The high level objective of performing the process [52]
Process outcomes (applicable to Building PRM)	An observable and assessable result of the successful achievement of the process purpose [52]
BIM outcomes (applicable to BIM PRM)	An observable and assessable result of the successful achievement of the process purpose in terms of BIM
Base practices	An activity of a set of activities which contributes to process purpose achievement [52]

these tags as classifiers. Hence, this classification does not have any role in calculating the overall score.

Work product is an artefact associated with the execution of the processes in Building PRM whereas BIM work product is associated with the execution of the processes included in BIM PRM. They are used as assessment indicators when rating BIM attributes. The work products and BIM work products of the Make Architectural Detail Design are presented in Fig. 6. The BIM work products can be the same as BIM outcomes; for example, in Fig. 6, the BIM work product “design review of architectural global model” corresponds to BIM Outcome 1, “design review: design review is conducted for ARCH global model”.

4.2. BIM measurement framework

BIM MF is the schema used to characterize the BIM capability of an executed AEC/FM process. The purpose of BIM MF is to support and

Table 2
Frequent keywords utilized for BIM outcome development.

Keyword	No of occurrences	Keyword	No of occurrences
Design	27	Review	5
Construct	22	As built	5
Site	20	Real time	5
Analysis	19	Edit	4
Manage	13	Laser scanning	3
Plan	12	Feasibility/bid	3
Cost	10	Green	3
Schedule	10	Sustain	2
Fabrication	7	Program	2
Coordination	5	Clash detection	1
Visualization	5	Rule checking	1

Table 3
Frequent keywords utilized for BIM capability levels and BIM attributes development.

Keyword	No of occurrences
Team	11
Collaboration	9
Access	9
Share	8
Communicate	4
Interoperable	3
Training	3
Customization	2

Table 4
Frequent keywords utilized for generic BIM work products and generic resources development.

Keyword	No of occurrences
Device	9
Format	8
2D/drawing	7
Software	6
Cloud	5
Policy	2

enable BIM capability assessments of AEC/FM processes. BIM-CAREM is composed of BIM capability levels and a set of associated BIM attributes and a rating scale. A BIM capability level indicates the BIM leverage capability of their organization in their AEC/FM processes and is characterized by BIM attributes. A BIM attribute is an observable phenomenon that can be measured to identify the BIM capability level of an organization in formal assessments. Rating scale is a rating schema to be used in BIM capability assessments to identify the degree of achievement of BIM attributes. BIM capability levels and their BIM attributes of BIM-CAREM are presented below.

- *BIM capability level 0 - Incomplete BIM*: BIM is not implemented or partially implemented and fails to achieve the BIM outcomes.
  - There are no available BIM attributes.
- *BIM capability level 1 - Performed BIM*: BIM is implemented to achieve the process purpose and used to perform base practices and produce standalone BIM outcomes. However, BIM has not been integrated into the facility life-cycle phases, and there is no significant BIM-based collaboration or data exchange between the facility life-cycle phases and the processes.
  - *BIM attribute 1.1 - Performing BIM* is a measure of the extent to which the defined BIM outcomes are achieved.
  - *BIM attribute 1.2 - BIM skills* is a measure of the extent to which the organization prefers to work with BIM trained and/or BIM experienced employees.
- *BIM capability level 2 - Integrated BIM*: The previously performed BIM is now implemented using an integrated BIM capable of enabling collaboration between the project stakeholders and enabling data exchange throughout the facility life-cycle phases and the processes.
  - *BIM attribute 2.1 - BIM collaboration* is a measure of the extent to which the BIM is used to support the collaboration and information exchange between the facility life-cycle phases and the processes.
  - *BIM attribute 2.2 - Interoperability* is a measure of the extent to which interoperability and flexible data exchange between BIM software applications are supported.
- *BIM capability level 3 - Optimized BIM*: The previously integrated BIM is now used at the enterprise level and is continuously improved to support the business goals of the organization.
  - *BIM attribute 3.1 - Corporate-wide BIM deployment* is a measure of the extent to which BIM is diffused to each of the facility life-cycle phases and the processes and embraced by all team members.
  - *BIM attribute 3.2 - Continuous BIM improvement* is a measure of the extent to which changes to the BIM practices are planned from analysis of common causes of variation in BIM usage, and from investigations of innovative BIM approaches for the deployment of BIM.

During the operationalization of BIM capability assessments, users and assessors observe achievement of BIM attributes through objective evidence. These observable measures are generic practices, BIM attribute outcomes, generic BIM work products, and generic resources. A BIM attribute outcome is the observable result of a BIM attribute achievement. Generic practice is the activity that contributes to the achievement of a BIM attribute. A generic BIM work product is a BIM artefact associated with the execution of a process. A generic resource is required for executing a process. BIM capability levels, their associated BIM attributes, BIM attribute outcomes, and example generic BIM work products are presented at each level in Fig. 7.

Lastly, a four-point ordinal rating scale is used as defined in ISO/IEC 33020 [49]. BIM attributes are rated against the four points as follows:

- Not achieved (N, 0 point): There is little or no evidence of achieving the BIM attribute in the assessed process.
- Partially achieved (P, 1 point): There is some evidence of an approach toward achieving the BIM attribute in the assessed process.
- Largely achieved (L, 2 points): There is evidence of systematic approach toward achieving the BIM attribute in the assessed process.
- Fully achieved (F, 3 points): There is evidence of a complete and systematic approach to achieving the BIM attribute in the assessed process.

Additionally, when there is insufficient evidence to assess the defined BIM attributes in the assessed process, not applicable (N/A) is given as a rating. To gain composite rating, we aggregated the single ratings of BIM attribute outcomes. First, ordinal ratings F, L, P, and N were converted into the interval values 3, 2, 1, and 0, respectively. Later, the median of the single ratings was calculated. If there was an odd number of values, the result was the middle value. On the other hand, if there was an even number of values, the minimum of the two middle values was selected. The final result was converted back to the corresponding ordinal value. The achieved BIM capability level was derived according to the ratings of the BIM attributes ratings as presented in Table 6.

5. Evaluation of the model

BIM-CAREM was developed iteratively via expert reviews and an exploratory case study. Later, the model was evaluated through explanatory case studies in four different AEC/FM companies. Different AEC/FM processes were assessed to understand how BIM-CAREM could be applied to the AEC/FM industry and determine the difficulties/

Table 5
Key AEC/FM processes of BIM-CAREM and their relations to BIM.

Phase name and ID	Process ID	Process name	Related to BIM? (Y/N)
Conceptual planning (P)	P1	Assign planning team	N
	P2	Study/define needs	Y
	P3	Study feasibility	Y
	P4	Develop program	N
	P5	Develop project execution plan	Y
	P6	Select and acquire site	Y
Architectural design (ARCH D)	ARCH D1	Draw up brief	N
	ARCH D2	Draw up program	Y
	ARCH D3	Make global design	Y
	ARCH D4	Make detail design	Y
	ARCH D5	Do design tasks during construction	Y
Structural/building services/geotechnical design (STR/BS/GEO D)	STR/BS/GEO D1	Draw up brief	N
	STR/BS/GEO D2	Draw up program	N
	STR/BS/GEO D3	Make global design	Y
	STR/BS/GEO D4	Make detail design	Y
	STR/BS/GEO D5	Do design tasks during construction	Y
Construction (C)	C1	Acquire construction services	Y
	C2	Plan and control the work	Y
	C3	Provide resources	Y
	C4	Build facility	Y
Facility management (FM)	FM1	Plan/control facility	Y
	FM2	Manage operations	Y
	FM3	Monitor facility conditions and systems	Y
	FM4	Evaluate conditions and detect problems	Y
	FM5	Develop solutions	Y
	FM6	Select plan of action	Y
	FM7	Implement plan	Y

benefits perceived by different stakeholders working in different facility life-cycle phases. We also selected organizations working on different building/infrastructure types and with various frame types. The findings of the explanatory case studies showed that BIM-CAREM is applicable for use in assessing BIM capabilities of different AEC/FM processes. Details of the explanatory case studies can be found in the PhD dissertation of Yilmaz [25]. In the following sections, we present the results of expert reviews and explain how we conducted the exploratory case study and its results.

5.1. Expert reviews

Updates made to BIM-CAREM resulted in two iterations of the model. Those updates undertaken in response to the expert reviews which are explained in Section 3.3. Besides those reviews, each expert rated the BIM attributes and their associated BIM attribute outcomes via an online questionnaire. Each expert was asked to rate BIM attributes and BIM attribute outcomes metrics as not essential (1 point), important but not essential (2 points), or essential (3 points). The ratings given for the BIM attributes and BIM attribute outcomes are summarized in Figs. 8 and 9, respectively. In both figures, the blue, orange and gray boxes represent the ratings given by E3, E1 in the second meeting, and E4, respectively. Those ratings were used to make decisions about the required updates to the measures and give approvals. According to the results of the ratings in Fig. 8, we did not remove any BIM attributes nor added any new ones, since most were rated with 3 points. Corporate-wide BIM deployment was the only BIM attribute given a 2-point rating, since its applicability to different firms, such as general contractors and sub-contractors was found to be different. However, we did not revise this BIM attribute, since it is an important measure to be used to assess whether BIM is utilized in all AEC/FM processes of the organizations.

Fig. 9 presents the ratings given for BIM attribute outcomes which are represented by their IDs. The names of the BIM attribute outcomes with respect to their IDs are given in Fig. 7. Only two BIM attribute outcomes are rated as 1 point by E3: "3.1-a Model is used for all processes and embraced by all team members" and "3.1-d BIM objects and facility information are collected in a library for reusing this information on future projects". According to E3, there was a problem about the generality of 3.1-a and 3.1-d. For example, while 3.1-a can be

Table 6
Ratings that should be received for the BIM attributes to achieve the BIM capability levels.

Cap. Level \ BIM Att.	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.

Table 7
Assessed processes and their BIM outcomes.

Processes of the Phases	BIM Outcomes
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 modeling is conducted for a site/facilities on site/a specific area within a facility
P3 - Study Feasibility	P3-1 Feasibility information (Economic, environmental and technical) is studied
P5 - Develop BIM Execution Plan	P5-1 Define BIM as part of project delivery strategy and identify required BIM services
	P5-2 BEP is created
P6 - Select and Acquire Site	P6-1 Site analysis is conducted to determine the most optimal site location
ARCH D2 - Draw Up Program	ARCH D2-1 Draw up space program and requirements are developed (areas and volumes, etc.)
	ARCH D2-2 Programming is conducted to assess design performance in terms of spatial requirements
ARCH/STR/BS D3 - Make Global Design	ARCH D3-1/ARCH D3-2/ARCH D3-3/ARCH D3-6/ARCH D4-2/ARCH D4-4/STR D3-1/STR D3-4/STR D4-1/BS D3-1/BS D3-4/BS D4-1 Design authoring
	ARCH D3-4/ARCH D4-3/STR D3-3/BS D3-2/BS D3-3/BS D4-2 3D coordination
	ARCH D3-5 Code and compliance checking is performed
	ARCH D3-7 An application for a building permit is submitted
ARCH/STR/BS D4 - Make Detail Design	ARCH D4-1 Design review
	ARCH D4-5/STR D4-3/BS D4-3 Cost estimating
	ARCH D4-6/STR D4-4/BS D4-4 Phase and 4D planning
	ARCH D4-7/STR D4-2/BS D4-5 Engineering analysis
	ARCH D4-8 Sustainability analysis
	ARCH D4-9 Tender documents including BIM protocols are created
ARCH/STR/BS D5 - Do Design Tasks During Construction	ARCH D5-1/STR D5-1/BS D5-1 Record modelling

Table 8
Ratings received for the BIM attributes with respect to phases assessed in Company A.

C. Lev. and BIM A. / Phase	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
P	L	F	F	F	P	N
ARCH D	F	F	F	F	P	N
STR D	F	F	F	F	P	N
BS D	F	F	F	F	P	N

applicable to the processes of a contractor, it is not valid for the processes of a design firm. Based on this review, we updated 3.1-a to “Model is used from the initial phase to the final phase of the facility life-cycle”. Related to 3.1-d, E3 mentioned although having a BIM objects library is important for the firm, it is not very important for the projects. However, we did not make any changes to 3.1-d, since we thought that having a custom 3D object library is important both for projects and for companies to increase reuse of BIM information.

5.2. Exploratory case study

The aim of the exploratory case study was to identify whether any further updates were required for BIM-CAREM which was developed conceptually based on the ISO/IEC 330xx family of standards and the BIM uses identified in the literature. In this section, we explain the design of the exploratory case study and its results.

Case selection strategy: During the conceptual development of BIM-CAREM, we undertook face-to-face interviews with the BIM manager of Company A. Since they perform all the design processes belonging to the different design disciplines of architectural, structural, building services and geotechnical designs, we reviewed the BIM outcomes of the design processes of BIM PRM with the BIM manager of Company A. Moreover, assessing design processes was a better strategy than the evaluation of the construction processes to capture the factors that appeared during the appraisal, since BIM has been adopted recently by

Work Products	
1. Global design	7. Review of global design (Outcome 1)
2. ARCH detailed design (Outcome 2)	8. BS designs
3. Construction specification (Outcome 2)	9. STR designs
4. Description of design compatibility (Outcome 3)	10. Complementary designs for construction (Outcome 4)
5. Component suppliers designs	11. Invitations to tender (Outcome 4)
6. ARCH designs for construction (Outcome 5)	

BIM Work Products	
1. Architectural detail model (BIMout 2)	6. Design review of architectural global model (BIMout 1)
2. Clash detection results of ARCH and all other models (BIMout 3)	7. Quantity take off (BIMout 5)
3. Energy and environmental analyses (BIMout 7)	8. 5D cost estimation (BIMout 5)
4. Sustainability (LEED) evaluation (BIMout 8)	9. 4D planning (BIMout 6)
5. Architectural detail model for construction (BIMout 4)	10. Tender documents for BIM usage (BIMout 9)

Fig. 6. Work products and BIM work products of the Make Architectural Detail Design.

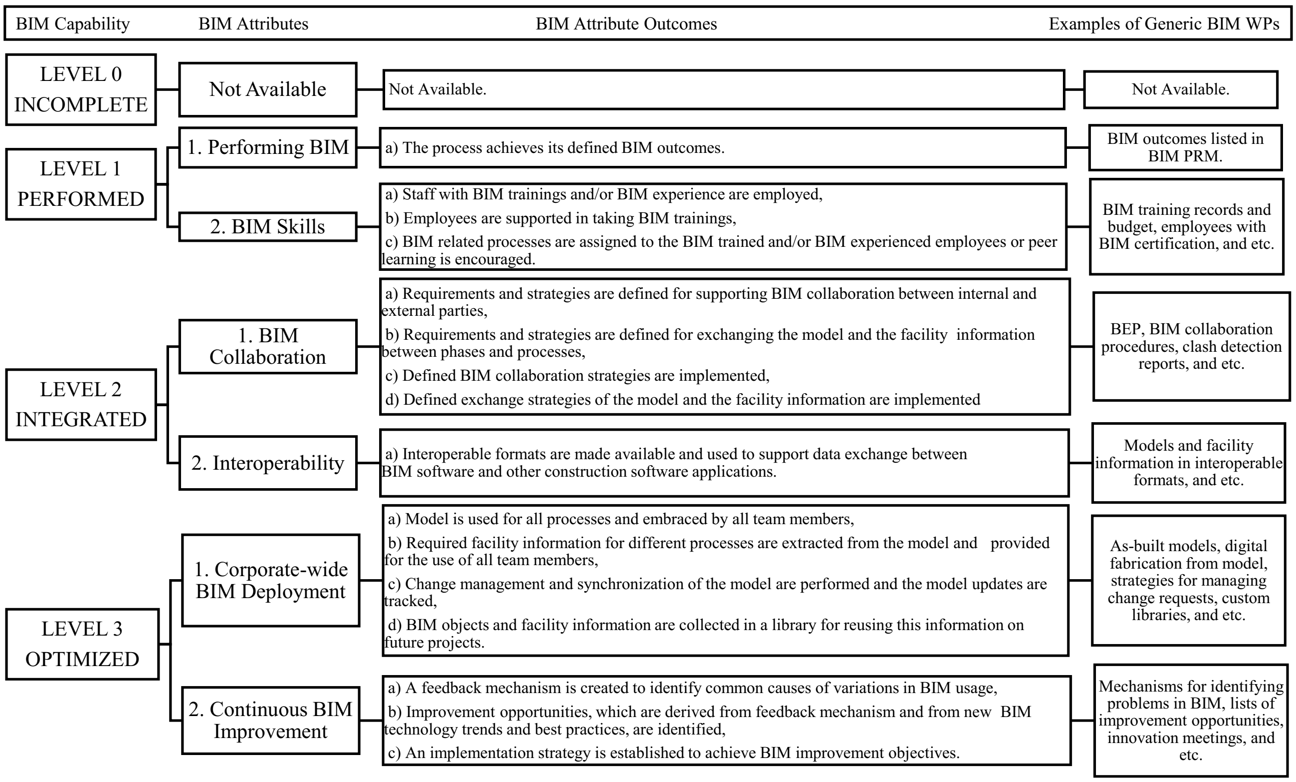

Fig. 7. BIM capability levels, BIM attributes and BIM attribute outcomes.

design firms in Turkey. Hence, Company A was selected to be the exploratory case study to identify the BIM capabilities of the design processes.

Company A is a design and engineering firm founded in the 1980s with about 10 years of experience in designing rapid transit public transport projects. It is a group of four companies, which include engineering, software, computer departments, and a training center. It has offices in three different cities in Turkey. We have conducted our case study in the first office in which they adopted BIM. There are more than 200 employees comprising architects, engineers, and technicians across the company. Company A has been using BIM for about five years, and BIM is a contract requirement in most of their transportation projects.

Data collection strategy: We performed a formal assessment to identify the BIM capabilities of design processes using BIM-CAREM. During the assessment, primary data was collected by conducting semi-structured interviews. We asked the BIM manager and the lead mechanical, electrical and plumbing (MEP) designer of Company A pre-defined interview questions. We took notes using the Excel-based assessment template regarding the answers to the questions. We also audio recorded the whole interview. The secondary data was collected via direct observations, which, according to Yin [80], allows the researcher (s) to observe behaviors and environmental conditions. We considered assessment indicators, such as models created using BIM tools. For example, when we were observing the 3D models of Company A, we examined whether these 3D models included information to be used in the later facility life-cycle phases, such as construction. We took detailed notes related to the models.

Data analysis methods: The case narrative based on the audio recording was transcribed, assessment notes were entered into the Excel sheet, and notes were taken concerning the assessment indicators. The ratings of the BIM attribute outcomes were given based on the case narrative. Later, those ratings were aggregated founded on the rules explained in Section 4.2 to calculate the ratings of the BIM attributes. Lastly, the BIM attributes ratings were used by applying the rules given in Table 6 to identify the BIM capability level of each design phase.

Validation strategy: The results of the assessment were shared with

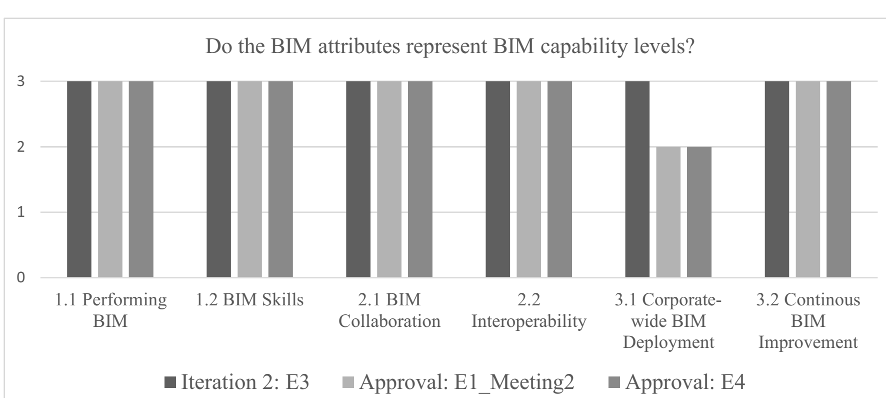

Fig. 8. Ratings of experts for BIM attributes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

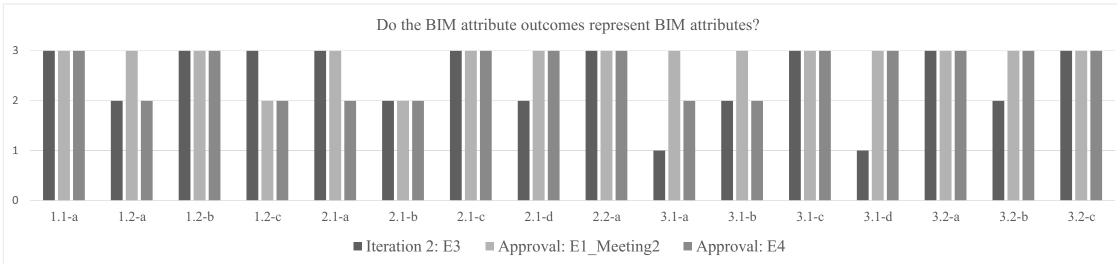

Fig. 9. Ratings of experts for BIM attributes outcomes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the BIM manager and MEP lead designer for clarification. Furthermore, an online questionnaire was implemented to validate the results and understand whether BIM-CAREM was able to identify the existing BIM capabilities of the conceptual planning and design processes belonging to the projects performed by Company A. The online questionnaire contained five questions aiming to obtain opinions from the BIM manager and MEP lead designer about the assessment results (see Fig. 12).

5.2.1. Findings of assessment of projects by company a

We reviewed the four projects on which the company was engaged with Istanbul Metropolitan Municipality as the client. Three projects concerned rapid transit lines in different districts of Istanbul, and one was a funicular railway project. Company A took on the role of designer in these four projects. They used BIM in conceptual planning and design disciplines apart from geotechnical design. Therefore, we performed formal appraisals for the conceptual planning, architectural, structural and building services design using BIM-CAREM. Each of these facility life-cycle phases is composed of a number of processes. Hence, in order to identify the BIM capability of each phase, first we needed to determine the BIM capabilities of their processes. The processes assessed within this case study and their BIM outcomes are given in Table 7.

A three-hour meeting was convened consisting of a semi-structured interview with the lead MEP designer and BIM manager of the company. We started the appraisal with evaluating the BIM attributes of BIM capability level 1 and continued with levels 2 and 3. As given in Section 4.2, the assessed BIM attribute pairs for levels 1, 2 and 3 are performing BIM and BIM skills; BIM collaboration and interoperability; and corporate-wide BIM deployment and continuous BIM Improvement, respectively. We took the BIM outcomes as basis for the assessment of performing BIM, and examined and rated the BIM attribute outcomes given in Fig. 7 to identify the rating of the reminder of the BIM attributes. The findings of the case study concerning each BIM attribute are summarized below.

BIM A1.1 Performing BIM: In conceptual planning, BIM related user needs are defined in their projects which can either be design-bid-build and design-build. They are using laser scanning for existing conditions modeling, and the model is created from point cloud data. BIM is not used for feasibility studies and site analysis; it is used for programming, but not at this phase. In most of their projects, BIM is defined as part of the delivery strategy and required BIM services are identified. 3D models are created according to ground conditions; for example, building type was changed according to ground conditions. BEP is created based on the BEP Planning Guide of Penn State University [65]. Space program is developed based on the technical specifications received from the client; but, BIM is not included in this process. Engineers working in Company A assess spatial performance using BIM; for example, in one of their projects they analyzed if metro stations were sufficient for passenger circulation. 3D models are created using Autodesk Revit [77] in architectural, structural and building services design disciplines. Architectural 3D model is created first and shared with the designers in other design disciplines. Design workflow consists of four steps; concept design, preliminary design, detailed design, and construction documents. Interference checks are performed using built-in categories of Revit to eliminate internal conflicts within each design discipline. Later, Autodesk Navisworks [81] is used for 3D coordination of the 3D models belonging to all design disciplines. Code validation and application for building permit usually completed by the owner/general contractor in most of their projects. 3D models were not included in the application for a building permit since these models are not requested by the governmental organizations. Design reviews are performed using BIM. 5D cost estimation is performed based on quantity take-offs which are gathered from Revit based on predefined units. Phase and 4D planning is conducted by importing schedules into Navisworks TimeLiner, and simulations are created. While LEED analysis and energy analysis are not conducted using BIM; lightening analysis and structural analysis are undertaken using BIM. BIM requirements and BIM protocols for tenders are created when building services design offices are selected. Change requests coming from site are collected in Excel format and the models are updated according to these change requests to create as-built models.

BIM A1.2 BIM skills: Job advertisements are published to employ BIM skilled professionals. Peer-learning is encouraged within Company A and employees take BIM trainings regularly. Since, one of the group of the Company A is the Autodesk Gold Partner trainer in Turkey, employees have taken trainings related to various topics such as using Autodesk Revit, and Navisworks. They also receive consultancy from a BIM consultant. On the other hand, there is not an allocated training budget in the company. BIM skilled employees are assigned to important BIM roles when a new project starts. Goal of the higher level management of Company A is to achieve a certain level of BIM usage in all of the offices located in three different cities in Turkey.

BIM A2.1 BIM collaboration: BIM collaboration and facility information sharing procedures are defined within the Company A. There are documented strategies for deliveries of models and facility information. Models are stored in shared servers in which files and folders have naming conventions in conformance to PAS 1192-2007 [9]. M-files and ACONEX are also being used to collaborate and share facility information with the stakeholders. BEP is created based on the BEP Planning Guide of Penn State University [48], and shared with the customer for approval.

BIM A2.2 Interoperability: 3D models are shared in IFC format with their stakeholders. Moreover, clash detection reports are stored in several formats, such as HTML, XML, tests, and viewpoints.

BIM A3.1 Corporate-wide BIM deployment: 3D models are used to create tenders and track construction progress. On the other hand, they are working on deploying Autodesk 360 to allow workers on site to view models through handheld devices and tablets. Change requests usually come from two different sources, which are clients, and site workers. Required changes are made on 3D models, and all versions of the models are archived including the requests. As-built models are created by implementing change requests coming from site workers to the models. Frequently used BIM objects are collected in a shared folder in the servers. Moreover, default objects in Revit are also used while

<table>
<tr><td colspan="6">P/ARCH D/STR D/BS D-Architectural, Structural and Building Services Design</td></tr>
<tr><td colspan="4">BIM A1.1</td><td>BIM A2.1</td><td>BIM A3.1</td></tr>
<tr><td>P2-1</td><td>ARCH D2-1</td><td>STR D3-1</td><td>BS D3-1</td><td rowspan="5">BIM A2.1-a</td><td rowspan="5">BIM A3.1-a</td></tr>
<tr><td rowspan="3">P2-2</td><td>ARCH D2-2</td><td>STR D3-2</td><td>BS D3-2</td></tr>
<tr><td>ARCH D3-1</td><td>STR D3-3</td><td>BS D3-3</td></tr>
<tr><td>ARCH D3-2</td><td rowspan="2">STR D3-4</td><td>BS D3-4</td></tr>
<tr><td rowspan="3">P3-1</td><td>ARCH D3-3</td><td>BS D4-1</td></tr>
<tr><td>ARCH D3-4</td><td rowspan="4">STR D4-1</td><td rowspan="4">BS D4-2</td><td rowspan="6">BIM A2.1-b</td><td rowspan="6">BIM A3.1-b</td></tr>
<tr><td>ARCH D3-5</td></tr>
<tr><td rowspan="4">P5-1</td><td>ARCH D3-6</td></tr>
<tr><td>ARCH D3-7</td></tr>
<tr><td>ARCH D4-1</td><td rowspan="2">STR D4-2</td><td rowspan="2">BS D4-3</td></tr>
<tr><td>ARCH D4-2</td></tr>
<tr><td rowspan="4">P5-2</td><td>ARCH D4-3</td><td rowspan="2">STR D4-3</td><td rowspan="2">BS D4-4</td><td rowspan="4">BIM A2.1.c</td><td rowspan="3">BIM A3.1-c</td></tr>
<tr><td>ARCH D4-4</td></tr>
<tr><td>ARCH D4-5</td><td rowspan="2">STR D4-4</td><td rowspan="2">BS D4-5</td></tr>
<tr><td>ARCH D4-6</td><td rowspan="5">BIM A3.1-d</td></tr>
<tr><td rowspan="4">P6-1</td><td>ARCH D4-7</td><td rowspan="4">STR D5-1</td><td rowspan="4">BS D5-1</td><td rowspan="4">BIM A2.1-d</td></tr>
<tr><td>ARCH D4-8</td></tr>
<tr><td>ARCH D4-9</td></tr>
<tr><td>ARCH D5-1</td></tr>
<tr><td colspan="4">BIM A1.2</td><td>BIM A2.2</td><td>BIM A3.2</td></tr>
<tr><td colspan="4">BIM A 1.2-a</td><td rowspan="3">BIM A2.2-a</td><td>BIM A3.2-a</td></tr>
<tr><td colspan="4">BIM A 1.2-b</td><td>BIM A3.2-b</td></tr>
<tr><td colspan="4">BIM A 1.2-c</td><td>BIM A3.2-c</td></tr>
</table>

Fig. 10. Ratings of BIM outcomes and BIM attribute outcomes.

creating the models.

BIM A3.2 Continuous BIM improvement: Professionals working in company A usually follow new technologies about BIM. They also attend related conferences, and join competitions. However, they mostly create solutions when a problem arises. They work with BIM consultants to solve BIM related problems. On the other hand, they do not have a systematic approach for identifying BIM-related problems and implementing continuous BIM improvement plans.

Based on the findings summarized above, a rating is given for each of the BIM outcomes, and the BIM attribute outcomes. In Fig. 10, the BIM outcomes and the BIM attribute outcomes are represented by their IDs. The names of the BIM outcomes and BIM attribute outcomes can be found in Table 7 and Fig. 7, respectively. Ratings presented in Fig. 10 are represented using color codes. The interval values 3, 2, 1, and 0 are represented by green, blue, yellow, and red, respectively. Not available (N/A) value is colored gray.

The composite rating value of each BIM attribute was found by obtaining the median value of the ratings of the BIM outcomes/BIM attribute outcomes presented in Fig. 10 using the rules explained in Section 4.2. The final ratings of the BIM attributes with respect to conceptual planning and each design phase are presented as ordinal values, which are F, L, P, and N in Table 8 and represented by green, blue, yellow, and red, respectively For example, for conceptual planning, the interval value of BIM A1.1-Performing BIM was “2”, which is “L” in ordinal value (Table 8).

The final BIM capability levels of conceptual planning and design phases (architectural, structural, and building services) are determined based on the ratings of the BIM attributes presented in Table 8 using the rules explained in Section 4.2. Due to the limited usage of BIM in conceptual planning, performing BIM is rated as “L”. Even though the ratings of BIM collaboration and interoperability were found to be “F”, conceptual planning was at BIM capability level 1-Performed BIM due to the rating of performing BIM. The BIM capability level of conceptual planning is given in graph format in Fig. 11. As presented in Table 8, performing BIM in the design phases are rated as “F” since most of their BIM outcomes are achieved using BIM. Employees, who are responsible for BIM related processes in design, are supported for BIM training and BIM consultancy is also provided by a BIM expert. Internal and external BIM collaboration is supported between processes and phases performed by employees and/or stakeholders, and interoperable formats are used in all assessed phases. Hence, BIM attribute outcomes of BIM skills, BIM collaboration, and interoperability are rated as “F” for all phases. However, enterprise usage of BIM was not supported between processes/phases, and there is no systematic approach to improve BIM usage in processes/phases. Thus, architectural, structural and building services designs are found at BIM capability level 2-Integrated BIM. The BIM capability level of each phase is presented in Fig. 11.

BIM capability levels of conceptual planning and design phases (architectural, structural and building services) of transportation projects being performed by Company A are determined as BIM capability level 1-Performed BIM and BIM capability level 2-Integrated BIM, respectively (Fig. 11). Neither of the interviewees had previously experienced a similar assessment. When the findings and ratings were discussed with them, both interviewees stated that BIM-CAREM identified the same BIM capability level as they expected. Ratings of the interviewees (1 to 5) for assessment findings are presented in Fig. 12, which shows that BIM-CAREM can identify BIM capability in AEC/FM processes.

According to the lead MEP designer, BIM-CAREM can be utilized in different organizations to identify the BIM capability in AEC/FM processes. However, BIM manager thinks it may not be possible to use BIM-CAREM for assessing all processes because the model does not include metrics to evaluate sub processes. The findings were found to be helpful in understanding what needs to be done in order for BIM to be used more efficiently, especially in design processes. The BIM manager mentioned that the BIM capability of individual processes was very

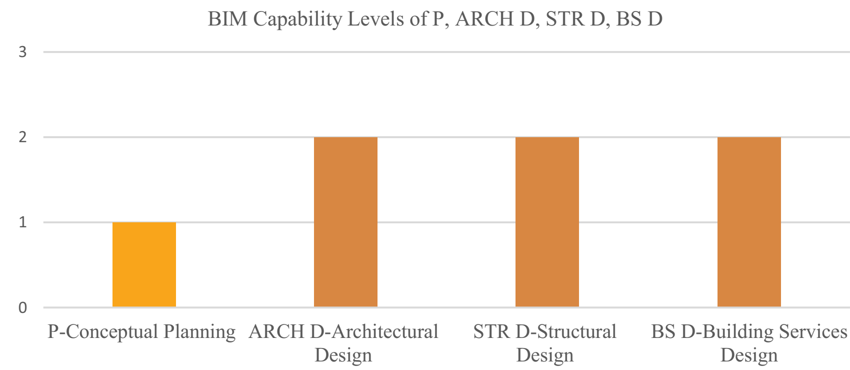

Fig. 11. Achieved BIM capability levels of conceptual planning and design phases for Company A.

useful in understanding the relationships between the processes.

5.2.2. Validity threats

According to Yin [80], there are threats to the validity of case study research since it use qualitative data and provide solutions in its own context. Below, we discuss the limitations of the exploratory case study in terms of construct, internal and external validity. Construct validity ensures the correct operational measures for the concepts being studied [80]. Triangulation, which uses one or more approaches for data collection, sources of data, and data analysis [82], was used to address this threat. We collected data from the face-to-face interviews, direct observation of assessment indicators, and the online questionnaire. Internal validity may arise from investigator's inferences based on an interview [80]. Respondent validation [82] was used to clarify our understanding and the case study findings. We performed informal checks by sharing the case study findings and understanding of the interviewers with interviewees for clarification.

Since external validity deals with the threat of whether the findings of a case study are generalizable [80], we mitigated the problems related to external validity by using four explanatory case studies, because the focus of the exploratory case study was to identify whether any further updates were needed on the model. Four explanatory case studies were conducted to evaluate AEC/FM processes belonging to projects performed by four different organizations one on structural design, one on architectural design, and two on general contracting. Within the context of explanatory case studies, we assessed different AEC/FM processes such as make detail design, build facility and plan/control facility. Moreover, different building/infrastructure types, such as hospitals and airports, and various frame types; e.g., steel and reinforced concrete frames were included in these case studies. We concluded that we could use BIM-CAREM to specify the BIM capability levels of processes based on the responses of the interviewees on the identified BIM capability levels. The details of the explanatory case studies and the results can be found in the PhD dissertation [25].

5.3. Discussions

After examining the responses of experts who completed the online questionnaire specifying the importance level of each BIM attribute and BIM attribute outcome in BIM MF, it was found that all BIM attributes had been marked as essential or important. Only two of the BIM attribute outcomes, 3.1-a and 3.1-d (Fig. 7), were marked as not essential. We modified 3.1-a according to the feedback from the expert but kept 3.1-d as it was. Apart from this update, we did not perform any major modifications on BIM MF based on the questionnaire results.

During the implementation of the exploratory case study, we did not face any significant difficulties in applying BIM-CAREM. We asked the interviewees pre-defined evaluation questions specific to BIM outcomes of conceptual planning and design processes, and there appeared to be no ambiguity in the questions. According to the findings of the exploratory case study performed to assess BIM capabilities of conceptual planning and design processes belonging to transportation projects performed by Company A, BIM is mostly used in detailed design processes. Most of the BIM outcomes of design processes were achieved by using BIM (see Fig. 10). We observed that similar responses were collected when we asked pre-defined questions to give ratings for achievement of BIM skills and continuous BIM improvement in different processes. In order to achieve BIM collaboration in different processes belonging to these two phases, which are conceptual planning and design, different tasks were performed. While BIM collaboration in conceptual planning was achieved by creating BEPs, 3D models were used to collaborate with the stakeholders in design. Furthermore, it was also easier to assess BIM collaboration in design processes. We did not face any difficulty in measuring achievement of interoperability, since interoperable formats were used in all evaluated processes. We also observed that assessing achievement of corporate-wide BIM deployment in conceptual planning and design processes were hard, since enterprise usage of BIM was more visible in construction and facility management processes where 3D models were used to conduct

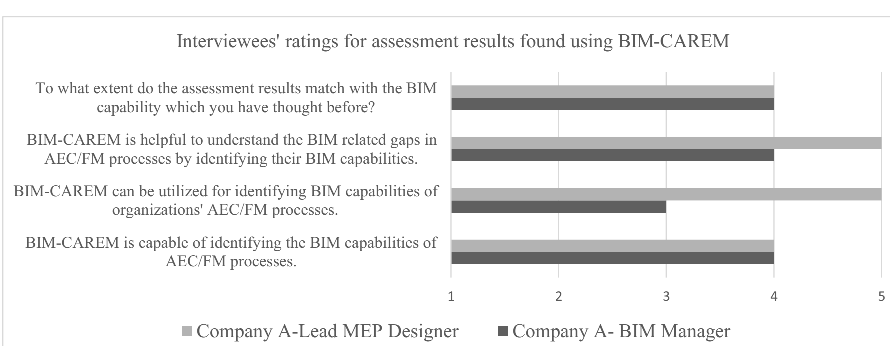

Fig. 12. Validation ratings of assessment results found using BIM-CAREM.

construction and operate facilities, respectively.

According to the questionnaire results (see Fig. 12), BIM capability levels and their associated BIM attributes belonging to BIM MF were able to identify the same BIM capability levels of the assessed processes as expected by the interviewees. In terms of BIM PRM, no missing or redundant processes were identified. In conclusion, the results of exploratory case study showed that BIM-CAREM does not require any major change. However, we observed that we needed more detailed assessment questions to evaluate different practices within the evaluated processes, and a checklist can be used to support conducting systematic appraisals.

6. Conclusions

Within the context of this study, BIM-CAREM was developed based on the meta-model of the ISO/IEC 330xx family of standards and the BIM uses identified in the literature. It has two parts, namely Building PRM/BIM PRM and BIM MF. Building PRM consists of definitions of AEC/FM processes consisting of process purpose, base practices, process outcomes, and work products. BIM PRM consists of definitions of BIM-related AEC/FM processes. BIM PRM is a subset of Building PRM, and their main difference is that the processes of the former are defined in terms of BIM outcomes instead of process outcomes. BIM MF enables BIM capability assessments by including a schema composed of BIM capability levels, associated BIM attributes, and a rating scale. Four BIM capability levels and six BIM attributes are defined in total. BIM attribute outcomes, generic BIM work products, and generic resources are also defined as assessment indicators to help assessors for rating the BIM attributes based on the observations of these indicators. The rating scale defined in ISO/IEC 33020 is used without any change.

BIM-CAREM was updated based on expert reviews and an exploratory case study. According to expert reviews, one of the major updates of BIM PRM was marking the BIM outcomes as one of the two values; “essential use” and “enhanced use”. Initially, we planned to use this tagging for assigning more weight to essential BIM uses, instead of using the median values for aggregating assessment results. However, since all BIM outcomes cannot be tagged we assumed that the weights of all BIM outcomes were equal. One of the major update to BIM MF was the addition of two BIM attributes; BIM skills and corporate-wide BIM deployment. After the necessary updates were completed on BIM MF, the results of the online questionnaire showed that BIM MF did not require further significant modifications.

The exploratory case study was performed in a design and engineering company, in which we assessed the BIM capability levels of the conceptual planning and design phases (architectural, structural and building services) of transportation projects being performed by Company A. Based on the opinions of the interviewees on the results and the feedback from the experts, we conclude that BIM-CAREM could be used to identify the BIM capability levels of processes. Furthermore, BIM-CAREM was evaluated via explanatory case studies in four different Turkish AEC/FM companies. The results of these cases showed that BIM PRM is comprehensive in providing definitions of BIM-related AEC/FM processes, and BIM capability levels and BIM attributes are suitable for assessing the AEC/FM processes with different levels of BIM capability.

The measures of BIM-CAREM were also compared to those of Organizational BIM AP and BIM QuickScan. The results showed that BIM-CAREM provides users to perform assessments of specific AEC/FM processes [83] as opposed to organizational capability assessments in the compared models. Identifying the BIM capability levels of specific processes is useful for understanding possible BIM implementations in these processes. For example, users in designer firms can conduct clash detection via models if BIM is used for creating models in all design disciplines; i.e., architectural, structural and building services. Moreover, assessments via BIM-CAREM allow process owners to analyze causal relationships about implementation of BIM between the processes. For example, 5D cost estimation in architectural detail design can be performed if a model contains necessary information.

In future work, the weights of all BIM outcomes can be adjusted in terms of the two values; “essential use” and “enhanced use”. More detailed assessment questions to evaluate different practices within AEC/FM processes, and a checklist can be prepared to support conducting systematic appraisals. More case studies, especially those conducted with subcontractors, are needed to further test the applicability of BIM-CAREM. BIM-CAREM does not have a self-assessment tool, hence a web based assessment tool can be developed which may also allow collecting benchmark datasets with BIM-CAREM.

Appendix A. Comparison of BIM-CAREM with BIM capability and maturity models (adapted from Wu et al. [27])

1. NBIMS CMM
2. BIM PM
3. BIM QuickScan
4. VDC Scorecard
5. Organizational BIM AP
6. VICO BIM Scorecard
7. BIM MM
8. Multifunctional BIM MM
9. BIM-CAREM

Aspects			Models								
			1	2	3	4	5	6	7	8	9
Process	1	Change orders management process through BIM	x			x		x			x
	2	Co-ordination and handover processes between project phases	x		x	x		x		x	x
	3	Interaction co-ordination and communication among multiple disciplines or stakeholders	x	x	x	x	x	x	x	x	x
	4	Information collection and response information flow management	x		x	x		x		x	x
	5	Information generation and documentation (e.g., quantity take-offs, week schedules, etc.)		x	x			x		x	x
	6	Delivery processes of BIM relating products and services	x					x	x	x	x
	7	Knowledge sharing processes							x		
	8	Reuse procedures of BIM-related information and data			x			x			x
	9	Documentations of actually gained benefits or impacts on working processes through applying BIM									
	10	Records of actual performance and the contribution of BIM related processes to objectives compliances				x					
	11	Target BIM relating processes and developments of plans of transitions toward the targets					x				
Technical	12	Data and information richness (rich data on both graphical and non-graphical information and life-cycle information uses)	x	x	x	x	x				x
	13	Information or data accuracy in BIM models	x	x						x	x
	14	Location or spatial capabilities and awareness	x	x						x	x
	15	model-based calculations and analysis	x	x		x		x			x
	16	BIM functions adoption and software selections			x		x	x	x	x	x
	17	BIM relating hardware implemented (e.g., equipment purchasing and relating physical space building)					x	x	x	x	x
	18	BIM networking establishments (e.g., intranets, extranets, and platforms, etc.)	x					x	x	x	x
	19	Data exchange qualities, formats and information loss			x	x		x		x	x
	20	Information security and access control				x			x	x	x
	21	Modeling cost-effectiveness and efficiencies						x			
	22	Records of actual performance and the contribution of BIM related techniques to objectives compliances				x					
	23	Documentations of the gained benefits or impacts of BIM techniques on productions									
	24	Match degree between techniques and strategies					x		x		
Organizational	25	BIM visions, goals and strategies at organization level			x		x		x		x
	26	BIM missions and objectives at operation level				x	x				x
	27	Senior management supports (e.g., personnel, finance)			x	x	x		x	x	x
	28	Attitude of management and leadership toward BIM				x			x	x	x
	29	Research and development efforts (r&d)							x		x
	30	Objectives establishments and degree of compliances				x					x
	31	Actual impacts of BIM on organizations									
Human Aspect	32	BIM related staff experiences, skills and knowledge of BIM staff/stakeholders			x	x			x		x
	33	Arrangement of BIM-related duties and roles				x	x		x	x	x
	34	BIM related training and education			x	x	x		x		x
	35	Existence and functions of BIM champion/leader			x	x	x				x
	36	Awareness, attitudes, enjoyments and involvements of employees/stakeholders toward BIM			x	x					x
	37	Change readiness among employees/stakeholders					x				
BIM Standards	38	Development of BIM execution plan (bep) or adoptions of bep templates		x		x	x				x
	39	Development of contracts of BIM related rewards and risks allocations			x				x		x
	40	Guidelines to implement and improve BIM in current businesses					x				x
	41	general procedures, protocols and regulations routine BIM related works						x	x	x	x
	42	Data exchange standards					x				x
	43	BIM products and services delivery guidelines							x	x	x
	44	Guidelines of BIM related information needs and information/model breakdown structure			x		x	x		x	x
	45	BIM training and education standards									x
	46	Quality control plans			x				x	x	x
	47	BIM benchmarking procedures							x		x
	48	Match degree between implemented standards and status and goals of the organization							x		

References

[1] U.S. General Services Administration, GSA Building Information Modeling Guide Series 01 – Overview, https://www.gsa.gov/real-estate/design-construction/3d4d-building-information-modeling/bim-guides/bim-guide-01-bim-overview, (2007) , Accessed date: 27 June 2018.

[2] Cabinet Office, Government construction strategy, 96 (43) (2011), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/61152/Government-Construction-Strategy_0.pdf , Accessed date: 3 July 2018.

[3] Senate Properties, Senate Properties and BIM, http://media.rilem.se/2015/12/Sem-2008_5_Karjalainen_Open-BIM-Senate-Properties-and-BIM.pdf, (2008) , Accessed date: 3 July 2018.

[4] Building and Construction Authority, The BIM issue, build smart magazine, 4 (2011), http://www.bca.gov.sg/publications/BuildSmart/others/buildsmart_11issue9.pdf (accessed July 3, 2018).

[5] buildingSMART Australasia, National Building Information Modelling Initiative, http://buildingsmart.org.au/wp-content/uploads/2014/03/NationalBIMIniativeReport_6June2012.pdf, (2012) , Accessed date: 27 June 2018.

[6] R. Edirisinghe, Comparative analysis of international and national level BIM standardization efforts and BIM adoption, Proceedings of the 32nd International Conference CIB W78, Eindhoven, The Netherlands, 2015, pp. 149–158.

[7] NBIMS, National BIM Standard - United States® Version 3 - Scope, (2015), pp. 1–5 https://www.nationalbimstandard.org/ , Accessed date: 1 July 2018.

[8] BSI, PAS 1192 - 5 Specification for Security-minded Building Information Modelling, Digital Built Environments and Smart Asset Management, http://bim-level2.org/en/standards/, (2015) , Accessed date: 3 July 2018.

[9] The British Standards Institution, BS 1192 - 2007 Collaborative Production of Architectural, Engineering and Construction Information, http://bim-level2.org/en/standards/, (2007) , Accessed date: 1 July 2018.
[10] The British Standards Institution, BS 1192 - 4 Collaborative Production of Information: Fulfilling Employer's Information Exchange Requirements Using COBie, http://bim-level2.org/en/standards/, (2014) , Accessed date: 1 July 2018.
[11] The British Standards Institution, PAS 1192 - 3 Specification for Information Management for the Operational Phase of Assets Using Building Information Modelling, (2014), pp. 1–44 http://bim-level2.org/en/standards/ , Accessed date: 3 July 2018.
[12] The British Standards Institution, PAS 1192 - 2 Specification for Information Management for the Capital/delivery Phase of Construction Projects Using Building Information Modelling, http://bim-level2.org/en/standards/, (2013) , Accessed date: 1 July 2018.
[13] Gravicon Oy, T. Henttinen, COBIM Series 1: General Part, https://buildingsmart.fi/wp-content/uploads/2016/11/cobim_1_general_requirements_v1.pdf, (2012) , Accessed date: 27 June 2018.
[14] Building and Construction Authority, Singapore BIM Guide - V2.0, https://www.corenet.gov.sg/media/586132/Singapore-BIM-Guide_V2.pdf, (2013) , Accessed date: 27 June 2018.
[15] NATSPEC, NATSPEC National BIM Guide, https://bim.natspec.org/documents/natspec-national-bim-guide, (2011) , Accessed date: 27 June 2018.
[16] Statsbygg, Statsbygg BIM Manual Version 1.2.1, http://www.statsbygg.no/Files/publikasjoner/manualer/StatsbyggBIM-manual-ver1-2-1eng-2013-12-17.pdf, (2013) , Accessed date: 27 June 2018.
[17] McGraw Hill Construction, The Business Value of BIM in North America, (2012), pp. 1–72 https://bimforum.org/wp-content/uploads/2012/12/MHC-Business-Value-of-BIM-in-North-America-2007-2012-SMR.pdf , Accessed date: 27 June 2018.
[18] McGraw Hill Construction, The Business Value of BIM in Europe, http://images.autodesk.com/adsk/files/business_value_of_bim_in_europe_smr_final.pdf, (2010) , Accessed date: 27 June 2018.
[19] McGraw Hill Construction, The Business Value of BIM in South Korea. SmartMarket Report, (2012), pp. 1–60 http://big.yonsei.ac.kr/pdf/biglists/1.SmartMarket/9.SMR_2012_ENG.pdf , Accessed date: 3 July 2018.
[20] McGraw Hill Construction, The Business Value of BIM in Australia and New Zealand: SmartMarket Report Managing Editor, SmartMarket Report, (2014), pp. 1–64 https://www.autodesk.com/temp/pdf/McGraw_Hill_Business_Value_of_BIM_ANZ.pdf (accessed July 3, 2018).
[21] NBS, NBS National BIM Report 2016, https://www.thenbs.com/knowledge/national-bim-report-2016, (2016) , Accessed date: 27 June 2018.
[22] NBIMS, National BIM Standard United States® Version 3 - Minimum BIM, https://www.nationalbimstandard.org, (2015) , Accessed date: 1 July 2018.
[23] B. Succar, Building information modelling maturity matrix, Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies, 2010, pp. 65–103, , https://doi.org/10.4018/978-1-60566-928-1.ch004.
[24] G. Yilmaz, A. Akcamete-Gungor, O. Demirors, 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, Heriot-Watt University, Edinburgh, 2017, pp. 627–636, , https://doi.org/10.24928/JC3-2017/0309.
[25] G. Yilmaz, BIM-CAREM: A Reference Model for Building Information Modelling Capability Assessment, (2017), p. 252 http://lib.metu.edu.tr/metu-theses-collection-search , Accessed date: 28 June 2018.
[26] IU Arhictect's Office, BIM Proficiency Matrix, http://www.iu.edu/~vpcpf/consultant-contractor/standards/bim-standards.shtml, (2009) , Accessed date: 27 October 2018.
[27] C. Wu, R. Estate, B. Xu, R. Estate, C. Mao, R. Estate, X. Li, Overview of BIM maturity measurement tools, J. Inf. Technol. Constr. 22 (2017) 34–62.
[28] RIBA, RIBA Plan of Work, 2013 (2013) https://www.ribaplanofwork.com/ , Accessed date: 9 November 2017.
[29] L. Van Berlo, H. Hendriks, BIM Quickscan: Benchmark of BIM performance in the Netherlands, Proceedings of the 29th International Conference CIB W78 2012, Beirut, 2012, pp. 17–19.
[30] C. Kam, D. Senaratna, Y. Xiao, B. McKinney, The VDC Scorecard: evaluation of AEC projects and industry trends, CIFE working paper #WP136, 136 (31) (2013), https://stacks.stanford.edu/file/druid:st437wr3978/WP136.pdf (accessed July 3, 2018).
[31] PennState CIC, Organizational BIM Assessment Profile, http://bim.psu.edu/resources/owner/bim_planning_guide_for_facility_owners-version_2.0.pdf, (2012) , Accessed date: 27 June 2018.
[32] VICO Software, Vico BIM Scorecard, http://www.vicosoftware.com/what-is-your-bim-score, (2011) , Accessed date: 24 August 2017.
[33] C. Liang, W. Lu, S. Rowlinson, X. Zhang, Development of a multifunctional BIM maturity model, J. Constr. Eng. Manag. 142 (2016) 06016003, , https://doi.org/10.1061/(ASCE)CO.1943-7862.0001186.
[34] B. Giel, T. McCuen, MINIMUM BIM - 2nd edition proposed revision, Building Innovation, 2014, pp. 1–35.
[35] BIM Excellence, BIMe, http://bimexcellence.com/, (2013) , Accessed date: 24 August 2017.
[36] B. Giel, R.R.A. Issa, Synthesis of existing BIM maturity toolsets to evaluate building owners, Computing in Civil Engineering, American Society of Civil Engineers, Reston, VA, 2013, pp. 451–458, , https://doi.org/10.1061/9780784413029.057.
[37] The Pennsylvania State University CIC, An Integrated Building Process Model, https://www.pennstatecic.org/uploads/5/1/2/1/51219339/tr_001_sanvido_1990_ibpm.pdf, (1990) , Accessed date: 1 July 2018.
[38] Technical Research Center of Finland, Construction Process Model, https://www.vtt.fi/inf/pdf/tiedotteet/1997/T1845.pdf, (1997) , Accessed date: 1 July 2018.
[39] Automative Sig, Automotive SPICE Process Assessment Model, http://www.automotivespice.com/fileadmin/software-download/Automotive_SPICE_PAM_30.pdf, (2007) , Accessed date: 1 July 2018.
[40] A. Cass, C. Völcker, R. Ouared, A. Dorling, L. Winzer, J.M. Carranza, SPICE for SPACE trials, risk analysis, and process improvement, Softw. Process. Improv. Practi. 9 (2004) 13–21, https://doi.org/10.1002/spip.190.
[41] M. Zanoni, F. Perin, F.A. Fontana, G. Viscusi, Development of MDevSPICE – the medical device software process assessment framework Marion, J. Softw. Evol. Proc. 26 (2014) 1172–1192, https://doi.org/10.1002/smr.
[42] ISO/IEC, ISO/IEC 33052 Information Technology — Process Reference Model (PRM) for Information Security Management, https://www.iso.org/obp/ui/#iso:std:iso-iec:ts:33052:ed-1:v1:en, (2016) , Accessed date: 1 July 2018.
[43] ISO/IEC, ISO/IEC 33063 Information Technology — Process Assessment — Process Assessment Model for Software Testing, https://www.iso.org/obp/ui/#iso:std:iso-iec:33063:ed-1:v1:en, (2015) , Accessed date: 1 July 2018.
[44] ISO/IEC, ISO/IEC 33071 Information Technology — Process Assessment — An Integrated Process Capability Assessment Model for Enterprise Processes, https://www.iso.org/obp/ui/#iso:std:iso-iec:33071:ed-1:v1:en, (2016) , Accessed date: 1 July 2018.
[45] ISO/IEC, ISO/IEC 33072 Information technology — Process Assessment — Process Capability Assessment Model for Information Security Management, https://www.iso.org/obp/ui/#iso:std:iso-iec:ts:33072:ed-1:v2:en, (2016) , Accessed date: 1 July 2018.
[46] ISO/IEC, 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, (2015) , Accessed date: 1 July 2018.
[47] IEEE, ISO/IEC TR 24774 - Systems and Software Engineering Life Cycle Management: Guidelines for Process Description, https://www.iso.org/obp/ui/#iso:std:iso-iec:tr:24774:ed-2:v1:en, (2012) , Accessed date: 1 July 2018.
[48] ISO/IEC, 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, (2015) , Accessed date: 1 July 2018.
[49] ISO/IEC, 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, (2015) , Accessed date: 1 July 2018.
[50] ISO/IEC, The ISO/IEC 15504 – 5 Information Technology - Process assessment - Part5: An Exemplar Process Assessment Model, https://www.iso.org/standard/60555.html, (2006) , Accessed date: 3 July 2018.
[51] G. Yilmaz, A. Akcamete, O. Demirors, Adapting SPICE for development of a reference Model for building information modeling - BIM-CAREM, 18th International SPICE Conference (SPICE 2018), 2018, pp. 119–135, , https://doi.org/10.1007/978-3-030-00623-5_9.
[52] ISO/IEC, 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, (2015) , Accessed date: 1 July 2018.
[53] R.J. Abbott, Program design by informal English descriptions, Commun. ACM 26 (1983) 882–894, https://doi.org/10.1145/182.358441.
[54] B. Bruegge, A.H. Dutoit, Object-oriented Software Engineering: Using UML, Patterns and Java, Prentice Hall, 2003 (ISBN 10 9780130471109).
[55] NBIMS, National BIM Guide for Owners, https://www.nibs.org/?nbgo, (2017) , Accessed date: 1 July 2018.
[56] BIM Industry Working Group, Strategy Paper for the Government Construction Client Group, (2011), pp. 1–7 https://www.cdbb.cam.ac.uk/Resources/ResoucePublications/BISBIMstrategyReport.pdf , Accessed date: 3 July 2018.
[57] W.R. King, T.S.H. Teo, Integration between business planning and information systems planning: validating a stage hypothesis, Decis. Sci. 28 (1997) 279–308, https://doi.org/10.1111/j.1540-5915.1997.tb01312.x.
[58] McGraw Hill Construction, Green BIM - How Building Information Modeling is Contributing to Green Design and Construction, https://www.construction.com/market_research/freereport/greenbim/MHC_GreenBIM_SmartMarket_Report_2010.pdf, (2010) , Accessed date: 27 June 2018.
[59] McGraw Hill Construction, Measuring the Impact of BIM on Complex Buildings, https://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/Docs/BIMSmartMarketReport.pdf, (2015) , Accessed date: 27 June 2018.
[60] McGraw Hill Construction, SmartMarket Brief: BIM Advancements No.1, http://www.smartmarketbrief.com/reports/SMBrief-BIM-Advancements-01.pdf, (2014) , Accessed date: 27 June 2018.
[61] McGraw Hill Construction, The Business Value of BIM for Owners, https://www.autodesk.com/solutions/bim/hub/report-the-business-value-of-bim-to-owners, (2014) , Accessed date: 27 June 2018.
[62] McGraw Hill Construction, Information Mobility: Improving Team Collaboration Through the Movement of Project Information, https://bradleybim.files.wordpress.com/2013/12/2013_information_mobility_bim_smart_market_report.pdf, (2013) , Accessed date: 27 June 2018.
[63] McGraw Hill Construction, The Business Value of BIM for Construction in Major Global Markets, https://www.icn-solutions.nl/pdf/bim_construction.pdf, (2014) , Accessed date: 27 June 2018.
[64] NBS, NBS National BIM Report 2015, https://www.thenbs.com/knowledge/nbs-national-bim-report-2015, (2015) , Accessed date: 27 June 2018.
[65] The Pennsylvania State University, BIM Project Execution Planning Guide, http://bim.psu.edu/, (2011) , Accessed date: 27 June 2018.
[66] B.B. Gerber, S. Rice, The perceived value of building information modeling in the U.S. Building Industry, J. Inf. Technol. Constr. 15 (2010) 185–201.

[67] RapidMiner, RapidMiner, (n.d.). https://rapidminer.com/ (accessed August 28, 2017).
[68] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2008, https://doi.org/10.1002/9780470261309.
[69] USC Capital Construction Development and Facilities Management Services, University of Southern California BIM Guidelines for Design-Bid Build Contracts, http://facilities.usc.edu/uploads/documents/cas/BIMGuidelines_VS1_6_2012.pdf, (2012) , Accessed date: 27 June 2018.
[70] BuildLACCD, LACCD BIM Standards for Design-Bid Build Projects, http://az776130.vo.msecnd.net/media/docs/default-source/contractors-and-bidders-library/standards-guidelines/bim/bim-design-build-standards-v4-1.pdf?sfvrsn=4, (2009) , Accessed date: 27 June 2018.
[71] U.S. Army Corps of Engineers, New York District U. S. Army Corps of Engineers Official Manual For Building Information Modeling Projects, http://www.nan.usace.army.mil/Portals/37/docs/EngDiv/CENAN_BIM_SUBMISSION_MANUAL.pdf, (2009) , Accessed date: 27 June 2018.
[72] Ohio Department of Administrative Services, State of Ohio Building Information Modeling Protocol, http://ofcc.ohio.gov/Portals/0/Documents/Resources/Publications/M830-01-BIMProtocol.pdf?ver=2015-02-25-171103-410, (2011) , Accessed date: 27 June 2018.
[73] Department of Veterans Affairs (VA), VA BIM Guide, http://www.cfm.va.gov/til/bim/BIMguide/, (2010) , Accessed date: 27 June 2018.
[74] Georgia Institute of Technology, Georgia Tech BIM Requirements & Guidelines for Architects, Engineers and Contractors, http://www.facilities.gatech.edu/files/DC/2011_0815_GT_BIM_Requirements_v1.0.pdf, (2016) , Accessed date: 27 June 2018.
[75] Indiana University Architect's Office, BIM Guidelines & Standards for Architects, Engineers, and Contractors, http://www.indiana.edu/~uao/docs/standards/IU BIM Guidelines and Standards.pdf, (2015) , Accessed date: 27 June 2018.
[76] CanBIM Designers Committee, AEC Canada BIM Protocol, http://s3.amazonaws.com/canbim-production/vol/www/apps/canbim_production/releases/20121021065404/en/public/documents/documents/original_63.pdf?1352735902, (2012) , Accessed date: 27 June 2018.
[77] Autodesk, Autodesk Revit, (n.d.). https://www.autodesk.com/products/revit-family/overview (accessed August 28, 2017).
[78] Trimble, Tekla Structures, (n.d.). https://www.tekla.com/products/tekla-structures (accessed January 1, 2017).
[79] Autodesk, Autodesk Vault, (n.d.). http://www.autodesk.com/products/vault-family/overview (accessed July 28, 2017).
[80] R.K. Yin, Case Study Research: Design and Methods, SAGE Publications, 0761925538, 2003.
[81] Autodesk, Autodesk Navisworks, (n.d.). https://www.autodesk.com/products/navisworks/overview (accessed August 23, 2018).
[82] R. Fellows, A. Liu, Research Methods for Construction, Wiley, 9781118915745, 2015.
[83] G. Yilmaz, A. Akcamete, O. Demirors, An assessment of BIM-CAREM against the selected BIM capability assessment models, Advances in Informatics and Computing in Civil and Construction Engineering, Springer International Publishing, Cham, 2019, pp. 387–395, , https://doi.org/10.1007/978-3-030-00220-6_46.