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REVIEW

Metric-based BIM implementation assessment: a review of research and practice

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ABSTRACT

Building information modeling (BIM) is one of the most significant developments in the construction industry, as it introduces new technologies, processes, and interactions into practice. Prior research shows that there is an increasing interest among practitioners and academics to assess maturity, productivity, and performance of BIM implementation. This suggests that as BIM adoption grows, the need for BIM implementation assessment arises to facilitate monitoring, measuring, and improving BIM practices. However, so far, no single study has comprehensively reviewed and reported the existing approaches, metrics, and criteria used for assessing BIM practices. This study aims to review and analyze the literature and synthesize existing knowledge relevant to the topic. The author develops a thematic framework of BIM aspects, BIM goals, and performance evaluation trends to define grounds for assessing BIM implementation. Based on the framework, this research analyzed a total number of 97 references (selected out of 322 studies) to identify, extract, and classify metrics/criteria used for assessing BIM implementation. This study has practical implications for developing future BIM maturity models and BIM assessment tools as it synthesizes the existing developments on this topic, highlights gaps and limitations in metric-based BIM assessment, and provides recommendations for further research and developments.

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BIM assessment; BIM implementation; criteria; metrics; performance

Introduction

Building information modeling (BIM) now plays an increasingly important role in the best practice of architecture, engineering, construction, and facility management (AEC/FM). BIM virtually incorporates required information for facility design, construction, and operation, from the conception stages of a project throughout life-cycle stages of a constructed facility (Aouad, Wu, & Lee, 2011; Eastman, Teicholz, Sacks, & Liston, 2011). The BIM adoption rate in the industry has significantly grown in the past several years (e.g. from 28% in 2008 to 75% in 2012 in the US; McGraw-Hill Construction, 2012). This significant growth coincided with increased research on BIM implementation in order to improve BIM tools, processes, and products; and to further enhance business performance of professional practice from the standpoints of productivity, functionality, and waste reduction (Deutsch, 2011; Smith & Tardif, 2009). However, BIM adopters do not implement BIM at the same level (Porwal & Hewage, 2013). They also do not have similar performance, even if they adopt matching levels of BIM staff, tools, and processes. Hence, there is a growing demand for developing BIM assessment measures that are compatible with different BIM maturity levels to facilitate adopting, monitoring, and improving BIM practices (Chen, Dib, & Cox, 2014).

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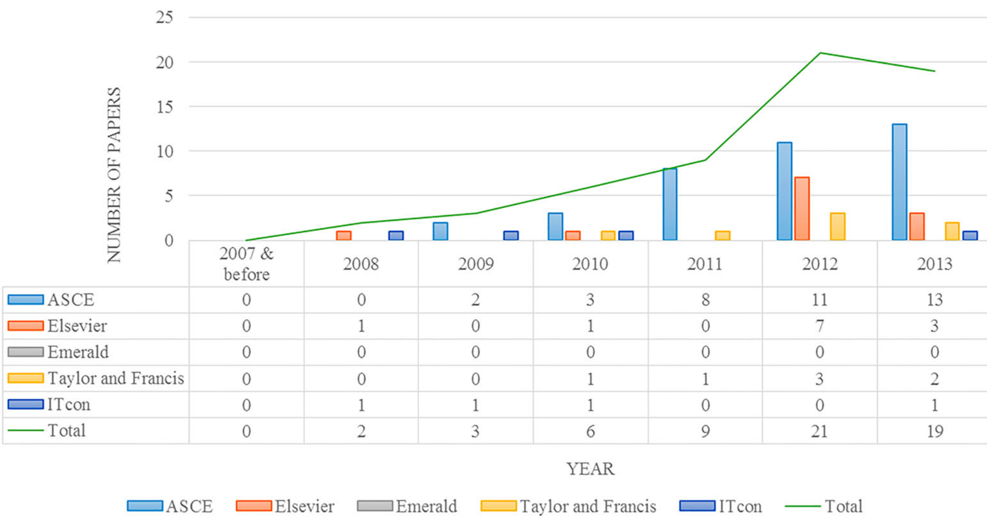
Developing metrics and criteria for assessing BIM implementation is challenging due to the variety of business interactions, project delivery methods, workflows, and processes in practice (Smith & Tardif, 2009). Although the literature shows that many different evaluation methods and tools have been used for BIM implementation assessment, they are fragmented. For example, one approach is assessing the impact of BIM on project outcomes to compare BIM projects to non-BIM projects (e.g. Barlish & Sullivan, 2012; Chelson, 2010; Coates et al., 2010). Another approach is measuring BIM financial benefits and return on investment (ROI) at higher organizational levels (e.g. McGraw-Hill Construction, 2009). Assessing BIM processes from the standpoints of human interactions and model development is another area of research on this topic (e.g. Manzione, Wyse, Sacks, Van Berlo, & Melhado, 2011; Senescu, Haymaker, Meza, & Fischer, 2013). Some researchers have also focused on qualitative BIM maturity and capability assessment (e.g. Mom & Hsieh, 2012; National Institute of Building Sciences, 2007; Succar, Sher, & Williams, 2012). To date there has been no single study that reviews and synthesizes these approaches. To bridge this gap in the research this study aims to: (1) extract, synthesize, and report existing knowledge and state-of-the-art approaches to assessing BIM implementation; (2) highlight trends, areas of interest, and gaps in research on BIM implementation assessment; and (3) facilitate future research on this topic by reporting metrics, indicators, and criteria used for assessing BIM developments and BIM practices.

Research method

The author designed a narrative review method with an approach to thematic synthesis of findings (Snilstveit, Oliver, & Vojtkova, 2012). This form of review has to bring coherence to the literature, propound new perspectives on a topic, offer a critical evaluation of the findings, and provide conclusions based on the literature (Day & Gastel, 2012; Rosnow & Rosnow, 2011). This study used a systematic approach for locating and selecting relevant research published in bibliographic databases along with a traditional review approach for locating and selecting white papers, organizational standards, and industry guidelines. The author followed the steps required for qualitative review of papers: (1) question formulation, (2) locating studies, (3) study selection and evaluation (systematic selection and traditional selection methods), (4) analysis and synthesis, and (5) reporting the results (Denyer & Tranfield, 2009). For searching peer-reviewed papers, the author used search engines in major databases, including American Society of Civil Engineers (ASCE), Emerald, Elsevier (ScienceDirect), and Taylor and Francis. Papers from the Journal of Information Technology in Construction (ITcon) were also included in the process. Two keywords, 'BIM' and 'metric', were used in the search engines. The search engines located a total number of 292 studies, including 152 items from ASCE, 58 items from Elsevier, 54 items from Taylor and Francis, 18 items from Emerald, and 10 items from ITcon (papers published online before April 2014).[1] After reviewing the papers, 67 relevant papers were identified for the analysis and synthesis process. The selected studies have proposed, or used, metrics/criteria for assessing different aspects of BIM implementation. The publication timeline of the selected papers is shown in Figure 1. The trend shows there has been an increasing interest to develop metrics for assessing BIM implementation since 2007. The publication venues (journals and conferences) of selected research papers are presented in Table 1.

In order to review developments published outside the major databases, the author located a combination of different types of informative documents, including white papers and organizational standards, reports, and guidelines by using generic search engines until a saturation point was reached. As Suter (2011) puts it, a saturation point signals that there is a little need for more samplings because new data only confirm perspectives and categories previously selected studies already offered. Thirty references selected by this method include: 9 peer-reviewed conference and journal papers, 3 master's/Ph.D. theses, 3 technical BIM articles, a large industry survey, and 14 organizational reports, standards, and industry guidelines (e.g. AGC of America, 2006; National Institute of Building Sciences, 2007; The Construction Users Roundtable, 2010; U.S. General Services Administration, 2007, 2009). As a result, a total number of 97 references were selected for the analysis and



	2007 & before	2008	2009	2010	2011	2012	2013
ASCE	0	0	2	3	8	11	13
Elsevier	0	1	0	1	0	7	3
Emerald	0	0	0	0	0	0	0
Taylor and Francis	0	0	0	1	1	3	2
ITcon	0	1	1	1	0	0	1
Total	0	2	3	6	9	21	19

Figure 1. Trend of publishing research papers that developed metrics for assessing different aspects of BIM implementation.

synthesis process. Based on the literature review and data analysis presented in the following sections, a thematic framework was developed to classify 'themes' used for identifying, extracting, and categorizing metrics and criteria reported in the literature.

Themes and grounds for assessing BIM

BIM goals, objectives, and outcomes

Low productivity and huge waste in construction, and high operation costs in facilities are the most important current challenges facing the AEC industry (Smith & Tardif, 2009). The significant waste in

Table 1. Publication venue of selected papers in bibliographical databases.

Publication venues/bibliographical databases	Number of selected papers
ASCE	
Journal of Construction Engineering and Management	10
Journal of Computing in Civil Engineering	7
Computing in Civil Engineering Conference	9
Construction Research Congress	4
Journal of Professional Issues in Engineering Education and Practice	2
Journal of Management in Engineering	1
Practice Periodical on Structural Design and Construction	1
Journal of Architectural Engineering	1
Structures Congress	1
AEI Conference	1
Emerald	
Construction Innovation: Information, Process, Management	1
Elsevier	
Automation in Construction	12
Advanced Engineering Informatics	4
Taylor and Francis	
Architectural Engineering and Design Management	3
Construction Management and Economics	1
International Journal of Computer Integrated Manufacturing	1
Building Performance Simulation	1
Structure and Infrastructure Engineering	1
Journal of the Chinese Institute of Engineers	1
Journal of Information Technology in Construction (ITcon)	5
Total	67

design practice also impacts the industry in forms of reworking design errors and changes, waiting for information, unnecessary information processing, and overproduction (Deutsch, 2011). For these reasons, state-of-the-art technologies and innovations in the construction industry aim to improve design and construction productivity, enhance facilities' functionality, and reduce waste. Most developments on BIM implementation assessment have also focused on analyzing the extent to which BIM enables practitioners to achieve these goals, although the underlying issues of BIM implementation such as process inputs and processing issues still require more attention (Chen et al., 2014). Therefore, metrics to be developed for BIM implementation assessment should measure both BIM processing aspects and BIM outcomes.

BIM outcomes are realized at different business levels, including organizational levels, project levels, and project stages. At a project level, BIM applications and benefits can be categorized based on roles of involving parties in different life-cycle stages of a project. From an owner or a facility manager's perspective, BIM improves building performance, reduces financial risks, provides accurate and reliable plans, and optimizes operations and maintenance in facility management stages. Architects and engineers perceive benefits of BIM in design stages in forms of improved decision-making in conceptual design, consistency in construction documentations, and integration among disciplines. Constructability and clash analysis, automated and accurate quantity takeoff, offsite fabrication, simulated construction management, and facilitated commissioning and information handover are BIM applications for contractors and subcontractors in the construction and fabrication stages (Eastman et al., 2011). These categories of business and project levels for analyzing BIM outcomes are considered as themes for classifying metrics/criteria identified in this study.

BIM implementation aspects

According to the literature, BIM implementation has several different dimensions that must be addressed inclusively in BIM adoption and adaptation. BIM is often perceived as a process or as a tool (Deutsch, 2011). Many practitioners have also considered a human dimension for BIM implementation (e.g. Reddy, 2011), considering that 'BIM is about people and process as much as it is about technology' (Specialist Engineering Contractors Group, 2013, p. 10). 'BIM deliverable' (models) is another important aspect of BIM that has been considered in BIM implementation assessment (Kymmell, 2008). These all suggest that BIM implementation should be analyzed as a set of interacting dimensions (Love, Edwards, Han, & Goh, 2011). In this research, the author synthesizes the abovementioned BIM implementation aspects based on the 'input–process–output' model (Landy & Conte, 2007, p. 550), in which items such as people and technologies are considered as process inputs. Integrating inputs by interaction, communication, and analyzing decisions shapes processes. BIM deliverables and outcomes are process outputs, as discussed in the previous section (Landy & Conte, 2007). Accordingly, the author added these dimensions to the themes selected for analyzing and synthesizing findings in the review process: BIM users/staff and BIM tools as inputs, human–human interactions and human–computer interactions as BIM processing themes, and BIM models and performance at different life-cycle stages as BIM outputs.

Approaches to measuring performance and processes

According to the literature, measurement is the essential basis for improvement, and attempts to control and manage performance will not be successful without measuring practices (Garvin, 1993; Martin, Petty, & Wallace, 2009). Interpreting measurements helps to determine goals, responsibilities, and required actions of team members (Constructing Excellence, 2006; Parmenter, 2010). Both tangible and intangible criteria can be measured by metrics (Kerzner, 2011). For tangible criteria, quantitative metrics (QT) directly measure the outcomes, while for qualitative criteria expert judgments would be scaled statistically (Project Management Institute, 2003). In this study, the author extracts metrics as well as criteria-like factors developed in the literature for assessing BIM practices.

Although the identified criteria (e.g. collaboration, communication, interoperability, etc.) may not reflect any measure or metric, the author intends to report them to facilitate developing quantifiable metrics or indicators in future research. It is important to note that metrics and measures are used either as benchmarks or as performance indicators. Performance indicators are not for benchmarking and comparing practices, but they show internal trends in an organizational unit. Key Performance Indicators (KPIs) are the most important of these indicators as they strongly correlate with critical success factors in business functions (Levitt, 2011). Therefore, some metric/criteria reported in this study may not be suitable for benchmarking across different practices, but they are useful for tracking process and performance trends in a BIM practice.

Findings

This research reports on a large number of studies and numerous metrics/criteria they used to assess BIM implementation. Therefore, instead of explaining and comparing how different studies measured each BIM aspect in a lengthy report, the author codes and summarizes the findings in several classifications based on the thematic framework developed for this study (Figure 2) (see Ritchie & Lewis, 2003, p. 220). This framework lists the themes identified in the literature review section and themes emerged from data in an iterative and recursive process of coding and synthesizing findings. In this section, the extracted metrics/criteria are reported in the way suggested by their original reference. The author coded QT, qualitative metrics (QL), and criteria-like factors/indicators (C) for each item in each theme to show how each study used each metric/criterion.

BIM inputs

BIM tools

There is a common perception that technology is the most important aspect of BIM. According to Eastman et al. (2011), the technological aspect of BIM fits into a hierarchy that has three levels of BIM tools, BIM platforms, and BIM environments. Each level may impact certain functions in an organization. BIM tools are single-purpose applications that produce single-purpose models, which cannot be introduced into other applications for other functions (e.g. only for quantity takeoff). BIM platforms enhance applications to produce models readable by various tools for multiple purposes. BIM environments integrate data-management functions, platform coordination, communication channels, and information exchange with modeling functions. These definitions are essential to identify assessment metrics/criteria related to capabilities of BIM developments.

In the data analysis process, the author found that there is a large number of metrics used for assessing the performance of image scanning and processing tools. As these metrics are too specialized to be classified as general BIM tool-related metrics/criteria, the author has categorized metrics/criteria into two sets; (1) general tool-related metrics (Table 2) and (2) scanning and image-processing metrics (Table 3). For the general metrics, the themes emerged from data include direct time and cost-related metrics, maturity of BIM platforms, tools' functionality and accuracy, interoperability and information exchange, BIM objects/libraries, software attributes/qualities, and other software selection criteria such as transaction-related issues and indicators related to technology vendors. These emerged themes reveal the challenging areas of adopting new BIM technologies in the industry. The level of maturity in BIM tools addresses the coherence among BIM technologies and existing processes of an organization. Issues of interoperability and information exchange are the most important challenges in the current implementation of BIM developments (McCuen, Suermann, & Krogulecki, 2012). Regarding BIM objects and libraries, the number and quality of geometries and information in pre-loaded BIM objects must be assessed to facilitate selecting software packages and determine whether it is required to modify available objects or to develop in-house BIM libraries (Hjelseth, 2010). In regard to software vendors, the technical support, software version management, and future plans to support users and provide up-to-date packages, must all be addressed (Won &

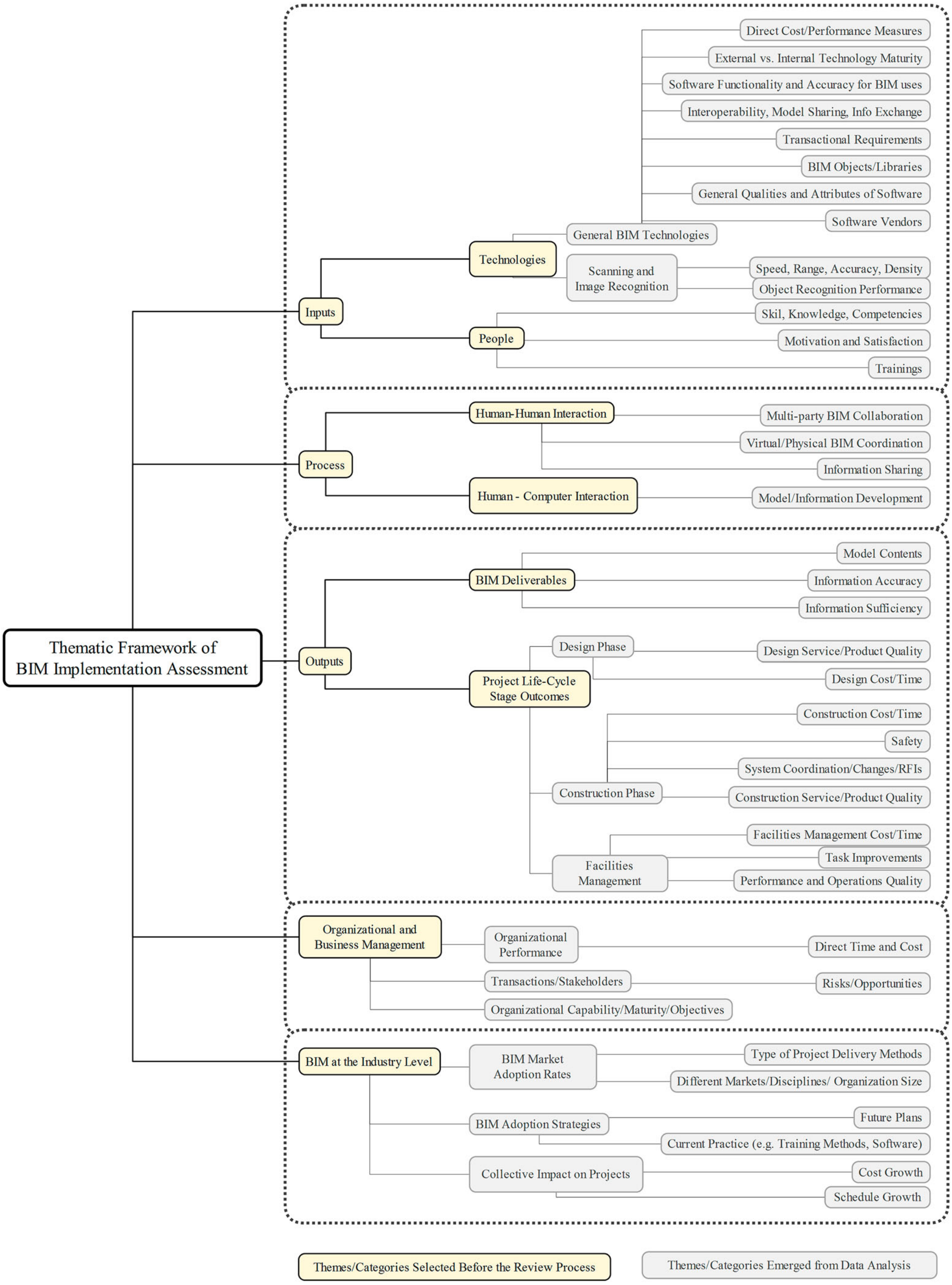


Figure 2. The thematic framework of BIM implementation assessment approaches.

Lee, 2010). For the scanners and image-recognition tools, two major themes are (1) performance of tools in scanning and registering information to a BIM model and (2) performance of algorithms (or tools) in recognizing objects within the scanned/registered information (Table 3). These two themes reveal the most important challenges of capturing and reusing models from existing facilities and infrastructure.

Table 2. Metrics/criteria for assessing BIM tools: general metrics.

Metrics/criteria for assessing BIM tools: general metrics	
Direct cost/time/performance	'Cost of software' (QT) (McGraw-Hill Construction, 2009); 'Cost of required hardware upgrades' (QT) (McGraw-Hill Construction, 2009); 'Ongoing costs of software and training' (QT) (McGraw-Hill Construction, 2009); 'Continuous investment' (C) (Won, Lee, Dossick, & Messner, 2013); 'Initial investment costs including hardware and software costs and training fees' (C) (Won et al., 2013); 'Technology Performance: Actual vs. Target' (QL) (Kam, Rinella, Mak, & Oldfield, 2012)
External maturity vs. internal maturity level	'Use of modelling software' as BIM Tools (C) (Sebastian & van Berlo, 2010); 'How well current BIM technologies can support area/service of interest' (QL) (Won et al., 2013); 'How well a software application currently supports services of interest' (C) (Won et al., 2013); 'Whether there are known successful BIM cases of the software application' (C) (Won et al., 2013); 'Whether software application is already in use in other departments' (C) (Won et al., 2013); 'Maturity in data delivery method' (QL) (National Institute of Building Sciences, 2007); 'Competency in technology sets in software, hardware and data/ networks' (QL) (Succar et al., 2012); 'Technological capability of organization' (C) (Mom, Tsai, & Hsieh, 2014); 'Robustness of BIM modeling operations and methods and its impact on the geometry and the embedded data' (C) (El Khaldi, 2011)
Software functionality and accuracy	'Type of software package' (C) (Sebastian & van Berlo, 2010); 'Accuracy of BIM developed energy analysis tools, compared to commercial products' (C) (Kim & Anderson, 2012); 'Accuracy of energy estimates of simulating software' (C) (Stadel, Eboli, Ryberg, Mitchell, & Spatari, 2011); 'Measure the level of detailing, interoperability, and integration' (QL) (Manzione, Wyse, Owen, & Melhado, 2011); 'How well a large model can be handled (scalability)' (C) (Won et al., 2013); 'Accuracy of tools and Ability to simulate Detailed and Complex building Components' (Attia, Hensen, Beltrán, & De Herde, 2011); 'Functionality' (C) (Mom et al., 2014); 'Validity of BIM simulations' (Energy) (QT) (Raheem, Issa, & Olbina, 2011); Integration with Building Design Process' (Attia et al., 2011); 'Tightness between BIM and 2D' (QL) (Kam et al., 2012); Accuracy and Thoroughness of VDC platforms (C) (Yee, Fischer, & Kam, 2013); 'Functionality' (C) (AGC of America, 2006)
Interoperability, model sharing and exchanges	'Application Interoperability' (QL) (Mom et al., 2014); 'Interoperability' (C) (Mom et al., 2014); 'How interoperable a software application is with other applications' (C) (Won et al., 2013); 'Interoperability of Building Modelling' (Attia et al., 2011); 'Maturity in interoperability/ IFC support' (QL) (National Institute of Building Sciences, 2007); 'Import and export efficiency indicators' (C) (London & Singh, 2012); 'Interoperability' (C) (El Khaldi, 2011); 'Software interoperability (import/export) efficiency' (QL) (CRC Construction Innovation, 2009); 'Improved Interoperability of Data' (C) (The Computer Integrated Construction Research Group, 2012); 'Support for collaboration: supporting the IFC open standards' (C) (El Khaldi, 2011); (Won et al., 2013); 'Functionality and success of IFC exchange' (implementation of the ATC IFCs for structural domain) (QL) (Dean, 2010); 'Reliability of modeling exchanges' (QL) (Kam et al., 2012); 'Model view definitions' (C) (Sebastian & van Berlo, 2010); 'Impeccable collaboration' (technological aspect) (C) (Kam et al., 2012); 'Collaboration management tools' (C) (Won et al., 2013); 'Level of support (recall) in a new BIM [object extraction] approach vs. conventional BIM' (QT) (Nepal, Staub-French, Pottinger, & Zhang, 2012); 'Up-to-date data exchange support' (C) (El Khaldi, 2011); 'Type of data exchange' (C) (Sebastian & van Berlo, 2010); 'Type of data in each project phase' (C) (Sebastian & van Berlo, 2010); 'File management: Extracting data from a central source, multi-user functionality – especially multi location scenarios' (C) (El Khaldi, 2011); 'Type and capacity of model server' (C) (Sebastian & van Berlo, 2010); 'Use of model server' (C) (Sebastian & van Berlo, 2010); 'Open ICT standards' (C) [53]; 'Supporting [exchange] rules' (C) (Sebastian & van Berlo, 2010); 'Interoperability of virtual mock-ups environments with BIM software' (QL) (Yang et al., 2013); Virtual mock-ups environments: 'Compatibility in accepting inputs in different formats' (QL) (Yang et al., 2013); Virtual mock-ups environments: 'Simplicity in converting a BIM to a navigational virtual mock-up' (QL) (Yang et al., 2013); 'Interoperability' (C) (AGC of America, 2006)
Transaction related	'Whether major subcontractors or business partners are currently using the software application' (C) (Won et al., 2013); 'Whether the use of the software application is required by contract' (C) (Won et al., 2013); '[Transactional] Environment' (C) (AGC of America, 2006).
BIM objects/libraries	'Availability of pre-defined objects' (C) (El Khaldi, 2011); 'Abundant BIM libraries' (C) (Won et al., 2013); 'Providing object libraries' (C) (Sebastian & van Berlo, 2010); 'How good content libraries are' (C) (Won et al., 2013); 'Maturity of the IT infrastructure library' (QL) (National Institute of Building Sciences, 2007); Virtual mock-ups environments: 'Availability of built-in libraries to display semantic information' (QL) (Yang et al., 2013); Accessing standard BIM Libraries (QL) (Specialist Engineering Contractors Group, 2013)

(*Continued*)

Table 2. Continued.

Metrics/criteria for assessing BIM tools: general metrics	
Software attributes/qualities	'Extendibility' (C) (El Khaldi, 2011); 'Ability to construct user-defined objects' (C) (El Khaldi, 2011); 'Ease of modeling and adding new libraries' (C) (Won et al., 2013); Virtual mock-ups environments: 'Extensibility through customized functions' (QL) (Yang et al., 2013); 'Portability' (C) (El Khaldi, 2011); 'Learning curve' (C) (El Khaldi, 2011); 'Learning curve' ('required time to adopt services')(QL) (Won et al., 2013); 'Application Security' (Mom et al., 2014); 'Speed of information system' (Grilo, Zutshi, Jardim-Goncalves, & Steiger-Garcao, 2012; Mom et al., 2014); 'Usability and Information Management of interface' (Attia et al., 2011); 'Integration of Intelligent design Knowledge-Base' (Attia et al., 2011); 'Tool performance: memory handling, model update times, and integrity of BIM data throughout the model life cycle' (C) (El Khaldi, 2011); 'Intelligent update' (C) (El Khaldi, 2011); 'Data integrity of BIM objects,' 'backups and archiving methods,' 'ownership and access rights control' (C) (El Khaldi, 2011); 'Knowledge Management support by BIM tools' (C) (El Khaldi, 2011); 'Support for manufacturing' (pre-fabrication) (C) (El Khaldi, 2011); 'Remaining up-to-date' (C) (El Khaldi, 2011); 'Simplicity' (C) (AGC of America, 2006)
Software vendors	'Technical support from suppliers' (C) (Mom et al., 2014); 'Availability of technical support and community' (C) (El Khaldi, 2011); 'Possibility of getting targeted BIM services in near future in association with software vendor's long-term strategy' (C) (Won et al., 2013); 'Providers Longevity' (C); 'Support/Training' by the provider (C) (AGC of America, 2006)

BIM users

Eastman et al. (2011) highlight that BIM users are error-prone by human nature, and they may be imperfect in their BIM-related skills. Actually, these challenges in skills, training, learning curves, and understanding of the processes and workflows are the most important barriers and concerns of professionals reluctant to adopt BIM (Ku & Taiebat, 2011; Specialist Engineering Contractors Group, 2013). For this reason, various human factors such as training, different skills, and attitudes should be considered and assessed in BIM adoption. This assessment of human factors must be continuous at both project and organizational levels in order to improve BIM capacities through time (Arayici et al., 2011). Identified metrics, contributing to assess BIM users, are presented in Table 4. Skills and knowledge to use BIM, training levels, and attitudes toward BIM are three major themes that emerged from the data.

BIM processing

BIM processing is about interactions of BIM users with each other and with BIM technologies. These interactions are the most important aspect in BIM processing, although they are often disregarded in BIM implementation. These issues consist of both human–computer interactions and human–human interactions. Both are important and subject to attention, because attempts to insert, extract, update, modify, and observe building information and models are mostly performed by BIM users (Deutsch, 2011). Furthermore, project success, in integrated design-construction practices, is dependent on tight collaboration of all project participants, and developing and maintaining collaboration requires continuous assessment using measurable indicators. Therefore, Eastman et al. (2011) indicate that essential factors such as collaboration, communications, workflows, and work processes should be assessed for the effective implementation of BIM. Findings in Table 5 present the metrics/criteria developed to assess human–computer and human–human interactions in BIM practices. Themes that emerged from data include performance in model/information development, sharing information/models, virtual /physical coordination, and multi-party BIM-based collaboration.

BIM outputs

BIM models

Models and information are important products of BIM as they support decision-making and project realization processes (Eastman et al., 2011). A poor-quality model negatively impacts project life-cycle

Table 3. Metrics/criteria for assessing BIM tools: scanning and image-recognition metrics.

Metrics/criteria for assessing BIM tools: scanning and image-recognition metrics	
Scanners and registration tools	'Time of creating 3D point cloud models' (QT) (Bae, Golparvar-Fard, & White, 2013); 'LOA: level of accuracy (positioning error) in laser-scanned point clouds' (QT) (Tang & Alaswad, 2012); 'LOD [level of details] in laser-scanned point clouds' (QT) (Tang & Alaswad, 2012); 'Data richness' – 'Point cloud precision & density' (QT) (Canter, Chumbley, Morrison, & Stenning, 2009); 'Percentage of un-scanned area(s)' .e.g. inaccessible areas (QT) (Canter et al., 2009); 'scanned as-built post processing time' (Jung et al., 2014); 'time and accuracy of scanning devices' (laser-scanning, total-station, photogrammetry, etc.) (QT) (Lagüela, Díaz-Vilariño, Martínez, & Armesto, 2013); 'point registration speed' (QT); 'point registration accuracy: the final number of points matched to the 3D model and the root mean square error of the distances of those points to the 3D model' (QT) (Bosché, 2012); 'The accuracy and precision (Density – Distance) of laser-scanning process' (QT) (Randall, 2011); 'laser-scanning equipment selection criteria include the range accuracy, useful range (QT), field of view (QT), resolution (QT), scanning speed (QT), and geo-referencing and registration methodologies used for combining multiple scans within a common coordinate system' (QT) (Randall, 2011); 'Automation of spatial data retrieval' (QL); 'spatial data accuracy' (QT); 'spatial data resolution: measured using the number of retrieved 3D points' (QT); 'equipment cost' (QT); 'equipment portability' (C); 'spatial data speed: measured using the capability to retrieve the data real time' (QT); 'range distance' (QT); 'operation time: whether the equipment is dependent on day light for operation' (QT) (Bhatla, Choe, Fierro, & Leite, 2012); 'Measurement errors: a) location errors (QT) and b) orientation errors in spatial data processing' (QT) (Tang & Pradhan, 2012); 'Registration accuracy and efficiency' (QT) (Bosché, 2010); 'Camera data geo-referencing precision' (QT) (Canter et al., 2009); 'Using photographs for localization in an augmented reality': 'Accuracy of the localization method' (QT) (Bae et al., 2013); Recognition performance for site laser scans: 'Specificity: the number of properly not recognized model objects divided by the total number of model objects that are not in the investigated scan' (QT) (Bosche, Haas, & Akinci, 2009); 'Localization error: the distance between the estimated location and the actual location' (QT) (Akanmu, Rasheed, & Qader, 2013)
Image and object recognition algorithms (tools)	'Surface based recognition metric': 'percentage of recognition of objects in 3D laser scanned point clouds' (QT) (Turkan, Bosché, Haas, & Haas, 2013); 'Running time of an algorithm': 'is evaluated based on the size of its inputs in spatial data processing' (QT) (Tang & Pradhan, 2012); 'Percentage of recognized surfaces / recognizable surfaces' (QT) (Turkan, Bosché, Haas, & Haas, 2014); 'Precision (reliability of the detection)' (QT); 'time delay of detection in construction worker detection in video frames' (QT) (Park & Brilakis, 2012); 'Percentage of correctly identified planes and the accuracy in locating boundary lines in a videogrammetric as-built data collection method' (QT) (Fathi & Brilakis, 2013); 'Range point matching metric' (ΔRange compared to the threshold) (QT); 'Object recognition metric' (retrieval metric) (QT) (Bosche & Haas, 2008a, 2008b) Object recognition performance: 'Recall is the percentage of 3D elements present in the scan(s) that are actually recognized (QT); "Precision is the percentage of recognized 3D elements that are actually in the scan(s)' (QT) (Turkan, Bosche, Haas, & Haas, 2012); 'Ability to use low-resolution images (in assessing project progress by using daily site photographs)' (QT) (Golparvar-Fard, Peña-Mora, & Savarese, 2011); 'Accuracy in recognizing of the 4D IFC model over the point-cloud model' (QT) (Golparvar-Fard et al., 2011); 'Recall: The fraction of truly recognized model elements relevant to the total number of model elements that are used for the detection model' (QT) (Bosche et al., 2009; Golparvar-Fard, Peña-Mora, & Savarese, 2015; Nepal, Staub-French, Pottinger, & Webster, 2012); 'Precision: The fraction of relevant model elements relevant to the total number of model elements that are recognized' (QT) (Bosche et al., 2009; Golparvar-Fard et al., 2015; Nepal et al., 2012)

stages – from conception to construction – and product life-cycle stages – from operation to renovation or disposal of a facility (Crotty, 2012). Although developing grounds for model assessment is not well documented in the literature, efforts to identify information exchange requirements have been addressed in Industry Foundation Classes (IFC) implementations (Hietanen & Final, 2008). For example, developing Information Delivery Manuals (IDM) and Model View Definitions (MDV) in the past several years (for information handover, special trade exchanges, etc.) was a momentum to accurately define required information in product models and set a basis for developing and assessing BIM models (East, 2007; Eastman, Jeong, Sacks, & Kaner, 2010; Teicholz, 2013). However, the challenges to assess models with MVDs–IDMs are still significant due to the insufficient level of

Table 4. Metrics/criteria for assessing BIM users.

Metrics/criteria for assessing BIM users
'Employee skills and knowledge development' (QL) (Coates et al., 2010); 'How well current employees can use BIM services' (C) (Won et al., 2013); 'BIM acceptance among the staff and workers' (QL) (Sebastian & van Berlo, 2010); 'Individual satisfaction' of BIM users (QL) (Kam et al., 2012); 'BIM training programs' (C) (Building and Construction Authority, 2013; Won et al., 2013); 'Group and individual motivation to use BIM' (QL) (Sebastian & van Berlo, 2010); 'Resistance factors' to use BIM (C) (Kam et al., 2012); 'Presence and influence of the BIM coordinator' (C) (Sebastian & van Berlo, 2010); 'Initial cost of staff training' (QT) (McGraw-Hill Construction, 2009); 'Number of BIM software experts in company' (QT) (Won et al., 2013); 'Training Effectiveness' (QL) (Sebastian & van Berlo, 2010); 'Level of BIM Training' (QL) (McGraw-Hill Construction, 2009); 'Use of different BIM training methods by experience level' (C) (McGraw-Hill Construction, 2009); 'Number of Trained Staff' (QT); 'Skill Level' (Knowledge, Years of Experience, Certification) (QL) (Building and Construction Authority, 2013); 'Human capability/resources' (C); 'Training' (C) (Mom et al., 2014); How well current employees use the software application (C) (Won et al., 2013)

support from the BIM software developers, validation issues, and limited adoption by industry participants (Katranuschkov, Weise, Windisch, Fuchs, & Scherer, 2010). Metrics/criteria developed for assessing BIM models are presented in Table 6.

BIM performance at project life-cycle stages

Goals and objectives of BIM are the same as those of the industry: improving productivity (cost and time), reducing waste, and enhancing functionality in different life-cycle stages of a project. These goals can be realized in three major life-cycle stages, including design, construction, and facility operations and management phases (Roper & Borello, 2013; Succar, 2009). Although one can define more detailed project stages like conceptual design, detailed design, and tendering stages (Kelly, Male, & Graham, 2008), most of the extracted metrics do not reflect any information about more detailed project stages. As all metrics/criteria synthesized in this section are lag indicators of BIM outcomes, themes that emerged from data include productivity-related (time and cost) and quality-related metrics in each phase.

As presented in Table 7, metrics used for assessing design outcomes are categorized into (1) time and cost and (2) service/product quality metrics. BIM goals in design stages should be realized in different design processes, such as design analysis, design review, and production of design deliverable (Betts, 1999). Table 7 shows that metrics/criteria for assessing design service/products are mostly developed to assess design errors, rather than evaluating intangible and qualitative aspects of design services.

For the construction phase, as presented in Table 8, metrics are categorized into (1) construction time and cost metrics, (2) scope changes, RFIs, and coordination issues, (3) safety, and (4) construction quality. BIM in the construction stage may impact both core construction processes (e.g. build-up, installation, and fabrication), and supporting construction processes (e.g. risk assessment, project planning, and procurement management) (Hua, 2013). Considering construction-specific BIM uses such as 4D simulation, constructability analysis (detecting hard and soft clashes), resource planning and allocation, as-built quality assessment, and prefabricating building components can improve productivity and quality and reduce waste (Akintoye, Goulding, & Zawdie, 2012; Eastman et al., 2011; Hua, 2013). Many practitioners have analyzed the impact of these BIM uses in assessing their BIM practice.

For facility operations and management, metrics/criteria and categories in Table 9 include (1) facility management time and cost metrics, (2) facility performance, and (3) quality of facility management tasks. Generally, integrating facility management tasks (e.g. inspection, maintenance, repair, renovation, etc.) with BIM application provides several advantages to owners, including higher accuracy of data, lower costs of data capturing and data use, faster and preventive situation awareness, more user-friendly asset-management platforms, and integrating building management systems with BIM. Such advantages all could result in higher productivity, reduced waste, and enhanced facility operations (Teicholz, 2013).

Table 5. Metrics/ criteria for assessing BIM processing.

Metrics/criteria for assessing BIM processing	
Model/information development	'Speed of model development' (QT) (Coates et al., 2010); 'Amount of reworks on models' (QT) (Keavney, Mitchell, & Munn, 2013; Manzione, Wyse, Sacks, et al., 2011); 'Actions of a BIM user over time' (rate of information transfer) (QT) (Manzione, Wyse, Sacks, et al., 2011); 'Number of BIM users vs. Week Numbers of project' (QT) (Kam et al., 2012); 'BIM planning performance: Actual vs. Target (QL) (Kam et al., 2012); "Productivity improvement of personnel' (QL) (McGraw-Hill Construction, 2009); 'Amount of contribution by each actor in developing the model' (QL) (Manzione, Wyse, Owen, et al., 2011); 'How much information is associated to team members as authors of the model' (QT) (Manzione, Wyse, Owen, et al., 2011); 'Measure the number of updates made in the central model from the several designers' (Manzione, Wyse, Owen, et al., 2011); Man-hours required to complete a specific BIM task (e.g. 'estimation via different BIM approaches' (QT) (Nassar, 2011); 'Accuracy of the various modeling methods' (cost estimation) (QT) (Nassar, 2011); 'Ratio of estimating cost to project cost by modeling method' (cost-effectiveness of BIM approach) (QT) (Nassar, 2011); 'Duration of updating information in the BIM to serve as electronic deliverable to owner' (QT) (Vaughan, Leming, Liu, & Jaselskis, 2012); 'Hours of design documentation and modeling' (QT) (Chen, Dib, & Lasker, 2011); 'Duration (QT), time-frame (QL), and frequency of BIM use' (QT) (Cerovsek, 2011); 'Action rate' (Actions/Time) (QT) (Demian & Walters, 2014); 'Revision rate' (Revisions/Time) (Demian & Walters, 2014); 'Dynamic documentation' (C) (Espinal & Saluja, 2010); 'Increasing Remote Working' (QT) (Specialist Engineering Contractors Group, 2013); 'Number of activities, resources used for results' (QT) (Cerovsek, 2011); 'Time Efficiency' and 'Accuracy' of BIM-assisted cost estimation (QT) (Shen & Issa, 2010); ' Efficiency of processes using new BIM-based plugins (QL) (Dore & Murphy, 2014); "Reduced human error' (C); 'Reduced Data Entry Time' (C) (The Computer Integrated Construction Research Group, 2012); 'Number of activities, objects and linkages, time spent to do the 4D model' (QT) (U.S. General Services Administration, 2009)
Information sharing	'Speed with which information is transferred to the project team' (QL) (Manzione, Wyse, Sacks, et al., 2011); 'Possible bottleneck partners in the process at any given time' (QL) (Manzione, Wyse, Sacks, et al., 2011); 'Level of information sharing within a process' (QL) (Demian & Walters, 2014); 'Effectiveness of information flows' (C) (Demian & Walters, 2014; Mom et al., 2014); Defining 'Information sharing/communication protocol' (C) (Demian & Walters, 2014); 'Information-sharing protocols' (C) (Won et al., 2013); Batching (The average number of packages transferred simultaneously') (QT) (Demian & Walters, 2014); 'Systems utilization' ('Proportion of packages transferred through each information system) (QT) (Demian & Walters, 2014); "Information inventory' ('The number of available but unused information packages') (QT) (Demian & Walters, 2014); 'Information iteration' ('Proportion of revised information') (QT) (Demian & Walters, 2014); 'Number of available but unused information packages' (QT) (Manzione, Wyse, Sacks, et al., 2011); 'Number of "physical/virtual locations'" or models' (information-sharing venues) (QT); 'Granularity and volume of exchange' (QT) (Cerovsek, 2011); 'Rates of improving the level of details in transferred information' (QT) (Manzione, Wyse, Sacks, et al., 2011); 'Amount of information in each transmission' (QT) (Manzione, Wyse, Sacks, et al., 2011); Internal and External information flow (C) (Sebastian & van Berlo, 2010); 'Centralization of information' (C) (The Computer Integrated Construction Research Group, 2012)
Virtual/physical coordination	'Commitment Reliability' ('Number of BIM clashes resolved on time/planned to be resolved') (QT) (Kam et al., 2012); Effects of the big room on work productivity and coordinating meetings (QL) (Espinal & Saluja, 2010); Meeting frequency (QT) (Espinal & Saluja, 2010); Meeting Effectiveness (QL) (Kam et al., 2012); Number of expressions of confusion (QT) (Senescu et al., 2013); 'Number of statements about design trends' (QT) (Senescu et al., 2013); 'Number of local iterations' (QT) (Senescu et al., 2013); 'Frequency of value-adding information transfer between designers' (QT) (Senescu et al., 2013); 'Time required to gain insight' (QT) (Senescu et al., 2013); 'Better communication because of 3D visualization' (QL) (McGraw-Hill Construction, 2009); 'Assessing model systems and verify if they were accessed and/or created by more than one actor' (C) (Manzione, Wyse, Owen, et al., 2011); 'Number of errors made implementing a shared process' (QT) (Senescu et al., 2013); 'Number of interventions made to the interactions and model development' (QT) (Love et al., 2011); 'Number of commentaries or suggestions given to partners during the process' (QT) (Manzione, Wyse, Owen, et al., 2011); 'Productivity of parallel coordination vs. Sequential cascading coordination' (QT) (Lee & Kim, 2014) 'Feedback loop for process improvement' (C) (Demian & Walters, 2014); 'Number of model uses during decision making meetings' (QT) (Kam et al., 2012)

(*Continued*)

Table 5. Continued.

Metrics/criteria for assessing BIM processing	
Multi-party Collaboration	'Team collaboration' (QL) (Kam et al., 2012); 'Leadership of senior management' (C) (Won et al., 2013); 'Willingness to share information among project participants' (C) (Won et al., 2013); 'Standardized work procedures for BIM' (C) (Won et al., 2013); 'Whether subcontractors can support services' (collaboration issues) (C) (Won et al., 2013); 'Percentage of dependencies captured among team members' (QT) (Senescu et al., 2013); 'Staff Buy-In' (C) (McGraw-Hill Construction, 2009); 'Effective collaboration among project participants' (QL) (Won et al., 2013); 'Organizational structure to support BIM' (C) (Won et al., 2013); 'Master BIM model team/manager' (C) (Won et al., 2013); 'Maturity of roles or disciplines' (QL) (National Institute of Building Sciences, 2007); 'Size of group' (QT) and 'Number of relationships' (QT) (Cerovsek, 2011); 'Number of actors, professional roles, and teams' (QT) (Cerovsek, 2011); 'Number of communication channels and capacity' (QT) (Cerovsek, 2011); 'Increased collaboration by project sponsor and project teams' (QT) (Strategic Forum for the Australasian Building and Construction Industry, 2014).

Table 6. Metrics/criteria for assessing BIM models.

Metrics/Criteria for Assessing BIM Models
'Quality of information and model for BIM information handover' (QL) (Fallon & Palmer, 2007); Model 'Conformance to BIM Execution Plan' and BIM Agreement (C) (Kam et al., 2012); 'Maturity in [model] information accuracy' (C) (National Institute of Building Sciences, 2007); 'Flexibility; Completeness; Generality; Correctness in reference models of existing buildings' (QL) (Dino & Stouffs, 2014); 'As-built quality for handover and managing a facility' (QL) (El Asmar & Francom, 2013); 'Improved quality of information' (C) (The Computer Integrated Construction Research Group, 2012)

Table 7. Metrics/criteria for assessing BIM performance in the design phase.

Metrics/criteria for assessing BIM performance in the design phase	
Design cost – time metrics	'Design phase man-hours' (QT) (Keavney et al., 2013); 'On-time completions in design phase' (QT) (Keavney et al., 2013); 'Reduced costs of travel, printing, document shipping' (QT) (Coates et al., 2010); 'Architecture & Engineering [services] costs' (QT) (Barlish & Sullivan, 2012); '3D background model creator costs' (e.g. 'laser scanning,' '3D block creation,' etc.) (QT) (Barlish & Sullivan, 2012); 'Design duration' (QT) (Espinal & Saluja, 2010; Kam et al., 2012); 'Design Productivity (duration/$ scope of work)' (QT) (Kam et al., 2012); 'Number of staff compared to traditional CADD projects' (QT) (Espinal & Saluja, 2010); 'Duration of construction documentation phase' (QT) (Espinal & Saluja, 2010); 'Planning-stage savings' (QT) (McGraw-Hill Construction, 2009); 'Measure how long it would take to complete a design phase or determine definitions between several disciplines' (QT) (Manzione, Wyse, Owen, et al., 2011); 'Cost of detailing services' (QT) (Clevenger & Khan, 2014) 'Reduction in the hours required for drawing production' (QT) (Love, Lopez, & Kim, 2013); 'Reconciliation of savings from Designer using BIM' (QT) (Barlish, 2011); 'Reducing drawings' (QT) (Specialist Engineering Contractors Group, 2013); 'Planning and Design Time' (QT); 'Design Costs' (QT) (U.S. General Services Administration, 2007)
Design service/product quality	'A better design product' (QL) (Coates et al., 2010); 'Innovation' (QL) (Kam et al., 2012); 'Number of design variation studies' (QT) (Espinal & Saluja, 2010); Number of complete and accurate design options (QT) (Senescu et al., 2013); 'Maturity in graphical information' (QL) (National Institute of Building Sciences, 2007); 'Reduction in number of design errors' (QT) (Love et al., 2013); 'Occurrences of errors by work type and detailed cause' ('illogical design, discrepancies, and missing items' in different trades) (QT) (Lee & Kim, 2012); Geometry Control: 'nonconforming geometry changes that are introduced by downstream participants' due to forces/actions initiated by interdisciplinary collaborators and/or miscommunication and misunderstanding (C) (Ku & Pollalis, 2009); 'number of clashes found in the design stage' vs. 'typical number of clashes found in the design stage on other similar projects' (QT); 'Number of errors and omissions' (QT) (U.S. General Services Administration, 2007)

BIM performance at the organizational level

Although BIM processes are spread out across different project stages, their cumulative impact on a business is subject to assessment. The business aspect of BIM focuses on higher-order goals of a firm and the collective value of BIM in a business. However, this is tightly integrated with business strategies and transactions. In this regard, Fox and Hietanen (2007) indicate that BIM is adopted in two

Table 8. Metrics/criteria for assessing BIM performance in the construction phase.

Metrics/criteria for assessing BIM performance in the construction phase	
Direct time-cost-related metrics	'Construction idle time' (QT) (Chelson, 2010); 'Cost of rework' (QT) (Boktor, Hanna, & Menassa, 2013; Chelson, 2010; Hanna, Boodai, & El Asmar, 2013) 'Planning effectiveness ($ field rework due to coordination errors)' (QT) (Kam et al., 2012); 'Cost of RFIs' (QT) (Chelson, 2010); 'Number and cost of change orders' (QT) (Chelson, 2010; Eadie, Browne, Odeyinka, McKeown, & McNiff, 2013; Giel & Issa, 2013); 'Change orders as a percent of standard costs' (QT) (Barlish, 2011; Hanna et al., 2013); 'Budget Variance' (QT) (Chelson, 2010); 'Schedule Compliance' (QT) (Chelson, 2010); 'Schedule conformance: percent of milestones that hit scheduled' (QT) (Kam et al., 2012); 'Owner controlled insurance program headcount dollar savings percent off site hours' (QT) (Barlish, 2011); 'Reconciliations of savings from Contractors using BIM' (QT) (Barlish, 2011); 'Actual durations as a percent of standard duration' (QT) (Barlish, 2011); 'Contractor costs' (QT) (Barlish & Sullivan, 2012); 'Cost Performance Predictability' (QL) (Kam et al., 2012); 'Ability to secure plan approval and construction permits faster' (QL) (McGraw-Hill Construction, 2009); 'Construction team time savings' (QT) (McGraw-Hill Construction, 2009); 'Direct collision-detection cost-avoidance savings' (QT) (McGraw-Hill Construction, 2009) 'Avoidance log and associated costs' (QT) (Barlish, 2011); 'Construction Schedule Growth' (QT) (El Asmar & Francom, 2013); 'Warranty Costs' (QT) (El Asmar & Francom, 2013); 'Material waste' (QT) (Clevenger & Khan, 2014); 'Material efficiency' (Hanna et al., 2013); 'Sustainability' (construction waste) (El Asmar & Francom, 2013); 'Reduction in cost of as-built drawings' (QT) (Boktor et al., 2013; Hanna et al., 2013); 'Comparison of Work Packages (work-hours)' (in using BIM based-structural quick connection systems) (QT) (Shan, Goodrum, Haas, & Caldas, 2012); 'Labor productivity' (QT) (Hanna et al., 2013); 'Production time of BIM based fabricated panel' (QT) (Lee & Kim, 2012); 'Cost per BIM based [prefabricated] panel' (QT) (Lee & Kim, 2012); 'Trim-Loss Waste Produced in Structural Models' (QT) (Porwal & Hewage, 2011); 'Rework Cost Factor' (QT) (Kang et al., 2012); 'Rework time' (impact of using Augmented Reality) (QT) (Hou, Wang, & Truijens, 2013); 'Payment to assemblers' (impact of using Augmented Reality) (QT) (Hou et al., 2013); 'Cost on correcting erroneous assembly' (impact of using Augmented Reality) (QT) (Hou et al., 2013); 'Savings in construction contract value' (QT); 'Percentage of elimination of unbudgeted change' (QT); 'Reduction in the time taken to generate a cost estimate estimation with accuracy within 3&per;' (QT) (Love et al., 2013) 'Person's hour worked' (QT) (Eadie et al., 2013) 'Impact of prefabrication' on cost and time: 'Acceleration in construction start time' (QT); 'Acceleration in construction, delivery and installation' (QT); 'Material cost savings' (QT); 'Worker productivity' (QT); 'Labor savings' (QT); 'Waste reduction' (QT) (Fishking, 2011); 'Offsite prefabrication man-hours' (QT) (Barlish, 2011); 'Avoiding costly rework' (QT) (Specialist Engineering Contractors Group, 2013); 'Construction Cost' (QT); 'Construction Duration' (QT) (U.S. General Services Administration, 2007); Construction Productivity Improvement (C) (AGC of America, 2006); 'Reduced Project Delays' (QT); 'Reduced rework' (QT) (Strategic Forum for the Australasian Building and Construction Industry, 2014); 'Time saved on project' as a result of 4D simulation (QT); 'Budget for 4D model' (QT) (U.S. General Services Administration, 2009)
System coordination/changes/ RFIs/scope	'Better system coordination' (QL) (Hanna et al., 2013); 'Number of RFIs' (QT) (Clevenger & Khan, 2014; Eadie et al., 2013; El Asmar & Francom, 2013; Espinal & Saluja, 2010; Giel & Issa, 2013; Hanna et al., 2013; Keavney et al., 2013; McGraw-Hill Construction, 2009; The Construction Users Roundtable, 2010); 'RFI quantities in 2D versus 3D' (QT) (Barlish, 2011); 'Number of Days (Ave) response latency of RFIs' (QT) (Kam et al., 2012); 'RFI Processing Time' (QT) (El Asmar & Francom, 2013); 'Processing time for change orders' (QT) (El Asmar & Francom, 2013; Hanna et al., 2013); 'Percentage spent on change orders relative to coordination errors' (QT) (McGraw-Hill Construction, 2009); 'Scope Creep' (QL) (Chelson, 2010); 'Number of punch-list items' (QT) (Hanna et al., 2013; Kam et al., 2012); 'Reduction in field conflicts' (Boktor et al., 2013; Hanna et al., 2013); 'System coordination' (QL) (Boktor et al., 2013); 'Reduction in resubmittals' (QT) (Hanna et al., 2013); 'Frequency of as-Built updates' (QT) (Rohena, 2011); 'Reducing Clashes' (QT) (Specialist Engineering Contractors Group, 2013); 'Number of RFIs vs. $ change directives ratio' (QT) (Kam et al., 2012); 'Number of Change Orders' (QT) (U.S. General Services Administration, 2007); 'Fewer field conflicts' (C); Reduced RFIs (C) (AGC of America, 2006); 'Fewer requests for information' (QT); 'Less Unplanned Changes' (QT); 'Reduces Errors and Omissions' (QT) (Strategic Forum for the Australasian Building and Construction Industry, 2014); 'Number of coordination detection' (QT); 'Number of Revisions' (QT) (U.S. General Services Administration, 2009)
Safety related	'Safety performance' (QT) (Chelson, 2010; El Asmar & Francom, 2013); 'Improved Safety' (QL) (The Construction Users Roundtable, 2010); 'Safety: Lost hour/job' (QT) (Kam et al., 2012); 'Impact of Prefabrication on workers safety' (QT) (Fishking, 2011); 'Reducing health and safety risks' (QT) (Specialist Engineering Contractors Group, 2013)

(*Continued*)

Table 8. Continued.

Metrics/criteria for assessing BIM performance in the construction phase	
Construction services/product quality	'Project Collective Quality' (QL) (Kam et al., 2012); 'Reduction in deficiency issues' (QT) (Boktor et al., 2013; Hanna et al., 2013); 'Percent built as designed' (QT) (Bosché, Guillemet, Turkan, Haas, & Haas, 2014); 'Level of confidence in accuracy of construction' (QT) (Bosché et al., 2014); 'Number of assembly errors' (impact of using Augmented Reality) (QT) (Hou et al., 2013); 'Number of deviating components for each type of deviation' (Point Clouds vs. Building Information Models) (QT) (Eybpoosh, Akinci, & Bergés, 2012); Built quality: 'Range of location deviation among as-built and designed components' (QT) (Liu, Eybpoosh, & Akinci, 2012); Built quality: 'Distance between the cloud points in the scanned data and their pairs in BIM' (QT) (Eybpoosh et al., 2012); Impact of prefabrication on quality: 'build quality improvement' (QL) (Fishking, 2011); 'Material measurement accuracy' (QT) (Keavney et al., 2013); 'Improvements in calculating quantities and other metrics directly from 4D models' (QT) (Kamat et al., 2010); 'Percentage and absolute difference between dimensions from the existing as-built documentation and the field survey' (QT) (Klein, Li, & Becerik-Gerber, 2011); 'The option to use more prefabricated elements' (QL) (Keavney et al., 2013); 'Prefabrication' (C) (Kam et al., 2012); 'Speed of Shop Drawing Development' (C); 'Accurate as-built drawings' (C); 'Increased Pre-fabrication' (C) (AGC of America, 2006)

Table 9. Metrics/criteria for assessing BIM performance in the facility management phase.

Metrics/criteria for assessing BIM performance in the facility management phase	
Direct cost-time metric	'Saving time by gathering work order information from the model' (maintenance personnel) (QT) (Jordani, 2010); 'Savings related to better building performance' (QT) (McGraw-Hill Construction, 2009); 'Cost of the effort involved in data exchanges' (in the information handover) (QT) (Fallon & Palmer, 2007); 'Efficiency of participants in terms of how long it took them to complete the tasks within given scenario settings (Yang & Ergan, 2014); "Operation Cost' (QT); 'Maintenance Cost' (QT) (U.S. General Services Administration, 2007)
Facility performance/operation quality	Impact of BIM on 'Facility Performance' (QT) (Kam et al., 2012); Impact on 'Building Function' (QT) (Corry, Keane, O'Donnell, & Costa, 2011); 'Sustainability outcomes' (QT) (The Construction Users Roundtable, 2010); 'Latent defects' (QL) (El Asmar & Francom, 2013)
Facility management tasks	Accuracy of completed tasks in terms of whether participants completed them correctly or not (QT) (Yang & Ergan, 2014); Participants' subjective preferences in using facility visualization techniques (QL) (Yang & Ergan, 2014)

interacting spectra of BIM adoption; (1) BIM in one organization only or in multiple interacting organizations and (2) BIM in one domain only or in multiple domains. These business decisions of BIM adoption are significantly dependent on construction clients' strategies over BIM (Porwal & Hewage, 2013). For this reason, at the business level, BIM implementers have to deal with variety of transactions that impact the organizational performance. At the business level, it is assumed that BIM should be adopted for multiple projects and for a longer timeframe than a single phase or a single project. Otherwise, using BIM assessment metrics/criteria may not reflect the overall business performance and the interpretation of assessments should be limited to project life-cycle stages. Table 10 presents metrics and criteria developed for assessing BIM performance at organizational and the business levels. Themes that emerged from data include direct time and cost-related metrics, transactions and stakeholders-related metrics, and organizational maturity and capabilities criteria.

BIM performance at the industry level

Finally, another aspect of BIM is the external environment of BIM practices (Mom & Hsieh, 2012), and the industry, in which BIM adoption could be assessed for benchmarking. This is important because as Azhar (2011) stated, BIM adoption rate is expected to grow, and therefore, analyzing industry trends provides benchmarks that help BIM implementers set organizational strategies and directions. Metrics/criteria that reflect trends in the industry are presented in Table 11.

Table 10. Metrics/criteria for assessing BIM implementation in a business/organization.

Metrics/criteria for assessing BIM implementation at the organizational/business level of a firm	
Direct time and cost	'Actual total project cost' (QT) (Maldovan & McCuen, 2010); 'IT investment per unit of revenue' (QT) (Coates et al., 2010); 'Investment cost for BIM' (C) (Mom et al., 2014); 'BIM Rate of Interest' (QT) (Giel & Issa, 2013; Kam et al., 2012; McGraw-Hill Construction, 2009); 'Revenue per head' (QT) (Coates et al., 2010); 'Impact of BIM on cash-flow' (QT) (Coates et al., 2010); 'Delivery schedule growth' (QT) (El Asmar & Francom, 2013); 'Expected economic impact by adopting BIM services' (QL) (Won et al., 2013); 'Actual BIM ROI' (vs. Perceived BIM ROI) (QT) (Lee, Park, & Won, 2012); 'VDC [Virtual Design and Construction] staff overhead or the cost of BIM that was charged to the [BIM] job' (QT) (Giel & Issa, 2013); 'Overall savings with BIM' (QL) (Barlish & Sullivan, 2012); 'Faster delivery – meeting deadlines' (QL) (Espinal & Saluja, 2010); 'Improved project outcomes such as lower cost and shorter duration for project execution' (QT) (The Computer Integrated Construction Research Group, 2012); 'Overall project's duration and budget in comparison to similar projects' (QT) (U.S. General Services Administration, 2009)
Transactions/stakeholders	'Incentive programs for using BIM' (C) (Won et al., 2013); 'External incentives or directives to use BIM' (C) (McGraw-Hill Construction, 2009); 'Client interest in/request for BIM' (QL) (Won et al., 2013); 'Bids won' or 'win percentage' in BIM-enabled projects (QT) (Coates et al., 2010; McGraw-Hill Construction, 2009); 'Outsourcing of BIM Work' (C) (McGraw-Hill Construction, 2009); 'Client satisfaction level on BIM projects' (QL) (Won et al., 2013); 'Number of subcontractors/partners experienced with BIM projects' (QT) (Won et al., 2013); 'Ability to win BIM project contracts' (QL) (Building and Construction Authority, 2013); 'Risk of losing intellectual property' and 'Risk of liability issues' (QL) (McGraw-Hill Construction, 2009); 'Shared liability among partners' (C) (Won et al., 2013); 'Client satisfaction and retention' (QL) (Coates et al., 2010); 'Stakeholder satisfaction' (QL) (Kam et al., 2012); 'Owner willingness to pay extra For BIM' (C) (McGraw-Hill Construction, 2009); 'Helpfulness of model sharing among participants' (QL) (Espinal & Saluja, 2010); 'stakeholder's satisfaction' (QL) (U.S. General Services Administration, 2009)
Internal capability/ maturity/ objectives	'Frequency of different BIM categories uses' in a firm (QT) (Kreider, Messner, & Dubler, 2010; Maldovan & McCuen, 2010); 'Level of value BIM generates for [different] project activities' (QL) (Hanna et al., 2013); 'Frequency of modeling elements [in different domains] with BIM' (QT) (McGraw-Hill Construction, 2009); 'Whether service can be adopted without conflicts with traditional work process' (C) (Won et al., 2013); 'BIM project experiences' (C) (Mom et al., 2014); 'Use of metrics for quantitatively evaluating effectiveness of BIM projects' (C) (Won et al., 2013); 'Competency in policy sets in benchmarks, controls, contracts, agreements and guidance supervision' (QL) (Succar et al., 2012); 'BIM Maturity levels: The quality, repeatability and degree of excellence within a BIM capability' (QL) (Succar et al., 2012); 'BIM capability: ability to perform a task or deliver a BIM service/product at different stages of object-based modelling, model-based collaboration and network-based integration' (QL) (Succar et al., 2012); 'Maturity in timeliness/ response of BIM use' (QL) (National Institute of Building Sciences, 2007); 'Maturity of integration in business processes' (QL) (National Institute of Building Sciences, 2007); 'Score of [BIM] projects selected to imitate' (as benchmarks) (QL) (Senescu et al., 2013); 'Maturity in lifecycle views of BIM use' (QL) (National Institute of Building Sciences, 2007); 'Extent of project stages conducted in BIM' (QL) (Building and Construction Authority, 2013); 'Whether [BIM] service is required by company's business strategy' (C) (Won et al., 2013); 'Integrating IPD and BIM [in] domestic projects' (C) (Kam et al., 2012); 'Integrating IPD and BIM globally' (C) (Kam et al., 2012); 'Organizational competency in process sets in activities/ workflows, products/services, and leadership/management' (QL) (Succar et al., 2012); 'Organizational learning capability' (C) (Demian & Walters, 2014); 'Innovation capability' (C) (Demian & Walters, 2014); 'BIM Adoption Performance: Actual vs. Target' (QL) (Kam et al., 2012)

Discussions

The findings showed that more than 420 metrics/criteria are developed in prior research to assess different BIM implementation dimensions. Themes that emerged from data highlighted the areas wherein there is consistency among metrics and criteria in terms of assessment aspects (Figure 2). These themes show that BIM implementers seek to mitigate the most important challenges of the AEC industry, that are, low productivity (cost and time), waste, and poor functionality. Therefore, there is a tendency among practitioners and researchers to promote fundamental concepts of lean thinking, including value, waste, and creating value without waste, in current assessment approaches (Oppenheim, 2011). Nevertheless, the findings show that there is overlap among more than 100 metrics/criteria that directly measure cost and schedule performance as lag indicators of

Table 11. Metrics/ criteria for assessing BIM adoption in the industry.

Metrics/criteria for assessing BIM adoption in the industry
'Percentage of projects with schedule growth' (QT) (Suermann & Issa, 2009); 'Percentage of projects with cost growth' (QT) (Suermann & Issa, 2009); 'Percentage of projects with construction timeline growth' (QT) (Suermann & Issa, 2009); 'Types of project delivery method that used BIM' (QT) (Maldovan & McCuen, 2010); 'Impact of BIM by staff experience level' (positive, neutral, negative) (QL) (McGraw-Hill Construction, 2009); 'Growth in BIM use on projects' (QT) (McGraw-Hill Construction, 2009); 'Awareness of BIM-Related Tools' (platforms and software) (QL) (McGraw-Hill Construction, 2009); 'Percentage of projects with financial closeout' (QT) (Suermann & Issa, 2009); 'Level of involvement of BIM users in green projects' (QL) (McGraw-Hill Construction, 2009); 'Level of value BIM generates for each project phase' (QL) (Hanna et al., 2013); 'Level of Knowledge on BIM' within the industry (QL) (Wu & Handziuk, 2013); 'Growth in BIM use by different parties' (QT) (McGraw-Hill Construction, 2009); Industry-wide 'intention for future investments on software, creating BIM procedures, creating BIM libraries, creating BIM procedures with other companies, training staff, and marketing BIM to customers' (QL) (Hanna et al., 2013); Overall 'impact of BIM adoption on users' in the industry (positive, neutral, negative) (QL) (McGraw-Hill Construction, 2009); 'Most celebrated benefits of BIM vs. CAD' (QL) (Wu & Handziuk, 2013); 'Excellence of project outcomes using BIM' (QL) (Wu & Handziuk, 2013) 'To what degree BIM is an integral component of projects that have used IPD' (QL) (Kent & Becerik-Gerber, 2010). 'Diversity of markets, disciplines and company sizes that used BIM' (QT) (Succar et al., 2012); 'BIM Training Methods' at different trades of the industry (QT) (McGraw-Hill Construction, 2009)

BIM implementation (e.g. costs, cost savings, time, time savings, rework time, rework cost). Along with these lag indicators, the number of RFIs and change orders, and the number and status of errors and omissions were among the most redundant measures reported in the literature. From a quality management perspective, this trend suggests that most practitioners have sought to analyze how BIM reduces the costs of non-conformance and inefficiencies in practice, while there is still need to develop metrics/criteria that address quality assurance and quality control means (e.g. training, tools, testing, inspection) to further improve BIM practices (Project Management Institute, 2008).

The findings also show that many metrics/criteria are similar but measured differently, that is, some researchers have used qualitative approaches to measure them while other researchers use quantitative measures. For instance, collaboration has been assessed both qualitatively (e.g. expert or team judgment) and quantitatively (e.g. number of communication channels, dependencies, etc.). Nevertheless, the number of unique metrics is still large enough to reflect that BIM implementation assessment could be a complex matter, and there is a need for structured frameworks to facilitate BIM assessment processes. Developing such a framework would be essential for internal performance assessment, external benchmarking purposes, formal certification systems, and qualification assessment of BIM service providers (Succar et al., 2012). However, measuring a large number of metrics may not be feasible and practical in all stages for BIM implementers. Therefore, prioritizing metrics/criteria is essential to develop KPIs for each BIM practice.

In this section, the findings will be further analyzed in order to reveal the gaps, provide critical insights, and offer recommendations for future research. Figure 3 presents the number of studies that developed metrics/criteria for assessing different BIM implementation aspects. It shows that metric-based assessment of BIM in some aspects, including BIM users, BIM models, BIM in facility management, and BIM in the industry, has only several contributing papers. In contrast, assessing BIM outcomes in construction, BIM tools, BIM processing, and BIM in the business were the major areas of interest in the prior research (Figure 3). Another analysis on the number of metrics/criteria developed in each aspect also confirms the abovementioned trend (Figure 4). This trend reveals that metric-based assessment of BIM users, BIM models, and BIM outcomes in the facility management phase needs more critical attention than it has currently received. In the following sections, a detailed discussion of trends, gaps, and recommendations for each major theme of BIM assessment is provided.

BIM inputs

BIM tools

Quantitative assessment of general BIM authoring and analysis tools has not received much attention in research, while BIM scanning and image-recognition tools are mostly assessed quantitatively

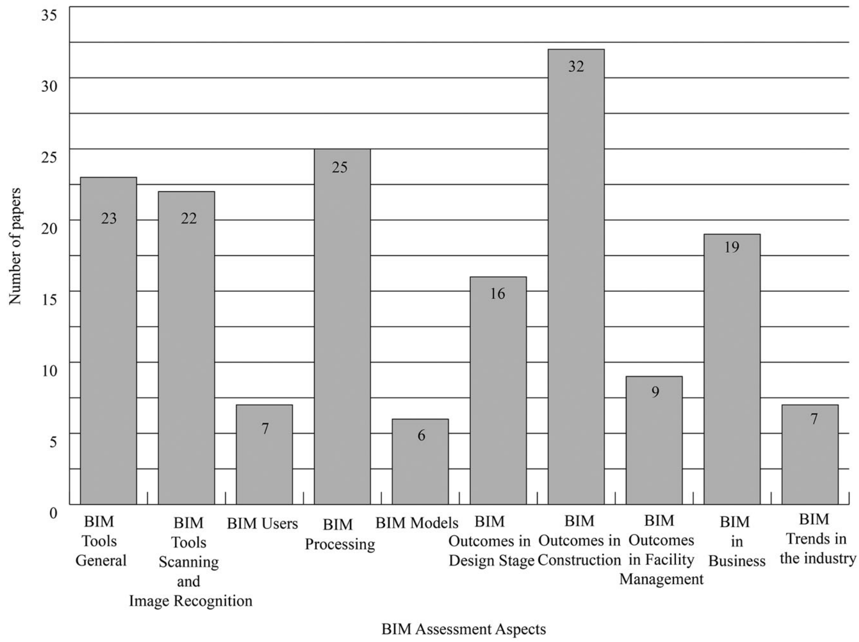


Figure 3. Number of studies developed metrics/criteria for assessing BIM implementation aspects.

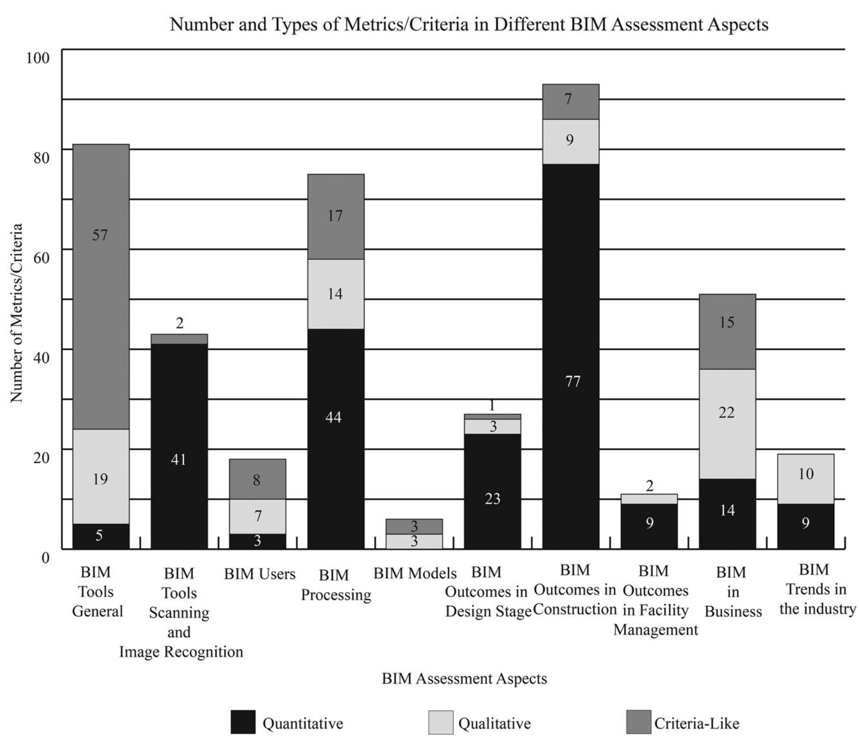


Figure 4. The number and types of metrics/criteria developed for assessing BIM assessment aspects.

(Figure 4). This is because of the more tangible and quantifiable focus of image-processing metrics in comparison to BIM tools general metrics, as they deal with dimensions, discrete shape types, and number of items. Many studies on BIM tools have been limited to listing assessment criteria, and they rarely documented and reported implementation of such measures in a real-world context. This large number of criteria-like indicators may be explained by the limited number of construction researchers who have the interest and ability to quantify and assess metrics related to software-development aspects of BIM (e.g. interoperability issues, software qualities). Further research should therefore attempt to provide an evidence-based assessment of general BIM tools for comparison and benchmarking purposes. Developing quantitative measures based on the existing assessment criteria is essential for this purpose. This could show shortcomings in existing BIM platforms and tools, and will provide a valuable ground for future BIM developments. Additionally, further developments should document (1) how BIM environments or their extensions can be integrated to other IT infrastructure and enterprise architecture systems to streamline information exchange and retrieval among different business units with different functions and (2) what measures practitioners should use for assessing and improving such integration.

BIM users

Assessing BIM users is becoming increasingly important in BIM implementation practices, although prior research has not dealt with in-depth assessment of BIM users yet. On one hand, developing and improving skills is necessary for implementing BIM efficiently. On the other hand, high initial investment and training costs are usually considered as the barriers to the implementation of BIM (Sacks & Barak, 2008). Despite the importance of BIM training, no research has adequately studied training methods in the industry and academia. For example, McGraw-Hill Construction (2009) has only reported that BIM professionals draw BIM knowledge from self-education, internal trainers, or external trainers. However, the effectiveness of different tutoring systems and methods for BIM training has not been studied. Moreover, BIM training is not just an internal issue. Some BIM contracting forms mandate that contractors/designers provide BIM training to other project participants (e.g. owners and facility managers), or ensure that subcontractors have technical proficiency in BIM implementation (Bay Area Headquarters Authority, 2012; Princeton University, 2012). However, prior research has rarely focused on such requirements and assessment approaches in the industry. Future research should therefore deal with quantitative assessment of BIM training method, tutoring systems, and on-the-job professional development. Assessing BIM users in different 'tool related, process related, and role-related' knowledge and skills is also recommended (Kymmell, 2008).

BIM processing

The findings show that future developments on metric-based BIM assessment should address few challenges in dealing with BIM processes. First, BIM assessment should be based on standard definitions of BIM uses as many metrics use the generic term 'BIM' for all functions and processes (e.g. actions of a 'BIM' user over time). As BIM developments and BIM uses have significantly grown, practitioners and researchers must use more specific terms and definitions. For example, Kreider and Messner (2013) categorize different BIM uses based on BIM functions, including (1) gathering and extracting information, (2) information generation and development, (3) information analysis and simulation, (4) representation and communication, and (5) realization of elements and/or implementing information. Second, such an assessment should address the individual, team, and collaborative levels of BIM processing; as many information/model development metrics, for example, the amount of reworks on models, do not reflect this issue (operational KPIs vs. personal KPIs; see Levitt, 2011). Third, BIM assessment should adequately distinguish between virtual and physical settings for collaboration. Existing literature has not yet dealt with metric-based BIM processing assessment in virtual settings. Although the number of developed metrics/criteria for assessing BIM processing is significant, the AEC/FM industry can also benefit from useful metrics/criteria developed in non-AEC literature (e.g. manufacturing industry and information technology projects), especially for issues such as computer-based design, interactions, and collaboration (e.g. Lee, Jung, Kim, & Jung, 2011; Moore, Manrodt, & Holcomb, 2005; Natter, Ockerman, & Baumgart, 2010).

BIM outputs

BIM models

As shown in Figures 3 and 4 , assessment of BIM models is largely disregarded in research, and only a few qualitative criteria have been developed to address this issue. As previously highlighted, due to the insufficient level of support from BIM software developers and validation issues, challenges to assess BIM models are still significant (Katranuschkov et al., 2010). Nonetheless, metrics may be developed to determine and assess in what aspects the models are proven to be incomplete (e.g. model geometries, information attributes). This approach can be supported by recent developments in BIM validation using IDM/MVD schemas as well as automated compliance checking platforms, which can facilitate tracking the model completeness (Eastman, Lee, Jeong, & Lee, 2009; See, Karlshoej, & Davis, 2011). Qualities of models from the standpoints of accuracy, correctness, completeness, and redundancy need to be assessed in this regard. Addressing geometries, taxonomy of object types and data attributes, and relationships or associations between elements and attributes in IDMs/MDVs is essential for such an assessment. For example, the recommended process for developing and exchanging Construction Operations Building information exchange (COBie) data includes creating information in a model supported by IFC and extracting data in different formats (National Institute of Building Sciences, n.d.). This necessitates developing a high-quality model that supports COBie MVD and follows the schema developed for IFC interoperability. For this reason, in further developments, model assessment tools/approaches should address both the contents (whether they fit the intended use) and the structure of contents (whether it follows the interoperability standards and domain-based taxonomies). It is expected that quality assessment of BIM models would increase in future, as some contractual developments have mandated such an assessment (Abdirad, 2015).

BIM in project life-cycle stages

In regard to assessing BIM practices in design stages, few challenges are noticeable. First, most quantitative measures are dedicated to assess direct cost and time metrics. Second, the assessment of design decisions has been limited to tangible design errors and omissions, although few QL metrics are suggested for assessing innovation in design products. Architectural knowledge and design reasoning are naturally expressed graphically in this practice, and the most important question relates to 'how knowledge is best represented in a computer to support reasoning of the kind in which architects engage' (Tzonis & White, 2012, pp. 16–17). This could be an important issue in BIM implementation as a considerable number of scholars argue that BIM models would restrict creative exploration, innovation, and the ability to generate solutions in design (Dossick & Neff, 2014; Mitchel, 2009; Sebastian, 2011). For this reason, developing metrics/criteria for assessing BIM-enabled designs from the standpoints of innovation and intangible design qualities is recommended for further research.

The findings have shown that assessing BIM outcomes in the construction stage is more prevalent than other project life-cycle stages. The reason may be that the cost impact of low productivity and huge waste is much higher in the fabrication and construction stages than other project stages. Hence, using metrics that directly measure productivity is more essential in construction. However, the way BIM implementers use some trending metrics has been criticized in the literature. For instance, Bilbo, Bigelow, Escamilla, and Lockwood (2014) reported a case study in which reducing RFIs was considered as a goal; as a result, RFIs were issued only when the team could not avoid them, and this made communication and tracking changes very challenging. Team members should therefore be careful about how they may unintentionally manipulate the measures on effectiveness of BIM implementation.

In regard to BIM outcomes in facility management, only a few metrics have been developed in the literature. This may be explained by the fact that BIM implementation in facility management is still in the early development stages (Akcamete, Akinci, & Garrett, 2010; Liu & Issa, 2013; Sabol, 2008), while design computing has been researched since the early 1970s (Tzonis & White, 2012). McGraw-Hill Construction (2014) also reported that only 47% of owners in the US have attempted to receive and use BIM models for their operations and facility management; and only 15% of owners follow COBie-like standards for this purpose. As the operations and maintenance phase has the largest portion of cost impact on life-cycle costs (Farr, 2011), facility management practices can significantly benefit from advances in BIM applications. For future research, providing quantitative measures and in-depth analyses that can compare pre-BIM with after-BIM practices, and critical comparisons of new BIM developments (different tools, standards, etc.) in facility management are recommended.

BIM in a business or an organization

Although much research has contributed to the development of metrics/criteria for BIM assessment at business/organizational levels, this study highlights gaps in the literature. First, most studies and most metrics/criteria have a focus on the suppliers' side of the industry (contractors and designers). Although owners and construction clients can perceive the largest benefits of BIM adoption in the industry (Porwal & Hewage, 2013), BIM implementation assessment in this demand side of industry has rarely been documented in research. McGraw-Hill Construction (2014) reported that only 16% of the US-based owners formally measure the implementation and impact of BIM in their organizations, although the majority of the survey participants were large-budget owners. For future research, developing criteria/metrics to assess BIM at owners' organizations is highly recommended. Second, further research needs to implement quantitative metrics to assess portfolios of multiple BIM projects in organizations. This assessment should not be limited to projects' cost and schedule; documenting how different projects and business units interact which each other in terms of BIM implementation, shared inputs and resources, and shared/integrated processes would be essential in future research.

BIM in the industry

As presented in Figure 3, few studies have contributed to the assessment of BIM status at the industry level. The challenge to assess BIM implementation at the industry level may be that such a study requires the support of a large number of industry participants to collect data and to draw conclusions. Most assessment metrics/criteria in the existing references have a more descriptive nature (e.g. most celebrated benefits of BIM) rather than an analytical nature (e.g. BIM impact at the industry level in terms of cost, schedule, waste, etc.). It is recommended that more in-depth assessment of BIM impact in the industry be presented in research. Although research has reported the positive impact of BIM by focusing on how BIM is growing and by developing metrics that directly measure positive impacts (e.g. benefits of different BIM uses, etc.), a survey showed that 31% of owners in the US and 20% of owners in the UK experienced that BIM had a negative or neutral impact on their practice (McGraw-Hill Construction, 2014). These unfavorable results of BIM implementation in the industry have rarely been the focus of academic researchers, neither for quantitative assessment nor for qualitative and in-depth root analysis.

Conclusion

BIM is one of the most significant developments in the AEC/FM industry, as it introduces new technologies, processes, relationships, and interactions into the practice (Ashcraft, 2008). Prior research shows that there is an increasing interest among the industry practitioners and academic researchers to assess different aspects of BIM implementation in order to monitor, measure, and improve BIM adoption (Figure 1). However, so far, no study has critically reviewed and reported the existing approaches, metrics, and criteria for assessing BIM implementation in this industry. To fill this gap in research, this study reviewed prior research and synthesized existing knowledge and criteria relevant to BIM implementation assessment. A limitation of this study is the search strings used for locating relevant research in bibliographic databases and search engines. The author suggests that future research may consider more search strings such as BIM 'maturity', 'capability', 'competency', 'qualification', and 'certification' in the review process and report on metrics, criteria, themes, and approaches other developments offer for BIM implementation assessment.

This study showed that a large number of metrics and criteria have been developed in the research to assess different aspects of BIM implementation. In the discussions section, it was also shown that there are several gaps in research, and recommendations were made for future research. The evidence from this study highlights that the metric-based assessment of individual BIM users, BIM models, and evaluation of BIM outcomes in facility management are not well documented in prior research, and the contribution of construction researchers in quantitative assessment of general BIM tools (software-development aspects) is not significant. Taken together, these results suggest that there is a steady increase in the level of interest in metrics/criteria-based BIM implementation assessment, and this is expected and needed to rise in the future.

This paper makes some noteworthy contributions to the existing knowledge. This is the first study dedicated to the review and report of the state-of-the-art trends, advances, and gaps in defining metrics/criteria for assessing BIM implementation by applying a comprehensive review method. This research also enhances our understanding of BIM implementation assessment by presenting a comprehensive collection of metrics that can serve as a basis for future developments of BIM assessment models. The classified metrics synthesized in this research can be incorporated to existing BIM maturity models, as these models mostly consist of general criteria of BIM maturity aspects, and they use very limited practical measures for assessing BIM implementation. These models may also be revised based on the recommendations and critiques offered in the discussion section, especially for topics on which BIM implementation assessment requires substantial improvement. It is also recommended that further research be undertaken to prioritize and rank metrics in different organizations for developing KPIs for BIM processes.

Note

1. The lists of papers located by search engines in bibliographic databases are available at: http://tinyurl.com/gwbt6on.

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