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SURVEY

Maturity Evaluation Methods for BIM-Based AR/VR in Construction Industry: A Literature Review

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ABSTRACT The architecture, engineering, and construction (AEC) industry has seen significant development, particularly with the increased adoption of Building Information Modeling (BIM). Despite this progress, the interaction between digital and physical environments remains limited due to the visual limitations provided by the built environment. Although integrating BIM with immersive technologies, such as Augmented Reality (AR) and Virtual Reality (VR), is thought to be an effective solution, not all companies are able to successfully implement these integrated technologies. Therefore, it is essential to learn lessons from maturity evaluation. However, a systematic literature review (SLR) of previous works on maturity evaluation of BIM, AR/VR, and BIM-based AR/VR is lacking. The goal of this research is to provide an SLR of these studies to gain a clearer understanding of the field. From an initial cohort of 942 studies, 27 primary studies were retained based on four search engines. The SLR addresses specific research questions related to demographic information, maturity evaluation background, maturity evaluation tools and approaches, their benefits and limitations, and new perspectives. The main findings reveal that the maturity evaluation of BIM-based AR/VR is still in its early stages. The review also suggests a critical analysis of existing maturity evaluation tools, enabling the interpretation of results in an objective manner. Future research should focus on developing a standardized solution that incorporates best practices and rules that meet the needs of practitioners and researchers.

INDEX TERMS Maturity, evaluation, SLR, augmented reality, virtual reality, BIM, BIM-based AR/VR.

I. INTRODUCTION

The architecture, engineering, and construction (AEC) industry has undergone significant development over the past few decades, with a focus on creating modern, complex, and sophisticated buildings [1], [2]. However, despite these advancements, the industry still struggles with a high rate of workplace injuries and fatalities [3], [4], [5], [6]. It also has a significant negative impact on the environment, as it is responsible for a large amount of waste, greenhouse gas emissions, and energy consumption [7]. To address these challenges, the use of Building Information Modeling (BIM) has been introduced. According to the British Standard Institute, BIM is defined as the *"process of generating and managing information about a building during its entire life"* [8]. In other words, BIM is a 3D digital modeling platform that allows for better coordination and collaboration among project members [9]. BIM is also an opportunity to integrate sustainable actions into the construction process [10], [11]. However, the full potential of BIM has not yet been realized due to current practices and expert insights, and there is a need for continued investment in this technology by industry players [12]. Recently, immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR) have been introduced in the construction industry to simplify and improve efficiency in areas such as risk management and

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safety planning [13], [14], [15]. These technologies allow for visualization of BIM 3D model data in both full and partial virtual environments, and they offer users the ability to fully immerse themselves in artificial environments using devices like head-mounted displays [16], [17], [18]. AR enhances the perception of the real world by overlaying digital information on top of it [19], [20], while VR is a digital simulation that allows for interaction with 3D elements [21], [22], [23]. Using these technologies in high-performance building design strategies is considered a cutting-edge approach in the construction field.

Over the past few decades, BIM has been integrated with AR and VR technologies, as noted by Garbett et al. [24] and Safikhani et al. [25]. This integration has provided workers, engineers, and architects with extensive capabilities to monitor construction sites, make informed decisions, and execute tasks during all phases of a project's lifecycle [26]. The emergence of BIM-based AR/VR environments has also offered a broad range of applications in various fields, including industry, construction, maintenance, and engineering [1]. According to [27], BIM-based AR technology can be used for on-site facility management, to improve techniques of representation, such as monitoring the reinforcement of concrete, by verifying the number of steel bars, minimum and maximum space between them and by visualizing the 3D assembly of the structure. Similarly, Getuli et al. [5] have indicated that virtual reality is a useful construction worksite planning system that can improve safety conditions by visualizing the site's health and safety plans on the BIM platform. In a more recent work, Assila et al. [23] have conducted a systematic literature review on the integration of augmented, virtual, and mixed realities with BIM. The review's primary focus was on the project lifecycle stages where these three immersive technologies are being implemented with BIM, as well as the approaches used to ensure this integration. The review identified limitations and proposed new perspectives to consider for better implementation of these technologies. In addition and referring to [28], the misapplication of AR/VR with BIM resulting from poor sharing of information, bad execution process, and competency issues can hinder the safe use of these technologies in the AEC industry. Such misapplications may discourage investors from adopting and using these technologies. Therefore, it is crucial to determine and evaluate the critical risk aspects that impede the implementation of these technologies.

In order to ensure the successful implementation, continuity, and sustainability of construction projects utilizing BIM-based AR/VR technologies, it is crucial to assess their maturity. This requires the application of the most appropriate evaluation method. In this case, the investment in a well-developed maturity evaluation method can lead to a safer and more stable project life cycle, as well as a longer asset life [28]. Based on the literature, numerous studies have been proposed concerning the implementation of BIM, AR/VR and BIM-based AR/VR technologies in construction projects [23], [29], [30]. Some other articles have focused on studying the maturity of BIM such as [31], [32], and [33]. Nevertheless, a systematic literature review regarding maturity evaluation methods for BIM, AR/VR, BIM-based AR/VR technologies is still lacking.

To summarize, the main objective of this paper is to provide a detailed analysis and review of recent advances in this field, in order to offer researchers and industrialists a complete and clear understanding of the current state of the art.

The primary focus of this paper is to review and analyze the existing approaches and tools for evaluating maturity in the literature on BIM, AR/VR, and BIM-based AR/VR. By conducting this review, the goal is to evaluate the relationship between these technologies in order to identify best practices to consider when assessing maturity.

The remaining part of this article is structured as follows: Section II describes the adopted SLR methodology. Section III presents the results of this review and provides a critical analysis of the existing studies. This section aims to address the research questions were defined. Finally, Section IV concludes this SLR.

II. RESEARCH METHODOLOGY

The methodology applied in this study was based on the systematic review protocol developed by Kitchenham and Charters [34]. It involved three main stages, namely: planning, conducting, and reporting the review. The following subsections discuss the steps involved at each stage. The research strategy, including the search and selection process, is shown in Fig. 1, and the details are described below.

A. PLANNING THE REVIEW

To ensure a successful review, a well-organized plan should be developed. The main goal of this SLR is to provide an up-to-date overview of the approaches and tools used for evaluating the maturity of BIM with immersive environments using AR and VR technologies for improving the building process. The following subsections provide details on the research questions (RQs) and the adopted search strategy, including the search strings, electronic databases used, inclusion/exclusion criteria applied to filter studies, and the search process.

1) RESEARCH QUESTIONS

In order to conduct a detailed review of the proposed topic, three research questions (RQs) were formulated to guide the study. Additionally, the third question has been divided into four sub-research questions (sub-RQs) to ensure comprehensive coverage. The RQs and sub-RQs are defined as follows:

- RQ 1. What are the demographic information of the primary studies?
- RQ 2. What are the key concepts of maturity evaluation?
- RQ 3. What are the existing approaches and tools for evaluating the maturity of BIM, AR/VR, BIM-based AR/VR?

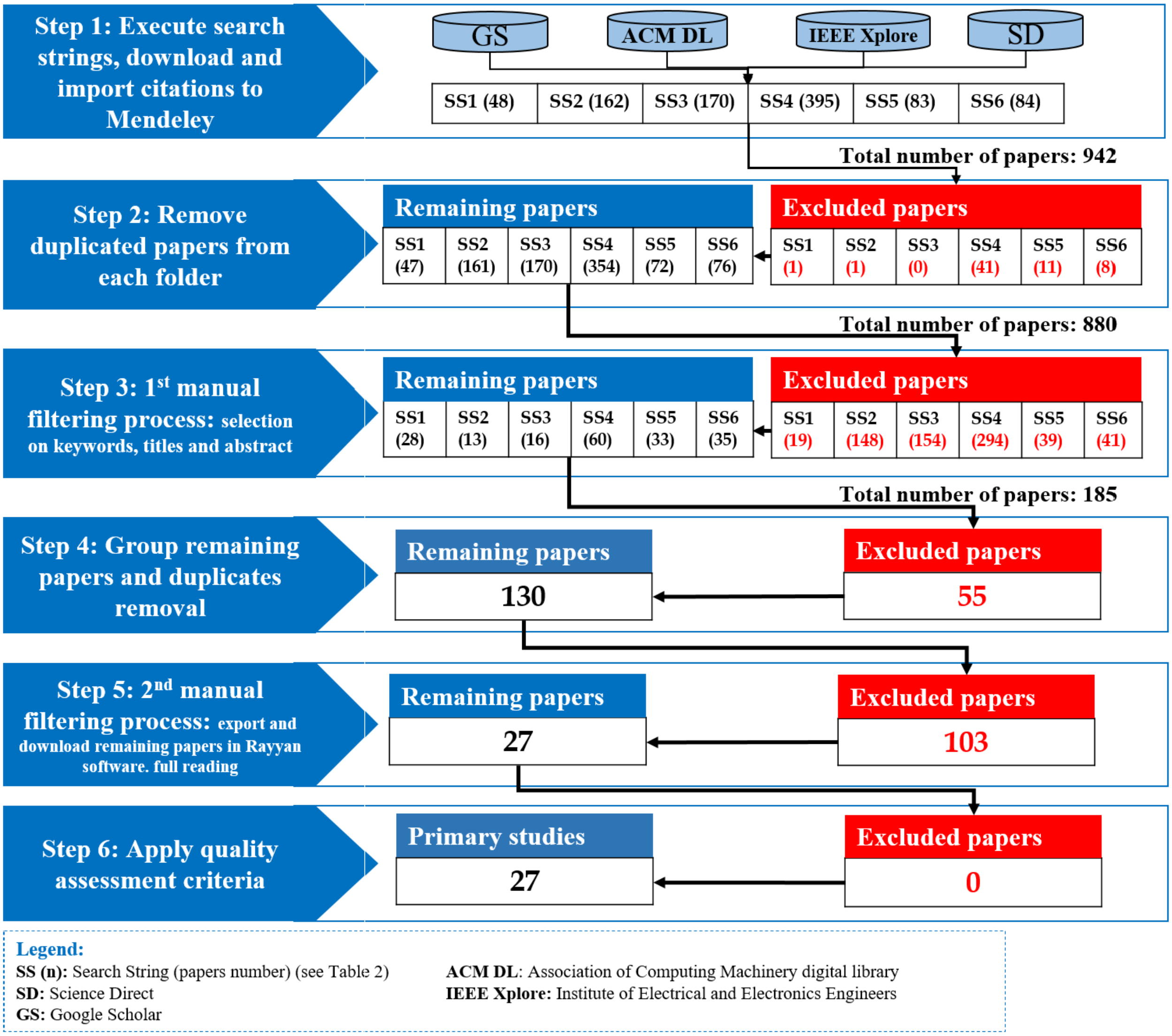

FIGURE 1. Search and selection process.

- RQ 3.1 What tools and approaches are used for BIM maturity evaluation, their benefits and their drawbacks?
- RQ 3.2 What tools and approaches are used for AR/VR maturity evaluation, their benefits and their drawbacks?
- RQ 3.3 What tools and approaches are used for BIM-based AR/VR maturity evaluation, their benefits and their drawbacks?
- RQ 3.4. What critical analysis can be made of the obtained results, and what are the implications for future development and research in these areas?

2) RESEARCH STRATEGY

a: SEARCH STRINGS (SS)

To complete the search process accurately, it is necessary to collect all words and terms related to the current topic, narrow down the search range, and obtain more specific search results related to the research questions. The selected keywords in the current study are divided into three parts: the first concerns *used technologies*, the second concerns *maturity*, and the third concerns *evaluation*. To increase the likelihood of obtaining more relevant results, acronyms, alternate spellings, and Boolean operators (AND and OR) should be considered. The set of keywords used is detailed in Table 1 below.

TABLE 1. Set of keywords related to the studied topic.

Used technology keywords	Maturity keywords	Evaluation keywords
Building information modeling; BIM; Augmented Reality; AR; Virtual Reality; VR	Maturity	Assessment; assessing; Assess; Evaluation; Evaluating; Evaluate Measurement; Measuring; Measure

Based on the keywords listed in Table 1, the global search string can be deduced as follows: ((''Building information modeling'' OR ''BIM'') AND/OR (''augmented reality'' OR ''AR'' ''OR ''virtual reality'' OR ''VR'')) AND (''maturity'') AND (''assessment'' OR ''assessing'' OR ''assess'' OR ''evaluation'' OR ''evaluating'' OR ''evaluate'' OR ''measurement'' OR ''measuring'' OR ''measure'').

Unfortunately, due to the large size of this search string, all selected search engines are unable to read it. For this reason, the decision was made to break it down into six search strings related to the identified research questions, covering the evaluation of BIM maturity, as well as VR, AR, BIM-based AR, and BIM-based VR (see Table 2).

b: ELECTRONIC DATABASES

To perform a cross-searching process using four online databases, the search strings defined in the previous section were used. The selected databases were Google Scholar, ACM Digital Library, IEEE Xplore, and ScienceDirect, chosen for their wide coverage of journals and functionality. The search was conducted based on the title, abstract, and indexed terms for journal papers and conference proceedings. The query writing process differed between databases. For example, on Google Scholar, the ''allintitle'' operator was used to exclusively search for articles with the search terms in the title. For ACM Digital Library, studies published between 2011 and 2022 were searched due to the large number of articles found within this period. No specific constraints were added for the remaining databases.

c: INCLUSION AND EXCLUSION CRITERIA

Referring to the Kitchenham and Charters SLR methodology [34], a set of inclusion and exclusion criteria were identified to filter out irrelevant papers.

The inclusion criteria were as follows:

- Papers that focus on the maturity evaluation of BIM and/or AR and/or VR.
- Only scientifically approved papers by peer review are selected.
- Title, abstract, or keywords match the search query.

On the other hand, the exclusion criteria were:

- Papers that do not deal with the maturity evaluation of BIM, AR, and VR during the entire lifecycle of a building (out-of-scope papers).
- Duplicated papers (in case of duplication, only the most complete work is considered).
- Papers not written in the English language.
- Papers not published in journals or conferences.
- Papers that are not available.

d: SEARCH PROCESS

Searching for and selecting appropriate papers is considered a critical process because the entire literature review is based on it. As shown in Fig. 1, the adopted search process includes six main steps aimed at carefully selecting papers that address the studied subject. These steps are described below:

- *The first step* was to adapt the format of each search string to suit each of the search engines used. The six main search strings were then executed, and the results from each search were imported into *Mendeley desktop*[1] and kept in separate folders.
- *The next step* was to identify and remove any duplicate papers from each folder. This step was performed automatically using *Mendeley desktop*.
- *In the third step* involved conducting the first manual filtering process. During this step, the titles, keywords, and abstracts of the studied papers were considered, and initial decisions were made based on the inclusion and exclusion criteria. The number of remaining papers in each folder was recorded.
- *The fourth step* involved grouping the remaining papers and removing any duplicates. During this step, the remaining papers from the previous step were grouped together and any duplicates were removed using *Mendeley desktop*.
- *In the fifth step*,the second manual filtering process was conducted. The remaining papers were exported and downloaded into *Rayyan*[2] software. A full reading of each paper was conducted to make decisions on whether to maintain or remove them based on the identified research questions.
- *The final step* involved applying quality assessment criteria (discussed below) to the obtained papers in order to filter out the most relevant ones. Thus, the final list of primary studies was obtained.

B. CONDUCTING THE REVIEW

As illustrated in Fig. 1, 942 papers were found in the search across the four databases. Next, all papers were exported to the *Mendeley desktop* software [35] and classified by assigning relevant subjects to be managed. In addition, 62 papers were excluded from the total number of papers for being duplicates. The remaining papers were then subjected to three stages of manual filtering processes.

In the first stage, the titles and abstracts of the remaining papers were read based on the inclusion and exclusion criteria, resulting in the exclusion of 695 papers. Before the second filtering stage began, all remaining papers were grouped and gathered, and an additional 55 duplicated papers were removed. In the second filtering stage, the remaining papers were quickly read after being exported and downloaded into the *Rayyan* software [36], and any papers that were unable to address one or more of the RQs related to this SLR were excluded. At this stage, each paper was voted on based on three voting decisions: ''include,'' ''exclude,'' or ''maybe.'' Papers that were voted ''maybe'' were checked by reading

TABLE 2. Search strings.

Search string number	Studied subjects	Search strings (standard format)
SS1	Evaluation of BIM maturity	("BIM" OR "building information modeling") ("maturity") ("assessment" OR "evaluation" OR "evaluating" OR "assessing" OR "measure" OR "measuring" OR "measurement")
SS2	Evaluation of AR maturity	("AR" OR "augmented reality") ("maturity") ("assessment" OR "evaluation" OR "evaluating" OR "assessing" OR "measure" OR "measuring" OR "measurement")
SS3	Evaluation of VR maturity	("VR" OR "virtual reality") ("maturity") ("assessment" OR "evaluation" OR "evaluating" OR "assessing" OR "measure" OR "measuring" OR "measurement")
SS4	Evaluation of BIM, AR and VR maturity	("BIM" OR "building information modeling" OR "AR" OR "augmented reality" OR "VR" OR "virtual reality") ("maturity") ("assessment" OR "evaluation" OR "evaluating" OR "assessing" OR "measure" OR "measuring" OR "measurement")
SS5	Evaluation of BIM-based AR maturity	("BIM" OR "building information modeling") ("AR" OR "augmented reality") ("maturity" OR "assessment" OR "evaluation" OR "evaluating" OR "assessing" OR "measure" OR "measuring" OR "measurement")
SS6	Evaluation of BIM-based VR maturity	("BIM" OR "building information modeling") ("VR" OR "virtual reality") ("maturity" OR "assessment" OR "evaluation" OR "evaluating" OR "assessing" OR "measure" OR "measuring" OR "measurement")

them again to make a decision on whether to exclude or include them. As a result, 27 papers were retained.

In the last stage of filtering, a qualitative assessment (QA) of the papers was performed, and a total of 27 primary studies were retained. This step was conducted based on predefined quality assessment criteria that allowed for the evaluation of the relevance and completeness of the 27 retained primary studies. The following QA questions were used:

- QA1: Are the research goals clearly stated?
- QA2: Was the study designed to achieve these objectives?
- QA3: Is the proposed solution clearly defined?
- QA4: Are the research results clearly reported?
- QA5: Are the limitations of the current study adequately addressed?
- QA6: Are new perspectives revealed?

Referring to [23] and [26], each QA question has one of three possible answers: ''Yes'' representing 1, ''No'' representing 0, and ''Partially'' representing 0.5. To be retained in the final phase, each paper must achieve a minimum score of 3 across all QA questions. Using this approach, the 27 studies qualified for further analysis. The main findings are discussed in Section III.

C. DATA EXTRACTION

This step consists of determining the needed attributes that allow recording all required information from the selected primary studies. These attributes are defined based on all the research questions related to this SLR. They includes: (1) title, (2) demographic information, (3) maturity evaluation background, (4) BIM maturity evaluation methods or tools, (5) AR maturity evaluation methods or tools, (6) VR maturity evaluation approaches or tools, (7) BIM-based AR maturity evaluation approaches or tools, (8) BIM-based VR maturity approaches or tools and (9) limitations and perspectives.

III. MAIN FINDINGS AND DISCUSSION

In this section, the 27 primary studies are analyzed to provide answers to all of the research questions proposed in the previous section. The section reports the main findings of the systematic review and highlights relevant information. The analysis of the articles was mainly carried out by examining bibliographic information, lifecycle stages, studied technology, and paper focus, which are displayed in Table 3. This Table presents key elements that allow for a more in-depth analysis in the review. The main results and observations related to each research question are presented in the following sections.

A. RQ 1. WHAT ARE THE DEMOGRAPHIC INFORMATION OF THE PRIMARY STUDIES?

This section aims to collect demographic information related to the 27 primary studies. The analysis considers five parameters, as follows: (1) the theme and publication date, (2) primary study keywords, (3) the authors and co-authors who made the most contributions, (4) the countries that made the most contributions, and (5) the venues that were most cited.

Fig. 2 (see page 7) shows a chart of the cumulative number of published papers, classified by their thematic focus, from 2012 to 2022. The red line graph represents the cumulative number of studies published during this period, which shows a gradual increase over time. In 2012, only two papers were published, but this number has steadily increased to reach 27 in 2022.

[1]Software that helps users to manage, share, and search for papers and generate bibliographies [35].

[2]Intelligent software that helps users to undertake the systematic review methodology and to manage references [36].

TABLE 3. List of the retained primary studies.

References	Year of publication	SLR	Publication type	Publication venue	Citation number	Life-cycle stage	Studied technology	Focus
[37]	2022	NO	Journal	Advanced Engineering Informatics	4	Design phase	BIM	Maturity evaluation
[38]	2022	Yes	Conference	Procedia Computer Science	0	Design phase	BIM	Maturity evaluation
[39]	2021	NO	Journal	Architectural Engineering and Design Management	9	-	BIM	Maturity evaluation
[40]	2021	NO	Journal	Journal of Computational Design and Engineering	10	Design phase	BIM-based VR	Maturity evaluation
[41]	2021	Yes	Journal	IEEE Access	15	All phases	BIM	BIM maturity stages reffered to ISO standard
[42]	2021	NO	Journal	International Journal of Construction Management	10	-	BIM	Maturity evaluation
[17]	2020	NO	Conference	IFIP International Conference on Product Lifecycle Management	2	All phases	BIM-based AR/VR	Maturity evaluation
[43]	2020	NO	Journal	Acta Astronautica	18	All phases	AR	Maturity evaluation
[44]	2019	NO	Conference	International Postgraduate Research Conference 2019	1	All phases	BIM	Maturity evaluation
[11]	2019	NO	Journal	Iranian Journal of Science and Technology	13	Design phase	BIM	Maturity evaluation of consultant companies
[33]	2019	NO	Journal	Automation in Construction	49	All phases	BIM	Maturity evaluation
[32]	2018	NO	Journal	Journal of construction engineering and management	43	All phases	BIM	Maturity evaluation
[45]	2018	NO	Conference	European Conference on Software Process Improvement	4	-	AR and VR	Maturity evaluation
[46]	2017	Yes	Journal	Journal of Information Technology in Construction (Itcon)	76	-	BIM	Overview of multiple maturity model
[[47]	2017	NO	Conference	Proceedings of the 33rd Annual Association of Researchers in Construction Management	5	-	BIM	Maturity evaluation
[48]	2017	NO	Conference	European Conference on Software Process Improvement	4	-	AR and VR	Maturity evaluation
[49]	2016	NO	Journal	Journal of construction engineering and management	67	All phases	BIM	Maturity evaluation
[50]	2016	NO	Conference	Proceedings of the First International Conference of the BIM Academic Forum	18	-	BIM	BIM maturity and benefits relationship
[9]	2015	NO	Journal	International Journal of Information Systems and Project Management	17	-	BIM	Maturity evaluation
[51]	2015	NO	Journal	Automation in construction	429	All phases	BIM	Assessment macro BIM adoption
[52]	2014	NO	Conference	International Conference on Project Management	59	-	BIM	Maturity evaluation
[53]	2014	NO	Journal	Smart Construction and Management in the Context of New Technology (ASCE)	5	All phases	BIM	Maturity evaluation
[54]	2013	NO	Journal	Computing in civil Engineering	26	-	BIM	Maturity evaluation
[55]	2013	NO	Conference	Proceedings of the second world construction symposium 2013	48	All phases	BIM	Maturity evaluation
[56]	2012	NO	Journal	Journal of Management in Engineering	71	-	BIM	Maturity evaluation
[57]	2012	NO	Conference	Proceedings of the CIB W78 2012	19	-	BIM	Maturity evaluation

A noticeable change in the trend can be observed in the Figure. From 2012 to 2016, the number of papers published increased by two each year. Furthermore, between 2017 and 2022, the number of papers published continued to rise, but at varying rates ranging from one to five per year. It is worth noting that in 2021, a significant increase occurred, with five papers published. This indicates that the topic has gained greater importance and interest among researchers, as more than 50% of the papers were published after 2018.

Referring back to the same chart, it can be observed that out of the selected papers, 22 studies have been proposed to evaluate the maturity of BIM. However, only two studies [45], [48] have been proposed in 2017 and 2018 to evaluate the maturity of both AR and VR. Furthermore, three

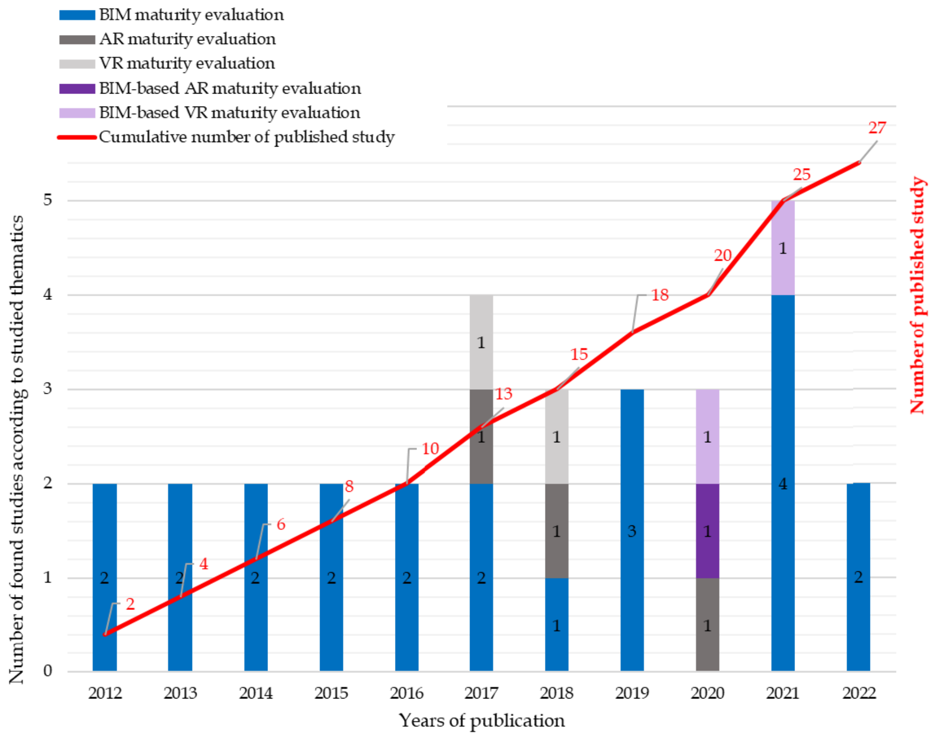

FIGURE 2. Cumulative number of published papers and papers classification according to studied thematic between 2012 and 2022.

studies proposed the evaluation of AR, BIM-based AR/VR, and BIM-based VR maturity, respectively, between 2020 and 2021. It is worth noting that the five studies related to AR/VR, BIM-based AR, and BIM-based VR maturity evaluation were published between 2017 and 2021. These results indicate that augmented and virtual reality are still relatively new technologies in the AEC industry. Among the primary studies selected, 80% of them focused on BIM maturity evaluation, while only 20% dealt with AR and VR technologies. Therefore, this review is important in shedding light on existing studies related to the maturity evaluation of these emerging technologies.

To further analyze the primary studies, the keywords used in each study were examined and compiled into a word cloud, as shown in Fig. 3. The size of each word in the cloud reflects its frequency of occurrence, with larger words indicating more frequent use and smaller words indicating less frequent use. Out of the 100 found keywords, the most frequently occurring words were: BIM (N = 24), Maturity (N = 17), Building Information Modeling (N = 15), Maturity model (N = 4), Measurement (N = 3), Assessment (N = 2), Augmented Reality (N = 2), Virtual Reality (N = 2).

As seen in Fig. 3, the most frequent keywords from the primary studies align with the keywords used in the paper, highlighted in red. This coherence between the two sets of keywords demonstrates the relevance of the primary studies in providing the necessary information to address the research questions.

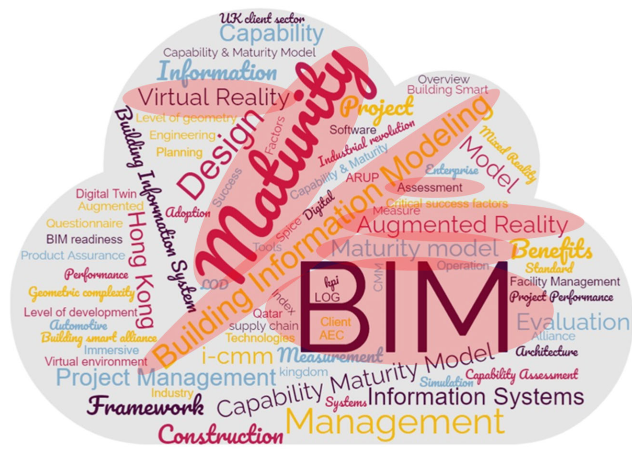

FIGURE 3. Word cloud of the primary studies keywords.

Different authors and co-authors contributed to the production of the primary studies that were included. As shown in Table 4, Romain Morlhon and Sonja Hammerschmid were the top first authors, with two research studies each. Among the co-authors, Robert Pellerin, Mario Bourgault, and Jason Underwood co-authored two papers each, making them the top three co-authors.

Table 5 (below) displays the number of papers published by each country and its collaborators, regarding the countries of the first author and co-authors of the primary studies. A diversification of the countries of the researchers

TABLE 4. Top authors and co-authors from primary studies.

Top First authors and co-authers		Studies number
Authors	Romain Morlhon	2
	Hammerschmid Sonja	2
Co-authors	Robert Pellerin	2
	Mario Bourgault	2
	Jason Underwood	2

TABLE 5. Countries of first author countries and collaborating authors.

Countries of publication	Number of papers	Collaborators	Number of papers
USA	4	Norway	1
China	3	Hong Kong	1
Netherlands	3	UK Spain	1 1
UK	3	South africa Serbia	1 1
Germany	2		
Iran	2		
Hong Kong	2	China, USA, South Korea	1
Canada	2		
Turkey	1	Australia	1
Australia	1	UK	1
Iraq	1	UK	1
France	1		
Norway	1		
Sri Lanka	1		

publishing is observed. The results show that the USA is the highest publishing country with four primary studies, while China, the Netherlands, and the UK tied for second place with three primary studies each. Germany, Iran, and Hong Kong are in third place, each with two published primary studies. Six countries - Turkey, Australia, Iraq, France, Norway, and Sri Lanka - each had one published paper, putting them in fourth place. As shown in Table 5, various collaborations have been established between authors from different countries. For example, the primary study's first authors from the USA, China, Turkey, and Australia respectively collaborated with co-authors from Norway, Hong Kong, Australia, and the UK. The first authors from the Netherlands collaborated with co-authors from the UK and Spain, while the first authors from the UK and Hong Kong collaborated with co-authors from South Africa and Serbia, and from China, the USA, and South Korea, respectively. In conclusion, it is worth noting that scientific collaboration between authors from different countries allows researchers to share skills and expertise, leading to improved research quality, increased efficiency, and productivity. In addition, international collaborations promote promising changes in researchers' practices.

The final parameter in the analysis of demographic information relates to the venues utilized by the authors of the primary studies. According to Table 3, out of the 27 primary studies, 17 were published in journals and 10 were presented at international conferences. Among the journals, the "*Journal of Construction Engineering and Management*" and "*Automation in Construction*" were the top two venues, each with two papers. In regards to conferences, it was noted that the "*European Conference on Software Process Improvement*" was the most frequently utilized with two publications. The remaining venues had one publication each.

B. RQ 2. WHAT ARE THE KEY CONCEPTS OF MATURITY EVALUATION?

In the AEC field, maturity refers to the level of development or advancement of a particular technology, process, or method. Generally, it is defined as a measurement of how well a company or organization has implemented and integrated a particular technology, process, or method into their business operations and how effectively they can apply it to real-world projects [50].

In a systems context, maturity can refer to the level of development, integration, and reliability of a system, as well as its ability to adapt and evolve to changing requirements and environments [44]. In other works, De Carolis et al. [58] have indicated that a system can be considered mature when it has reached a stable state and has proven to be effective and efficient in fulfilling its intended purpose over time.

According to Dakhil et al. [50] and Getuli et al. [5], organizations, stakeholders, and users need to evaluate the maturity of their invested technologies to determine their effectiveness in achieving business objectives and the potential for future improvement. Wu et al. [46] explain that maturity evaluation involves assessing the maturity of a system, process, or organization in a specific area of performance or capability, identifying strengths and weaknesses, determining current levels of performance, and identifying areas for improvement.

The key concepts of maturity evaluation can vary depending on the method being used, but some common ones include maturity model, maturity levels, and maturity benchmark, as noted by Yilmaz et al. [33] and Wu et al. [46].

A maturity model is a tool used to measure a project's maturity level according to key process indicators (KPIs) [17]. It provides a framework for evaluating an organization's capabilities in different areas such as strategy, process, and technology, as explained by Succar and Kassem [51]. By comparing a project's performance to established best practices, a maturity model can indicate the actual state of progress reached by a project, as opposed to the desired state, according to Wernicke et al. [59]. The framework of a maturity model comprises aspects, each of which is composed of sub-aspects and evaluation measures [60].

Maturity is typically classified into levels called "maturity levels," which are defined by a maturity model. These levels represent the stages of development that an individual or organization can reach in a particular domain. Maturity levels are usually numbered between 1 and 5, with higher numbers indicating a greater degree of maturity. Alternatively, maturity levels can be represented by categories such as "initial," "managed," "defined," "quantitatively managed," and "optimizing" [59].

According to Wu et al. [46], a maturity benchmark is a standard or point of reference used to evaluate the maturity of an individual or organization in a specific domain. A benchmarking system allows users to compare their project results to those of others in the industry, enabling them to position the maturity of their systems relative to others [49].

It is important to note that the maturity evaluation process should be tailored to the specific context and requirements of the system, process, or organization being evaluated. It should also be conducted regularly to track progress over time [33], [46].

In general, evaluating maturity requires following a specific process, which may include using standardized tools, models, and frameworks, as well as conducting interviews, surveys, and analyzing data [42]. The results of a maturity evaluation can be used to develop a plan for improvement and track progress over time [51].

As part of the study, a comprehensive examination was conducted to identify the most advanced maturity evaluation approaches and tools for evaluating BIM, AR, VR, and BIM-based AR/VR in the literature. An in-depth analysis of the results was then carried out to establish a correlation between the maturity models, with the goal of achieving the intended objective.

C. RQ3. WHAT ARE THE EXISTING APPROACHES AND TOOLS FOR EVALUATING THE MATURITY OF BIM, AR/VR AND BIM-BASED AR/VR?

Table 6 provides an overview of existing maturity approaches and tools related to BIM, AR/VR, and BIM-based AR/VR. The overview includes information on the framework type, name, objective, and development year. According to Yilmaz et al. [33], an analysis of existing approaches and tools was conducted using four criteria: the *number of aspects, sub-aspects and measures covered*, the *evaluation method* used to measure maturity, the *data collection* and *validation methods* used to gather and verify the data. This analysis includes an evaluation of the benefits and drawbacks of each proposed solution.

In the following, the approaches and tools that exist for assessing the maturity of BIM, AR/VR, and BIM-based AR/VR technology are discussed, and a critical analysis is provided in response to the four sub-RQs posed in RQ3.

1) RQ 3.1 WHAT TOOLS AND APPROACHES ARE USED FOR BIM MATURITY EVALUATION, THEIR BENEFITS AND THEIR DRAWBACKS?

Based on analysis conducted and as illustrated in Table 6, 19 maturity evaluation tools were identified. Some of these tools have been assigned specific names, such as the NBIMS CMM maturity model [56], which was developed in 2007 to assess business and management practices in construction projects [56]. This model has been considered a foundation for many subsequent maturity models, such as the Dutch construction industry maturity model developed in 2018 by McCuen et al. [56]. The latter was proposed to study the status of BIM at technological and organizational levels in Dutch industries and to be usable in all phases of a project lifecycle [56].

Among the other most well-known and referenced models in the literature, the BIM Maturity Matrix developed by Joblot et al. in 2009 [62]. This matrix helps organizations evaluate and improve their Building Information Modeling (BIM) processes and is divided into five levels, each representing a different stage of BIM maturity. It is based on a set of criteria, such as BIM software usage, project delivery processes, and data management that organizations can use to assess their current level of BIM maturity and identify areas for improvement [61]. This maturity model was used as a key model for establishing other models for more specific purposes, including the model developed by Dib et al. [57].

Other maturity models have been developed based on international standards, such as the BIM-CAREM maturity model for BIM developed in 2019 by Yilmaz et al. [33]. This model is related to international standards such as ISO 19650 and ISO 55000 and helps organizations assess and improve their ability to implement BIM processes and practices throughout the asset, construction, and maintenance phases of a facility lifecycle [33].

Apart from the range of maturity models presented in Table 6 for assessing BIM maturity in a project, there is another alternative that focuses on evaluating the maturity of Building Information Modeling (BIM) based on the Level of Development (LOD) or Level of Detail [37], [38]. This approach uses a five-level scale, ranging from 100 to 500, to determine the maturity of BIM in a project. Generally, the lowest level, 100, concerns the geometric representation of the building, while the highest level 500 is the most detailed one that concerns the built model of the studied project.

As mentioned above, all identified maturity models have been analyzed based on four criteria. The first one concerns the *number of aspects, sub-aspects and measures covered*. Each maturity model is usually composed of measures grouped into aspects (also known as categories or classification layers or areas) that can include sub-aspects [33]. The number of aspects, sub-aspects, and measures differ from one maturity model to another.

Table 7 presents the number of aspects, sub-aspects, and measures associated with some main existing BIM maturity models, along with examples of these measures. Out of the 32 aspects found in the selected BIM maturity evaluation frameworks, 26 aspects were considered after removing duplicates. As shown in Table 7, some maturity models, such as VDC Scorecard and BIM-CAREM, have a large number of measures, which make them flexible by covering different aspects or sub-aspects of a project. However, they are considered more complex to apply. On the other hand, the BIM Proficiency Index includes a higher number of measures, 32, that are grouped under 8 aspects, but it still doesn't cover most aspects of BIM due to its two layers of classification [33]. Conversely, some maturity models with a smaller

TABLE 6. A summary table of the approaches and tools proposed in the 27 primary studies.

Studied technology	References	Framework type	Framework Name	Objective of development	Year of devel-opment
BIM	[56], [54], [9], [46], [33], [52], [42]	Maturity model	NBIMS CMM	Business and management practices evaluation of construction projects	2007
	[50], [46], [33]	Framework	BIM Proficiency Index	Performance Measurement performance of companies and firms that manage BIM projects	2009
	[51], [50], [46], [33], [42]	Maturity model	BIM Maturity Matrix	Providing an online BIM assessment tool for companies, teams,and individuals	2009
	[54], [50], [46], [33], [42]	Approach	BIM quick scan	Benchmark and monitor BIM performance in the Netherlands	2009
	[54], [51], [42]	Maturity model	BIM Maturity Index	Evaluating information management and the quality of organizations and teams on a BIM-assissted project	2009
	[46]	Maturity model	Characterization Framework	BIM maturity assessment	2011
	[46]	Maturity model	BIM Assessment profile	Assessment of BIM maturity for facility owners	2012
	[54], [49], [50], [46], [33], [42]	Multi-functional Tool	VDC Scorecard	Evaluating the performance and the maturity of VDC (virtual design and construction)	2012
	[33]	Maturity model	Organizational BIM Assessment Profile	Measuring the organization's maturity of planning elements, in order to improve and enhance its performances	2012
	[57]	Maturity model	-	Evaluation of BIM maturity (BIMM) based on online academic and expert consultants related to BIM outside of the USA and existing surveys	2012
	[50], [46]	Maturity model	Owner's BIM CAT	BIM maturity assessment	2013
	[55]	Maturity model	BIM maturity assessment framework	Monitering the development of industries that have accomplished some BIM advancement	2013
	[46]	Approach	BIM Cloud Score	Maturity level Evaluation of BIM modeling techniques	2014
	[49], [33], [42]	Maturity model	Multifunctional BIM Maturity Model	Evaluation of BIM maturity in individual projects, companies that manage many projects, and industries	2016
	[38]	Maturity model	Model maturity index	Describing whole BIM maturity	2018
	[32]	Maturity model	-	Studying the status of BIM at technological and organizational levels in Dutch industries and to be usable in all phases of a project lifecycle	2018
	[33]	Maturity model	BIM-CAREM	Evaluation of the capability of BIM in the ACM / FM industry during all phases of the facility life-cycle (static and dynamic phases)	2019
	[37], [38]	Approach	Level of development	Describe the level of detail, complexity, and completeness of a building or infrastructure model	-
	[11]	Maturity model	-	Evaluating the maturity and the readiness of a project to run BIM	-
	[47]	Maturity model	BIM Maturity measure	Evaluation method to assess BIM in projects	-
AR/VR	[43]	Approach		Improving worksite performance in the aerospace industry	2020
	[48]	Maturity model	-	Examine the factors that drive or impede the adoption of mixed reality technology (AR/VR) in industrial companies	2017
	[45]	Maturity model	-	Identification of AR and VR maturity levels	2018
BIM-based AR/VR	[17]	Approach	-	Mapping between BIM, AR and VR maturity levels	2020
	[40]	Maturity model	-	Assessing BIM-based VR in the AEC industry at the design phase of a project	2021

number of measures are considered easier to apply but less flexible [33].

Based on the review performed, the NBIMS CMM has the simplest framework, consisting of only 11 measures classified into a single layer [62]. On the other hand, the BIM Maturity Matrix covers more aspects of BIM and is composed of three classification layers: process, technology, and policy, which are significantly detailed due to granularity

TABLE 7. Number of aspects, sub-aspects, and measures for some examples of BIM maturity models.

Maturity models	References	Number of aspects	Number of sub-aspects	Number of Measures	Examples of measures
NBIMS CMM	[56], [54], [52], [9], [46], [33], [42]	-	-	11	• Roles and disciplines • Business Process
BIM Proficiency Index	[50], [46], [33]	-	8	32	• IPD Methodology • Creation of a BIM Execution Plan
BIM Maturity Matrix	[51], [50], [46], [33], [42]	3	10	36	• Codes, regulations and standards • Physical and knowledge infrastructure
VDC Scorecard	[54], [50], [49], [46], [33], [42]	4	10	56	• Form of training • Level of Organization
Organizational BIM Assessment Profile	[33]	6	20	-	• Internal Organizational BIM Processes • Functional areas within a facility used to properly implement BIM within the organization
Multifunctional BIM Maturity Model	[49], [33], [42]	3	-	21	• Quality assurance and quality control • Information accuracy
-	[32]	6	16	-	• Job instruction and procedures • Task and responsibilities
BIM-CAREM	[33]	5	-	37	• BIM visions, goals and strategies at organization level • Research and development efforts
-	[57]	5	-	27	• Geospatial capability • Hardware upgrade

levels. It consists of 36 measures at its second granularity level [61].

As shown in Table 7, it can be noticed that some maturity models define sub-aspects corresponding to each aspect. For example, the Organizational BIM Assessment Profile consists of 20 sub-aspects that cover six BIM project aspects, namely strategy, BIM uses, process, information, infrastructure, and personnel [63].

The second criterion relates to the *evaluation methods* of maturity models. Table 8 presents some examples of evaluation methods, data collection, and validation methods for several BIM maturity models.

The BIM evaluation method can involve both qualitative and quantitative evaluations, depending on the specific maturity model being employed. Several BIM maturity models use qualitative evaluation methods, such as the NBIMS CMM [56], BIM Proficiency Index [46], BIM Maturity Matrix [1], Organizational BIM Assessment Profile [33], and Multifunctional BIM Maturity Model [42]. However, other maturity models such as the VDC Scorecard [31], [63], Dutch Industry Maturity Model [32], and BIM-CAREM [33] use a combination of both qualitative and quantitative evaluation methods. The only maturity model that uses a purely quantitative evaluation method is the one proposed by Dib et al. [57]. As illustrated in Table 8, most maturity models generally use a scaling system that depends on the number of maturity levels to be evaluated, while the VDC Scorecard and BIM Proficiency Index use a scoring system. The maturity model proposed by Dib et al. (2012) uses a specific ranking system based on a seven-point Likert scale to assess the relative importance of different factors [57].

Regarding the third criterion, it concerns *data collection methods*. Proper data collection is a crucial process for reliable evaluation. The use of an appropriate method for collecting data ensures gathering the necessary information to answer questions and analyze results [64]. As shown in Table 8, most maturity models collect data through online/offline questionnaires and/or interviews [63]. For instance, the NBIMS CMM, BIM Proficiency Index, and BIM Maturity Matrix use both offline questionnaires and interviews to collect data [42], [62]. Additionally, some maturity models employ specific data collection methods, such as direct observation and excel sheets in BIM-CAREM, document analysis in the Organizational BIM Assessment Profile, and quantitative blank fillings in the VDC Scorecard.

Validation methods represent the fourth criterion to consider in this analysis. Validation is the process of evaluating a system, model, or technique to determine how well it meets its intended purpose and requirements. It involves assessing the accuracy, reliability, and efficiency of the system or model, and verifying that it performs as intended and meets its objectives [65]. Validation can be applied to newly developed techniques or to existing data, and includes a range of procedures and measures to ensure the integrity and quality of the system or data being evaluated [65].

As illustrated in Table 8, there is a diversification of validation methods used by existing maturity models. Interviews with users and specialist consulting is the most commonly used validation method adopted by several Maturity Model, and BIM-CAREM. Some maturity models also employ multiple validation methods. For example, NBIMS CMM has used both professional examination and testing and interviews with users and specialist consulting. Additionally,

TABLE 8. Some examples of evaluation, data collection, and validation methods for some BIM maturity models.

		NBIMS CMM	BIM Proficiency Index	BIM Maturity Matrix	VDC Score-card	Organizational BIM Assessment Profile	Multifunctional BIM Maturity Model	(Siebelink et al. [32]) maturity model	BIM-CAREM	(Dib et al. [57]) maturity model
Evaluation methods	Scaling system	x		x		x	x	x	x	
	Scoring system		x		x					
	Specific ranking system based on Seven-Point Likert scale									x
Data collection methods	Offline questionnaires	x	x	x						
	Online questionnaires				x					x
	Open-ended questions				x					
	Interview	x	x	x		x		x		
	Site visit and data analysis							x		
	Multiple choice questions				x					
	Quantitative blank fillings				x					
	Taking notes using Excel sheet								x	
	Surveys					x	x			
	Direct observation								x	
	Workflow and document analysis					x				
	Interview with audio recording								x	
Validation methods	Professional examination and testing	x			x					
	Interviews with users and specialist consulting	x			x			x	x	
	Multiple types of statistical analysis				x					
	Analyzing real case studies					x				
	Offline surveys						x			
	Delphi method								x	
	Online questionnaires									x
	Quantitative experimental study									x
	Online questionnaires		x	x						x

some maturity models use more specific validation methods, such as the Delphi method in BIM-CAREM, offline surveys in the Multifunctional BIM Maturity Model, and real case studies in the Organizational BIM Assessment Profile.

Concerning the benefits and drawbacks of BIM maturity models, it depend on various factors such as flexibility, simplicity or complexity, the availability of a benchmark system and/or user guidelines, and specific features. However, subjectivity is a negative factor that can affect the effectiveness of maturity models for several reasons [33]. Subjectivity implies that a tool relies on the opinions and assessments of individuals, which can be influenced by factors such as personal biases, past experiences, and personal criteria. Additionally, it may not take into account all aspects and may not provide a complete or accurate picture of their performance. Table 9 presents a comparison between some examples of maturity models based on their main benefits and weaknesses.

As shown in Table 9, some maturity models, such as NBIMS CMM, BIM Maturity Matrix, VDC Scorecard, and Multifunctional BIM Maturity Model, are characterized by their *flexibility* due to their high coverage of aspects and their ability to be adjusted to fit the user's needs [33], [46]. On the other hand, BIM Proficiency index, Organizational BIM Assessment Profile, and BIM-CAREM maturity models do not cover enough BIM aspects to be considered flexible [33], [46], [61].

The second parameter considered is the level of simplicity in the structure of the maturity model. This parameter refers to how easy it is to implement or apply a maturity model. For instance, NBIMS CMM, BIM Proficiency Index, and Multifunctional BIM Maturity Model are known for their simple frameworks [42], [63]. Although the BIM Maturity Matrix model does not have a straightforward structure, it has been successful in identifying areas for improvement and setting goals for BIM implementation within an organization [61].

Regarding benchmarking system parameters, five maturity models are considered as benchmark tools, namely the BIM Proficiency Index, BIM Maturity Matrix, Multifunctional BIM Maturity Model, BIM-CAREM, and VDC Scorecard [33], [46], [63]. Additionally, the Organizational BIM Assessment Profile has provided a user's guideline [46]. As shown in Table 9, it is observed that only two maturity models, NBIMS CMM and BIM-CAREM, can be effectively implemented throughout all stages of a project's life cycle [33], [42].

In terms of subjectivity, the studied frameworks NBIMS CMM, BIM Proficiency Index, and VDC Scorecard are known for their subjectivity and have low levels of consistency and reliability [42], [46], [61]. This is a drawback to keep in mind when using these models.

Some maturity models possess specific features such as the VDC Scorecard that takes into account feedback from interviewees and encourages ongoing improvement [42]. As another example, the BIM-CAREM enables companies to gain a better understanding of the maturity levels of their processes, decrease the likelihood of errors, promote BIM advancements, and allows for multiple evaluations of the same process [33]. However, it is important to note that some maturity models have major drawbacks to consider when utilizing them. For example, the VDC Scorecard maturity model requires more data for its scoring system to be accurate [42], while the BIM Proficiency Index lacks a published validation method [46].

2) RQ 3.2 WHAT TOOLS AND APPROACHES ARE USED FOR AR/VR MATURITY EVALUATION, THEIR BENEFITS AND THEIR DRAWBACKS?

Based on the conducted literature review, there are a limited number of approaches and models for evaluating the maturity of AR and VR systems. Two maturity models, proposed by Hammerschmid et al. in 2017 and 2018 [45], [48], have been identified in the analysis as stated in Table 6. These models address the evaluation of both augmented and virtual reality. In Hammerschmid et al. [48], a first maturity model called MR-CMM (Mixed Reality Capability Maturity Model) was proposed. This model is based on the CMM and takes into account both the scientific significance and practical requirements of AR and VR applications. The MR-CMM provides valuable insights for industrial companies contemplating MR adoption and presents a useful framework for comprehending the factors that can affect MR implementation in industry [48].

In the work of Hammerschmid [45], a second AR/VR maturity model has been proposed to assist companies in making decisions about utilizing these technologies. This model separates the AR and VR technologies and involves five levels of maturity for both AR and VR technologies. Additionally, it can be used to provide a more comprehensive view of AR and VR adoption in construction companies.

As shown in Table 6, Alarcon et al. [43] have proposed an approach that focuses specifically on evaluating the maturity of AR. This approach has been adopted in the aerospace industry to enhance worksite performance and improve space product assurance and safety.

The AR and VR maturity models are evaluated using four criteria: *number of aspects and measures covered*, *evaluation methods*, *data collection methods*, and *validation methods*. Table 10 provides a thorough comparison of these models, highlighting their benefits and drawbacks and allowing for easy understanding of their characteristics.

Firstly, heterogeneity can be observed in the *number of aspects and measures covered*. Four main aspects have been proposed. Three key aspects for AR/VR evaluation include technological and process maturity, organizational maturity, and industry value-chain-related maturity [48]. Evaluation can be done using measures such as access to digital blueprints and process documentation, the company's attitude towards innovation, and the existence of competition, supplier, and customer driven events or projects. The other aspect of AR evaluation concerns technology [43]. It includes two sub-aspects, which are software and hardware. In terms of hardware, several components can be evaluated, such as

TABLE 9. Main benefits and weakness of some BIM maturity models.

		NBIMS CMM	BIM Proficiency Index	BIM Maturity Matrix	VDC Score-card	Organizational BIM Assessment Profile	Multifunctional BIM Maturity Model	BIM-CAREM
Strengths	Flexible	x		x	x		x	
	Simple structure	x	x				x	
	Benchmark system		x	x	x		x	x
	Coverage of all project lifecycle phases	x						x
	Availability of a user's guideline					x		
Weaknesses	Subjective	x	x		x			

TABLE 10. Summary table on the approaches and tools for evaluating AR/VR maturity.

	Mixed reality (AR/VR) capability maturity model [48]	AR/VR maturity model [45]	AR maturity evaluation approach [43]
Number of aspects, sub-aspects and measures covered	Three aspects: Technological and process maturity, organizational maturity and industry value-chain-related maturity	Not clearly introduced	One aspect: Technology, two sub-aspects: Hardware and software, and 14 components
Evaluation methods	Scaling system (six capability levels from 0 to 5) based on the CMM and ISO/IEC 33020 capability levels	Scaling system (five maturity levels from 1 to 5)	Subjective evaluation based on personal judgement
Data collection methods	Student engaging in the studied office to analyze business processes	Qualitative method through focus group discussion	• Online quantitative survey • Qualitative study through a semi-structured phone interview
Validation methods	Case study by applying the proposed maturity model in a Austrian office furniture manufacturer	Case studies in four construction companies	Multiple statistical tests
Benefits	It helps companies to measure their current status and identify areas for improvement when it comes to the implementation of VR and AR technologies	Using a guide during group discussions that leads to encouraging respondents to participate in a focused and structured discussion, which can lead to a deeper understanding of their perspectives	• It highlights areas for improvement and future research • It provides valuable insights for future development
Drawbacks	• The maturity model is considered a first step and still needs more enhancement • The validation method is based on only one case study, and more case studies are required	• Limited generalizability and applicability to a wider range of organizations • Need for further testing and validation to determine the validity and reliability of the maturity models	Lacks a clearly published evaluation method

sensors for 3D object and context detection, chips for high-performance graphics, optics for industrial devices, speakers for sound quality, and the AR display system. Similarly, the software aspect looks at components such as object recognition technology, 3D and planar object tracking, hand gesture and head-motion interaction libraries, authoring tools, remote assistance tools, and capture and management tools for AR.

In terms of *evaluation methods*, a scaling system is used to assess the maturity of AR and VR, as described by Hammerschmid et al. in their 2017 and 2018 works [45], [48]. According to Hammerschmid et al. [48], the capability maturity levels of CMM and the process capability levels of ISO/IEC 33020 can be utilized to evaluate AR and VR processes within an organization. However, in their 2018 work, Hammerschmid et al. proposed a new scaling system with five maturity levels for each AR and VR maturity model. Fig. 4 illustrates the current maturity levels suggested in both studies [45], [48].

	Capability level (Hamershmid et al. [48])
CMM	Level 0: Incomplete
	Level 1: Performed
	Level 2: Managed
	Level 3: Defined
	Level 4: Quantitatively Managed
	Level 5: Optimizing
ISO/IEC 33020	Level 0: Incomplete process
	Level 1: Performed process
	Level 2: Managed process
	Level 3: Established process
	Level 4: Predictable process
	Level 5: Innovating process

	Maturity level (Hamershmid et al. [45])	
VR	Level 5	Total immersion (e.g. physical laws, detailed environment, etc.)
	Level 4	Configuration of the 3D models
	Level 3	Interaction in the virtual world
	Level 2	Adjust background to 3D model
	Level 1	View 3D model in virtual world
AR	Level 5	Problem areas are automatically recognized and suitable solution suggestions are displayed
	Level 4	Connecting other people to share information and presentations
	Level 3	Objects and information can be configured
	Level 2	Objects and information are displayed
	Level 1	Products or environment are tracked (e.g. QR codes) and recognized by AR devices, e.g. smartphones, data glasses

FIGURE 4. **The existing maturity levels proposed in both Hammerschmid et al. 2017 and 2018 studies [45], and [48].**

Both the CMM and ISO/IEC 33020 frameworks have six capability levels, ranging from 0 to 5, as shown in Fig. 4. Level zero in both frameworks represents an incomplete implementation in an organization, while level 5 represents optimization in CMM and innovation in ISO/IEC 33020. In CMM, level 5 results in reduced operational costs, while in ISO/IEC 33020, it signifies an advanced stage of process innovation. Hammerschmid [45] proposed five maturity levels for both VR and AR evaluation.

On the one hand, VR maturity levels pertain to aspects such as visualization, adjustment, interaction, configuration of 3D models, and total immersion. On the other hand, AR maturity levels are centered around tracking, display, configuration, information sharing, problem detection, and solution display. However, Alarcon et al. [43] did not employ a defined evaluation method to assess the maturity of AR; instead, they evaluated each component individually.

Additionally, as presented in Table 10, diversification in the *data collection methods* has been observed. In the study conducted by Hammerschmid et al. [48], data was collected by involving a student in the office being studied. The student was responsible for analyzing various business processes in the office and collecting relevant data for the study. This data collection method provided a firsthand perspective on the processes being studied and yielded valuable insights into the office's operations.

Another method used by Hammerschmid [45] was a qualitative evaluation approach based on focus group discussions with participants from various companies. This method involves conducting structured conversations with 6 to 12 individuals facilitated by a moderator and using stimuli such as a film, image, website, or lecture. Focus groups foster collective understanding through discussion, but group dynamics can also affect the openness of certain perspectives.

Regardless of these methods, Alarcon et al. [43] utilized a data collection method that involved showing participants a video of 5 mock-up use cases for AR's contribution to safety processes and product guarantees in industries. They then conducted a two-part study, starting with an online quantitative survey of 23 questions to evaluate desirability, feasibility, identify additional use cases, drivers and barriers to adoption, and preferred delivery platforms. This was followed by a qualitative study using semi-structured phone interviews to gather information on choice justification and demographics. The team also conducted a simultaneous study to assess AR technology maturity, taking into account technology aspect.

Table 10 presents the *validation methods* used for Hammerschmid et al.'s models [45], [48], which were conducted through company case studies to offer practical insights on the models' usefulness. On the other hand, Alarcon et al. [43] quantitatively validated their AR maturity assessment framework using statistical tests, which established its reliability and generalizability for assessing AR maturity in various contexts.

To summarize, AR/VR maturity models have their advantages and disadvantages. The approach by Alarcon et al. [43] highlights areas for improvement and future research, providing valuable insights for future development. The MR-CMM can also help companies evaluate their AR/VR capabilities and enhance their use of these technologies [48]. Similarly, the AR maturity model by Hammerschmid [45] promotes involvement, encourages open communication, and provides a roadmap for group discussions. However, the usefulness of both Hammerschmid's models for a wider range of organizations still requires further testing for validation. Additionally, the approach by Alarcon et al. [43] lacks a clearly published evaluation method.

3) RQ 3.3 WHAT TOOLS AND APPROACHES ARE USED FOR BIM-BASED AR/VR MATURITY EVALUATION, THEIR BENEFITS AND THEIR DRAWBACKS?

The evaluation of the maturity of BIM-based AR/VR is a relatively new and underexplored topic. Currently, there are only two research studies available on the subject, as shown in Table 11. The first study is conducted by Assila et al. [17] who proposed an advanced approach to developing a maturity model for BIM-based AR/VR evaluation. They defined three maturity levels based on a mapping between existing BIM and AR/VR maturity models. The second study is conducted by Kim et al. [40] who presented a maturity model for evaluating BIM-based VR in the AEC industry during the design phase of a project. This model was developed by interviewing experts and studying existing research on evaluating BIM-based VR in other industries, as there was limited research on this topic within the AEC industry.

In summary, Table 11 presents key information on the aspects and measures considered, methods for collecting and validating evaluation data, and the advantages and disadvantages of existing studies on evaluating the maturity of BIM-based AR/VR.

In fact, the studies by Assila et al. [17] and Kim et al. [40] have identified 10 *aspects for evaluating* the maturity of BIM-based AR/VR. Assila et al. proposed seven aspects, including visualization, interaction, configuration, collaboration, full collaboration, full immersion, and problem detection and solution finding. Kim et al., on the other hand, identified five aspects, two of which overlap with the Assila study, including preparation, immersion, inspection, collaboration, and side effects. These aspects are divided into three phases: the commissioning phase, which focuses on preparation; the usage phase, which focuses on utilization, including immersion, inspection, and collaboration; and the post-usage phase, which deals with the consequences or side effects.

In addition, each aspect consists of one or more sub-aspects that are described as follows: The preparation aspect, which includes VR equipment and the BIM file. The immersion aspect, which refers to the level of realism in a BIM model when experienced in a virtual environment and includes the visual sensation sub-aspect. The inspection aspect, which assesses the functionality that allows users to interact with and view BIM objects and includes six sub-aspects, namely navigation, walkthrough, annotation, object manipulation, gathering non-geometric information, and gathering geometric information. The collaboration aspect involves three sub-aspects, namely multiple users, real-time modification, and real-time communication. Lastly, the side effects that may occur after using immersive VR include dizziness and fatigue sub-aspects [40].

It is worth noting that both studies emphasized collaboration and immersion as key factors in evaluating the maturity of BIM-based VR.

In addition, Kim et al. [40] employed a scoring system as a *method for evaluating* the advancement of BIM-based VR technology. This approach involves assigning scores to specific criteria to determine the overall maturity level of the technology. The scores are calculated by summing up the individual scores for each criterion, providing a systematic and objective evaluation. However, in the work of Assila et al. [17], a clear evaluation method was not mentioned. They defined three levels of maturity for the evaluation of AR/VR-based BIM by mapping the maturity levels of Dakhil et al. [66] to the maturity model of Hammerschmid [45]. As a result, these levels are ranked from 1 to 3. The first level is named BIM visualization with AR/VR. The second level is named BIM interaction, configuration, and collaboration with AR/VR, and the last level is named BIM full collaboration, immersion, problem detection, and solution suggestion with AR/VR.

Moreover, Table 11 illustrates that the BIM-based VR maturity model proposed by Kim et al. [40] involves *collecting data* through offline surveys and interviews to assess the maturity level of an organization in their use of BIM and VR technology. In contrast, the approach presented by Assila et al. [17] does not specify a specific data collection method.

Regarding *validation methods*, Kim et al. [40] used a case study approach and a five-point Likert scale to validate their proposed maturity model. The study involved 10 graduate students who were divided into four groups and were asked to evaluate 15 experiments. The final score was calculated based on the evaluations, and the experienced malaise symptoms were recorded to assess the fifth aspect of the framework. However, the approach presented by Assila et al. [17] did not include any validation process.

In summary, the BIM-based AR/VR maturity tools and approaches proposed by Assila et al. [17] offer several *potential benefits* for the construction industry. By helping to evaluate and identify maturity levels during the design, construction, and maintenance phases, this approach can lead to better overall systems. Additionally, it considers both AR and VR aspects with BIM and provides a clear description of each maturity level. However, the approach is not without *limitations*. There has been no testing or validation of the approach, and there is no guidance provided on how to implement it within companies. Furthermore, there is no mechanism for transitioning from one maturity level to another.

Regarding the study by Kim et al. [40], the BIM-based VR framework provides several benefits for users in selecting a BIM-based VR system that fits their needs and preferences. The framework offers a consistent quantitative assessment method based on well-defined measures and aspects. However, there are some *limitations* to the framework. One drawback is the absence of reference values or examples in the rating system, which can make it difficult to achieve consistent results. Additionally, the experiments evaluating the effectiveness of the framework have been limited to a small number of participants and only one building project.

TABLE 11. Summary table on the approaches and tools for evaluating BIM-based AR/VR maturity.

	BIM-based AR/VR advanced approach of [17]	BIM-based VR maturity model [40]
Number of aspects and measures covered	Seven aspects: visualization, interaction, configuration, collaboration, full collaboration, full immersion, detection problems, and finding solutions	Three stages: commissioning, usage, and post-usage; five aspects, 14 sub-aspects, and 29 measures
Evaluation methods	Proposed approach based on mapping between AR,VR and BIM matuiry levels	Scoring system based on a seven-point Likert scale
Data collection methods	Don't dispose	• Offline surveys • Interviews with professionals
Validation methods	Don't dispose	Case study by applying the proposed maturity model in 15 experiments
Benefits	Help companies to measure their current status and identify areas for improvement when it comes to the implementation of BIM-based AR/VR technologies	• Assists users in selecting a BIM-based VR system that aligns with their needs and preferences • Enables a consistent and systematic evaluation process using well-defined and comprehensive measures and aspects
Drawbacks	• Lack of evaluation measures • Lack of data collection methods • Lack of validation methods	• Inconsistency in scoring measures • Need for further testing and validation to determine the validity and reliability of the maturity models • Limited to the design phase only

Furthermore, the framework only addresses the design phase of construction projects and does not consider other stages of the process.

4) RQ 3.4. WHAT CRITICAL ANALYSIS CAN BE MADE OF THE OBTAINED RESULTS, AND WHAT ARE THE IMPLICATIONS FOR FUTURE DEVELOPMENT AND RESEARCH IN THESE AREAS?

This section presents a critical analysis of the review findings, enabling the systematic and objective evaluation and interpretation of the results. It summarizes the reviewed literature, identifies gaps in existing research, compares different studies and their findings, and identifies the implications of the findings for both practice and future research. Finally, the section presents recommendations based on the review results.

Figs. 5, 6, 7, and 8 present a synthesis of the review findings on BIM, AR/VR, and BIM-based AR/VR maturity evaluation. These figures correspond to the studied aspects, evaluation methods, data collection methods, and validation methods, respectively, and follow a standardized format. The blue circle represents the criteria studied for BIM maturity evaluation tools, the yellow circle symbolizes the criteria for AR/VR maturity evaluation tools, and the third circle is divided into three parts. The two green sections represent the criteria for BIM-based AR in the top section and BIM-based VR criteria in the bottom section, and the white portion in the middle signifies the common data found between them. The shared features of the systems being studied are depicted using small circles that intersect the main circles.

The illustration presented in Fig. 5 provides a comprehensive overview of the main aspects, including sub-aspects, of BIM, AR/VR, and BIM-based AR/VR maturity evaluation. Based on this illustration, several conclusions can be drawn.

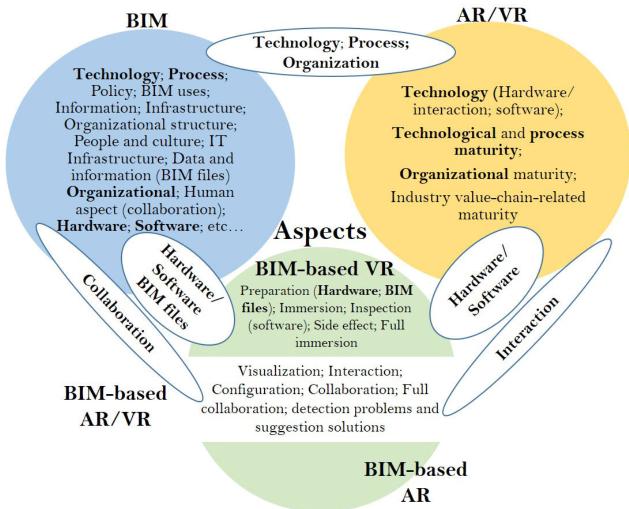

FIGURE 5. Comparative analysis of evaluation methods of BIM, AR/VR, and BIM-based AR/VR maturity evaluation.

One critical aspect of maturity evaluation is the technology component, which encompasses both hardware and software elements. For instance, BIM relies on software applications and hardware devices such as 3D laser scanners and drones to capture and integrate building data into a digital model. Software and hardware components are utilized in BIM to create, manage, and disseminate building information during the design, construction, and operation phases. Similarly, AR/VR employs hardware such as head-mounted displays and specialized software to develop immersive experiences that enable users to visualize and interact with building information. Finally, BIM-based AR/VR combines both technologies to create AR and VR experiences that are directly linked to the BIM model.

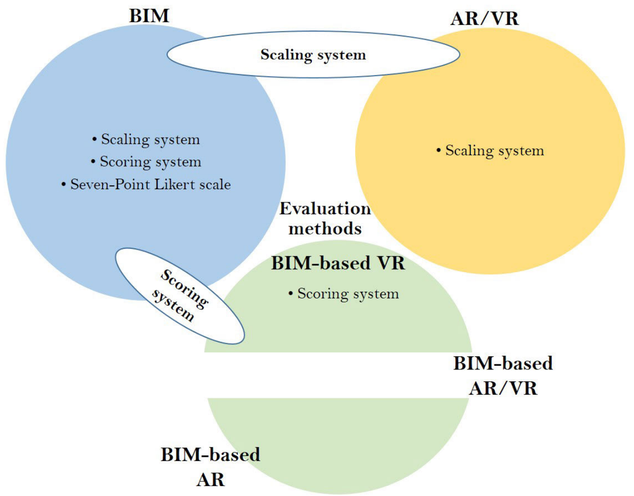

FIGURE 6. Comparative analysis of evaluation methods of BIM, AR/VR, and BIM-based AR/VR maturity evaluation.

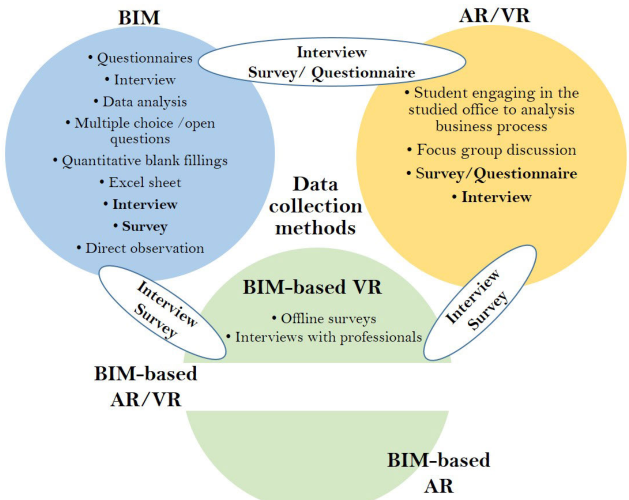

FIGURE 7. Comparative analysis of data collection methods of BIM, AR/VR, and BIM-based AR/VR maturity evaluation.

It can be concluded that both BIM and BIM-based AR/VR systems place a strong emphasis on collaboration. Collaboration plays a crucial role in both systems. In BIM, collaboration is facilitated by using a centralized digital model that can be shared among all stakeholders, including architects, engineers, contractors, and facility managers. This allows all parties to access up-to-date information and make informed decisions throughout the building lifecycle. In BIM-based AR/VR, collaboration is enhanced by using real-time, immersive environments. This allows stakeholders to visualize and interact with the building model in a more intuitive way, making it easier to identify and resolve issues before construction begins. By utilizing AR/VR technology, stakeholders can also experience the building virtually, helping to build consensus and make informed decisions more efficiently.

Furthermore, interaction aspect is a key focus in both AR/VR and BIM-based AR/VR frameworks. It enables users to engage more deeply with the virtual environment and manipulate objects or elements within it. In AR/VR, interaction enhances the sense of presence and immersion in the virtual world, allowing users to explore and interact with it in a more natural and intuitive way. In BIM-based AR/VR frameworks, interaction enables users to access and manipulate data and information about the building or structure being modeled, improving collaboration and communication among project stakeholders. Ultimately, interaction is important in both contexts because it enables users to more fully engage with the virtual environment, increasing the potential for effective learning, communication, and decision-making.

Additionally, BIM and AR/VR have many similarities, especially in terms of their reliance on digital models, their process-driven approach, and the importance of clear organizational structure and communication protocols. Both technologies require a collaborative effort from a range of stakeholders, including architects, engineers, and developers, to create accurate and effective representations of the real-world environment. Both BIM and AR/VR are rapidly evolving, and their continued growth and development will likely depend on technological advancements, the establishment of new standards and protocols, and the stakeholders' ability to collaborate effectively.

In conclusion, the results reveal that while there are shared aspects and sub-aspects between BIM-based VR and BIM-based AR, no specific aspects were identified for the latter system. This finding underscores the paucity of research on BIM-based AR. Unique aspects were only found for BIM-based VR, such as immersion, inspection, full collaboration, and side effects. Based on these results, it can be inferred that no specific aspects are available for the BIM-based AR system, emphasizing the importance of evaluating this system.

Fig. 6 illustrates the evaluation methods employed by maturity assessment tools for BIM, AR/VR, and BIM-based AR/VR. BIM is depicted as the most advanced system, utilizing three evaluation methods: scaling system, scoring system, and Seven-Point Likert scale. In contrast, both AR/VR and BIM-based VR systems have only one evaluation method each, which aligns with BIM and is the scaling system and scoring system, respectively. However, a crucial observation from the figure is the absence of a clearly defined evaluation method for assessing the maturity of BIM-based AR, highlighting a research gap in this area. Furthermore, the results indicate that AR and VR are relatively new technologies and are still in the early stages of developing methods for evaluating their maturity, with only one evaluation method available for each. This highlights the requirement for further investigation and advancement in these areas to improve and establish effective methods for evaluating the maturity of these technologies.

Fig. 7 illustrates the data collection methods used to assess the maturity of BIM, AR/VR, and BIM-based AR systems, highlighting commonalities. These methods include

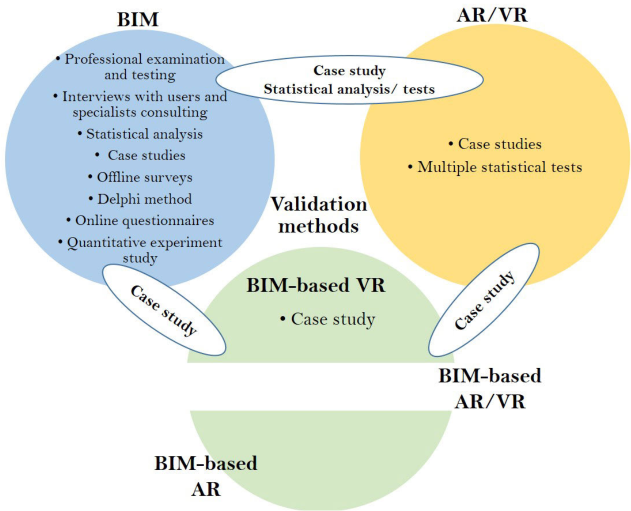

FIGURE 8. Comparative analysis of validation methods of BIM, AR/VR, and BIM-based AR/VR maturity evaluation.

interviews, questionnaires, multiple-choice questions, and focus group discussions. Interviews and questionnaires are commonly used for data collection in these systems, except for BIM-based AR, which lacks a defined data collection method. In comparison to the data collection methods available for BIM maturity evaluation, there are significantly fewer methods for AR/VR and BIM-based VR. This situation emphasizes the need for further research to develop appropriate and effective data collection methods for evaluating the maturity of AR, VR, BIM-based VR, and especially BIM-based AR systems.

Concerning the methods of validation, Fig. 8 depicts the various techniques utilized to assess the maturity of BIM, AR/VR, and BIM-based AR/VR systems. The results show that a variety of methods are employed for BIM maturity assessment, while only two methods are used for AR/VR and one for BIM-based AR/VR. Statistical analysis and testing are commonly used for both BIM and AR/VR maturity evaluations, while case studies are used for all evaluations except for BIM-based AR. These findings highlight the limited research on AR/VR and BIM-based AR/VR systems, as only a few validation techniques were identified. This underscores the need for further research in this area.

In summary, there is a lack of evaluation tools to measure the maturity of AR/VR and BIM-based AR/VR systems, in comparison to the BIM maturity models. This suggests a need for more research in this area. The existing models designed for evaluating BIM cannot accurately assess BIM-based AR or BIM-based VR systems due to the introduction of new aspects brought about by their integration. To develop a reliable maturity model, it is necessary to incorporate all relevant aspects and measures use a defined scaling system with well-defined maturity levels or a scoring system, implement a robust evaluation method, employ a data collection method that combines user interviews and questionnaires, validate through case studies and expert interviews, and provide a benchmark and user's guide for implementation and usability.

IV. CONCLUSION

In this paper, a systematic literature review was conducted using a structured research methodology to provide an overview of the maturity evaluation of BIM, AR/VR, and BIM-based AR/VR technologies. Cross-referenced evaluation approaches and tools were identified based on aspects, evaluation methods, data collection methods, and validation methods. A critical analysis was performed to capitalize on all the results and provide lessons to learn about this topic. This review helped us identify potential benefits and complementarities of validating the maturity of BIM-based AR/VR systems, including a lack of validation methods, inconsistency in rating measures, and limited applicability. Further research is needed to create a comprehensive tool for evaluating the maturity of these technological systems.

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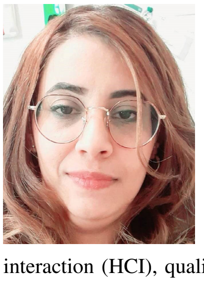

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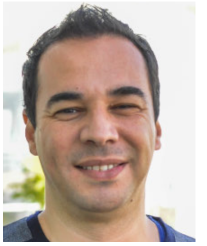

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