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Using virtual reality to facilitate communication in the AEC domain: a systematic review

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Abstract

Purpose – The architecture, engineering and construction (AEC) industry exists in a dynamic environment and requires several stakeholders to communicate regularly. However, evidence indicates current communication practices fail to meet the requirements of increasingly complex projects. With the advent of Industry 4.0, a trend is noted to create a digital communication environment between stakeholders. Identified as a central technology in Industry 4.0, virtual reality (VR) has the potential to supplement current communication and facilitate the digitization of the AEC industry. This paper aims to explore how VR has been applied and future research directions for communication purpose.

Design/methodology/approach – This research follows a systematic literature assessment methodology to summarize the results of 41 research articles in the last 15 years and outlines the applications of VR in facilitating communication in the AEC domain.

Findings – Relevant VR applications are mainly found in building inspection, facility management, safety training, construction education and design and review. Communication tools and affordance are provided or built in several forms: text-based tools, voice chat tool, visual sharing affordance and avatars. Objective and subjective communication assessments are observed from those publications.

Originality/value – This review contributes to identifying the recent employment areas and future research directions of VR to facilitate communication in the AEC domain. The outcome can be a practical resource to guide both industry professionals and researchers to recognize the potentials of VR and will ultimately facilitate the creation of digital construction environments.

Keywords Virtual reality, VR, Communication, Architecture, Engineering, Construction, AEC, Industry 4.0

Paper type Literature review

1. Introduction

The architecture, engineering and construction (AEC) industry exists in a dynamic environment that involves several parties, including owners, architects, engineers and contractors, to communicate constantly with each other in different phases of a project. Communication is defined as the transmission of recourses, such as knowledge, data and skills, among different parties by using shared symbols and media (Cheng *et al.*, 2001). Communication can also be interpreted as a process of understanding and applying the dynamics of sending and receiving both verbal and nonverbal messages (Pritchett, 1993). Within the practical context of the construction industry, communication takes place in both fundamental and high-level forms, i.e. from interpersonal communication to group or team communication and organizational or corporate communication (Dainty *et al.*, 2007; Gamil

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and Rahman, 2017). Interpersonal communication takes place within construction project environments that occurs directly between individuals, including both verbal and non-verbal cues (Dainty *et al.*, 2007). For instance, communication through face-to-face meetings or through other media (e.g. telephone, e-mail and fax) can be regarded as interpersonal communications. Group and team communication takes place in a team that involves groups of people with different skills, knowledge and abilities (Dainty *et al.*, 2007). To understand the communicate mechanism based on a unit of "team," it is fundamental to understand the formation and development of the team. Organizational and corporate communication refers to the total communication activity generated by a company to transmit its coherence, credibility and ethics (Jackson, 1987; Dainty *et al.*, 2007; Van Riel and Fombrun, 2007).

Efficient communication is an essential demand because of the intrinsic complexity of the AEC industry (Zhang and El-Diraby, 2012). It is widely believed and proved that efficient and frequent communication leads to better performance of construction processes. For example, the delivery process and quality of projects can be improved by successfully communicating facility requirements and construction prerequisites among major stakeholders in the early phase of a project (Du *et al.*, 2016). As another example, communicating in the design process can help optimize this process by stressing design requirements, reducing misunderstanding between designers, and improving customers' satisfaction on design outcomes (Koutsabasis *et al.*, 2011; Wu and Kaushik, 2015). The importance of communication is emphasized by not only industry but also academia. Efficient communication skills are most often considered valuable career enhancers (Polack-Wahl, 2000) and these skills reflect the key outcome requirements of undergraduate AEC programs [e.g. American Council for Construction Education (2014) student learning outcome 1and Accreditation Board for Engineering and Technology (2016) student outcome]. Riemer (2007) discussed various elements in communication skills education, such as oral, listening, written, visual, interdisciplinary and intercultural, which provides a hint on how to improve communication skills for individuals and ensure sufficient communication channels among stakeholders.

Drawings and specifications in digital or paper forms are traditionally and heavily used to facilitate communication between AEC professionals throughout the entire life cycle of a project (Laufer and Tucker, 1987; Shiratuddin and Thabet, 2011). Moreover, regular meetings are usually organized as another technique to facilitate communication through information exchange and problem identification (Gautier *et al.*, 2008). Building information modeling is later introduced as a more informative and detailed approach to facilitate communication (Manning and Messner, 2008). However, evidence still indicates current communication practices have failed to meet the requirements of increasingly complex projects in the AEC industry. The main type of information exchange on construction jobsites is still paper based (e.g. drawings, data collection forms, progress information and specifications), which is a major constraint in on-site information exchange (Bowden *et al.*, 2004; Chen and Kamara, 2008). Furthermore, such inefficient communication can result in onsite personnel overlooking issues that need a quick response and cause deferred decision-making (Singhvi and Terk, 2003). According to Project Management Institute's 2013 Pulse of the Profession report, US$135m is at risk per US$1bn on a project, and 56% of it (US $75m) is because of ineffective communication. From a pedagogical perspective, although communication intensive courses are provided in college (O'Donnell *et al.*, 2011) and other relative skills development methods, such as giving presentation, role-playing and submitting assignments in audio/video form, are suggested (Riemer, 2002), lack of communication skill is still found in students (O'Donnell *et al.*, 2011; Sheth, 2015; Clement and Murugavel, 2015).

Along with this situation, new communication challenges for the AEC industry are growing these years, which can be attributed to several factors. First, there is a steady increase in the clients' need for high-quality service and better project performance with higher profitability (Dainty *et al.*, 2007). This requires efficient communication between the clients and other stakeholders (e.g. designers, engineers, contractors) to accurately interpret and satisfy client needs and expectations. Second, the current communication practice in the industry has resulted in the separation of design and construction processes, which potentially leads to confusion and misunderstanding, and ultimately causes defects and rework (Chen and Kamara, 2008). Later, the importance of integrating processes has been emphasized, and such drive for process integration introduces new communication challenges for the industry. Furthermore, workforce diversification and globalization are increasingly prominent features of the nowadays AEC industry (Zelkowicz *et al.*, 2015). Various cultural and social backgrounds, language barriers and unfamiliar working environments can inhibit the development of trust and mutual understanding and results in less effective communication channels.

With the advent of Industry 4.0, there is an increasing trend of the creation of a digital value chain that enables the communication between the construction projects and various stakeholders, and the digitization and automation in manufacturing processes (Lasi *et al.*, 2014). Industry 4.0 was initially developed by the German Federal Government to approach its high-tech strategy and has now been used as a synonym of the Fourth industrial revolution because of its technological potential in improving productivity and quality (Lasi *et al.*, 2014; Oesterreich and Teuteberg, 2016). To implement Industry 4.0, two key features identified by Oesterreich and Teuteberg (2016) are horizontal integration of information technology (IT) systems, processes and data flow between different stakeholders and vertical integration of IT systems, processes and data flows within the company from product development to manufacturing for cross-functional collaboration. These key features reflect the demand on digital communication throughout the project life cycle, also emphasizes the significance of communication in this Fourth industrial revolution.

Identified as one of the major technologies that contributes to the digitalization of the construction environment in Industry 4.0, virtual reality (VR) represents innovative technological tools that may supplement current AEC practices to enhance communication between various stakeholders on a project. VR is defined as an entirely computer-generated environment where users can manipulate and interact with objects, immerse and navigate around in real time (Warwick *et al.*, 1993; Briggs, 1996). Rheingold (1991) described an experience in VR is "surrounded by a three-dimensional computer-generated representation, and is able to move around in the virtual world and see it from different angles, to reach into it, grab it, and reshape it." Compared with traditional communication methods, VR-based environments can support synchronous communication with shared 3D visualization of information, which reduces coordination latency and avoids misunderstanding caused by different interpretations of 2-dimensional (2D) documents made by different stakeholders (Carlsson and Hagsand, 1993; Dossick and Neff, 2011; Eastman, 2011; Anderson *et al.*, 2014). Because of its characteristics, it allows communication to take place in a "synthetic" manner (Regenbrecht and Donath, 1997). There are various levels of immersion a VR system can provide, and there are two most commonly applied VR systems, including fully immersed VR and partially immersed VR (Coulter *et al.*, 2007). Immersion indicates the objective level of sensory fidelity of a VR system and heavily depends on the rendering software and display technology of the system (Slater, 2003). Fully immersed VR, also named as immersive VR, has a higher level of immersion, and the user can only see the virtual world. High-end VR technologies such as head-mounted display (HMD), 3D tracking systems and stereoscopic projection displays are often needed to support fully immersed VR systems (Bowman and McMahan, 2007). On the other hand, the partially immersed VR system (aka desktop VR), is typically displayed using a computer screen, and users are aware of the real environment when they are experiencing a virtual environment. Although VR technology has identified as one major innovative technology in Industry 4.0, its specific effects in promoting the implementation of Industry 4.0 considering its communication-related characteristics have not been fully explored yet.

To further understand how VR can potentially enhance communication efficiency in the AEC domain, the very first step is to understand how they have been applied in this field and identify what aspects of communication they are facilitating. Numerous studies of VR applications in the AEC domain have been conducted over the last couple of years. And several studies investigated the trends of VR application within various aspects of the AEC domain including construction safety (Bhoir and Esmaeili, 2015; Li *et al.*, 2018; Zhou *et al.*, 2012), construction education (Wang *et al.*, 2018) and the general built environment (Kim *et al.*, 2013). For instance, Li *et al.* (2018) reviewed VR/ augmented reality (AR) applications from four aspects: VR/AR technology characteristics; VR/AR application domains in safety management; safety enhancement mechanisms; and safety assessment and evaluation, whereas Wang *et al.* (2018) investigated the use of VR in construction education and training and mainly discussed applications in the fields of architecture visualization and design, structural analysis, construction safety training and equipment and operational task training. Notably, these application contexts are not limited to classroom setting – the contents of architecture visualization, safety training and equipment and operational task training can be found for both industrial and educational settings. None of these studies investigated the communication aspect of the VR and how such a medium can enhance the communication processes within the AEC domain. Unlike previous review articles, this review article specifically investigates various contexts in both industrial and educational settings of applications with a focus on communication, identifies commutation affordances and assessment techniques used and discusses how VR was adopted to facilitate communication in the AEC domain. This study included both industrial and educational applications in the AEC domain to cover a more comprehensive range of papers. Though the purpose of the industry and education areas can be different, the application contexts can be very close to each other. For instance, building inspection (i.e. the inspection of a building to ensure building code requirements are met) is an essential step in industrial settings to ensure the project quality, whereas the exact context can also be applied in educational settings to train students on reading drawings and specifications. Therefore, both industrial and educational applications are included in this study without specific exclusion. This review aims to understand how VR technology developed and implemented for communication-relevant applications. Notably, all communication processes begin with interpersonal communication before manifesting in other forms of communication. In this study, the focus is on the most fundamental level of communication, which is the interpersonal communication between individuals at a fundamental level of human-to-human interaction. This study systematically explores the existing literature to specifically identify the recent employment areas of VR that facilitated communication in the AEC domain, the trends in using VR for communication purposes, communication affordance types, assessment techniques used in those applications and technology adoptions and challenges of such applications. Last but not least, the future research directions will be discussed based on the limitations and challenges found in current VR applications. The significance of this research lies in that it presents the state of the VR applications in facilitating communication in the AEC domain and brings more attention to their context and future research directions as well as communicational and technological implementation. The expected outcome of this content analysis-based review can benefit both industry professionals and researchers in the AEC-related contexts by helping them recognize potentials of such applications and understand the requirements, challenges and the future research directions of VR technologies and guiding future researchers and industry professionals in implementing VR, which will ultimately facilitate the creation of digital value chain that supports communication between various stakeholders throughout the project life cycle.

2. Research methodology

This research used the content analysis-based literature review method, which is a well-recognized method for reviewing works of literature and synthesizing outcomes (Li *et al.*, 2018). Compared with single research studies, this method can address much broader research questions (Siddaway, 2014) and explore research trend by generating overviews of researches; therefore, it is widely applied in the research field of AEC (Mok *et al.*, 2015; Liang *et al.*, 2016; Eiris and Gheisari, 2017; Oraee *et al.*, 2017; Li *et al.*, 2018). To perform an organized literature search and selection process, preferred reporting items for systematic reviews and meta-analyses (PRISMA) (Moher *et al.*, 2009) flow diagram, which is a systematic record selection process, was implemented. This diagram describes the information flow throughout the following four phases, *identification, screening, eligibility* and *inclusion,* and presents the number of the literature identified, included, excluded and the reasons for exclusions (Figure 1).

In identification phase, potentially relevant records would be identified. This research study identified critically evaluated and integrated relevant studies and research papers from bibliographic database. This study only included the peer-reviewed publications (journal publication and conference proceedings). Other publications such as book chapters or reports were excluded because they may not go through the same editorial process before publication and may not be peer reviewed ("Are books peer reviewed?", 2015). To search and identify potentially relevant records, research questions were broken into individual concepts to create keywords. Then collected literature was screened and filtered based on formulated exclusion criteria. Finally, all the included records were discussed and analyzed based on the review taxonomy, which will be discussed in detail in Section 4. This was a dynamic process where keywords were concluded and enriched by the screened records and used to collect more potentially relevant records. The language of the reviewed literature is limited to English only.

2.1 Identification

This study is to explore how VR is applied in the AEC domain to facilitate communication between stakeholders or individuals. To start the literature search, an unconstrained and unconstructed search was conducted to find any relevant publications. Based on the investigation of these publications and the authors' experience, possible keywords were identified, and the literature searching with relevant publication was further conducted in two directions: database searching and supplementary searching. Database searching was conducted based on the keywords identified during the unconstructed search, whereas the supplementary searching was conducted based on relevant publications identified from the unconstructed search and the database searching (Figure 2).

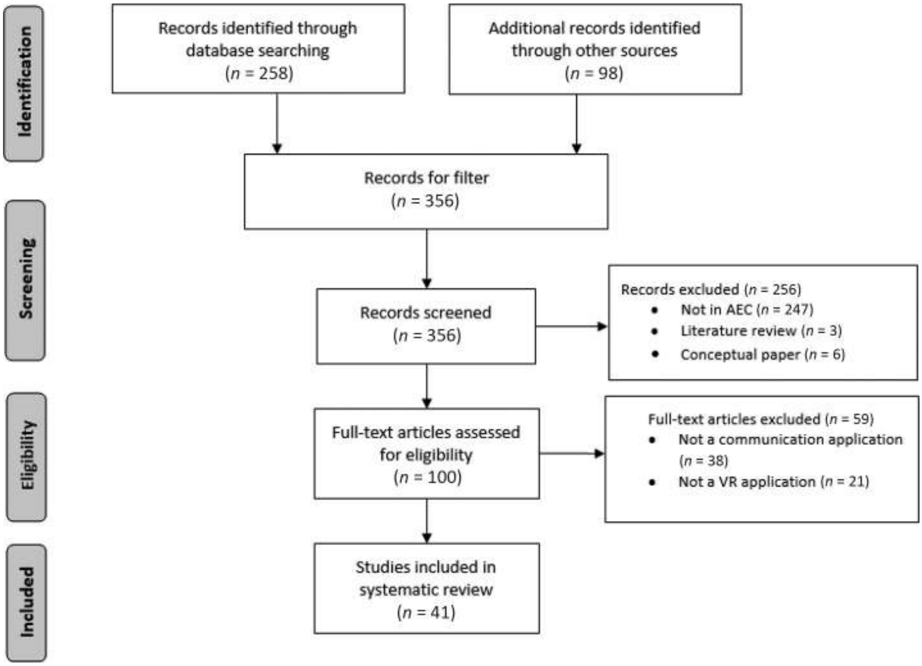

Figure 1.
PRISMA systematic records selection flow

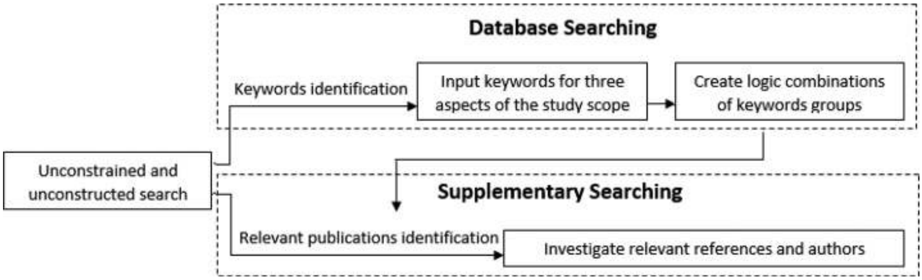

Figure 2.
Workflow of literature search

Research questions were broken down into three specific scopes of VR applications, communication-related procedures and field of AEC domain followed by creating keywords for each specific scope. As it is displayed in Table 1, alternative terms were identified to cover three scopes. The keywords for AEC were generated by enumeration; keywords for communication included its synonyms such as data/information exchange and broader terms such as collaboration and interaction; similarly, synonyms and narrower terms were selected as keywords to constrain VR scope. After keywords were generated from previous unconstrained and unconstructed search, a searching phase was conducted on one of the most popular sources of scientific information in biomedical sciences (Falagas *et al.*, 2008), namely, Web of Science. Web of Science is a bibliographic database that has a high coverage in the field of natural science and engineering (Mongeon and Paul-Hus, 2016) and is a popular data source that has been widely applied in the literature review in construction domain (Dutra *et al.*, 2015; Li *et al.*, 2018; Sun *et al.*, 2015; Taroun, 2014; Wang *et al.*, 2018). It offers more sophisticated and focused search options, and queries can be filtered and refined (Harzing, 2010). It can recognize logical relations between words (i.e. AND and OR) and furthermore, to build combined sets, where a set represents one search result within desired logical relations. Its powerful searching capability supported us in performing a well-constrained and well-organized database search with our generated keyword groups and designated logic relations. In this study, an advanced search was conducted in following two steps:

(1) using keywords in OR relation to search articles that represent respective aspect (AEC), and repeat for two more times for the rest tow aspects (communication and VR); and

(2) select three search results (sets #1, #2 and #3) and create an AND combined set. A total of 258 articles were identified through this process.

Meanwhile, a supplementary literature search was conducted beyond the Web of Science to cover a broader range. From the unconstrained search and database searching, several relevant publications were identified. Within these publications, potentially relevant references and authors were also further investigated, and related publications were included in our study. This manual literature search process was also critical to our study because some relevant studies that involve communication may not be included by the database searching process based solely on keywords. The concept of communication is relatively broad, and the authors of some publications may select more focused and detailed keywords for their study. For instance, Le *et al.* (2016) investigated students' interactive and experiential learning experiences in a VR-based construction inspection game, whereas communication between students was enabled and facilitated with enriched features in the VR application, the authors did not include communication in their keywords because communication is not their direct study focus. Therefore, the manual literature search, i.e. the supplementary searching, was essential to this study to cover more relevant papers.

In the end, there were 356 papers identified from the unconstrained and unstructured iterative query and structured search, including peer-reviewed journal publication and conference proceedings being identified as potentially relevant research studies for further exploring. Conference papers are recognized with several advantages, especially from the publication time aspect. Conference papers take a shorter time for feedback and can present the ongoing work so far, so they can be a convenient tool to communicate the lasted research work (Mansoori, 2013). Therefore, conference papers can help us better understand the latest and up-to-date VR applications within our scope.

2.2 Screening

In the PRISMA's "Identification" phase, a total of 356 manuscripts from peer-reviewed journal publication and conference proceedings was identified as potentially relevant

Filter	Individual scope	Keywords
Title	AEC	Architecture, engineering, construction, design
	Communication	Communication, multi-user, multi-player, collaborate, collaboration, collaborative, interaction, interactive, data exchange, information exchange
	VR	VR, virtual team, virtual environment, virtual world, virtual, visualization, serious game, game, digital, 3-dimensional, 3 D

Table 1. Literature review keywords

research studies and were used in the "Screening" phase. In this phase, 256 publications were excluded after reviewing their titles and abstracts. As words "architecture," "design" and "construction" are frequently used in other disciplines, the majority of searched publications (247 papers) were excluded because of their outside AEC scope. Moreover, three literature review papers and six conceptual papers with no specific applications of VR were excluded in this phase as well.

2.3 Eligibility

In the "Eligibility" phase, the full text of remaining 100 publications were reviewed, and 59 publications were excluded because they were either not a true VR application or did not explore any specific aspect of communication. It was observed that though communication or relevant terms appeared in some publications' texts, only the concept of communication was referred to generally. These research studies mentioned communication-relevant terms generally without exploring specific aspects of communication or describing what communication channels were provided by the applications, resulting in an uncertain relation between their applications and communication. In other words, there was not enough justification or details provided on how proposed applications were relevant or used for communication improvement. Furthermore, in some literature, the researchers took advantage of a basic feature of VR applications that is providing a shared visualization for users. Such applications were excluded from the review if they solely enabled shared visualization with no focus on specific communication channels. There were 38 publications classified into "Not a communication application" criteria and thus excluded.

A total of 19 publications were classified as "Not a VR application." During the "Identification" phase, "Digital," "3 Dimensional (3D)" and "4 Dimensional (4D)" were keywords to capture potential VR applications. However, in the "Eligibility" phase, some applications developing digital platforms and/or implementing 3D/4D models were not eligible to be defined under VR categories. According to Rheingold (1991), VR provides an environment where users are surrounded by the computer-generated world and able to move around to interact with it. Excluded applications were mainly digital platforms where the interaction between users and the virtual world was limited to clicking buttons with a very limited sense of immersion (the feeling of being there). These applications were considered as "Not a VR application." In other words, if there was no sufficient justification or details provided on how proposed applications were using VR to facilitate the communication process in the AEC domain, the papers had been excluded. After passing the "Eligibility" phase, 41 publications were induced in our systematic review.

2.4 Inclusion

A total of 41 publications were obtained from systematic selection flow for individual analysis. To develop a fundamental understanding on types of the contribution made by VR applications in facilitating communication, data included in this study were classified into "Direct Facilitation" and "Indirect Facilitation" criteria. "Direct Facilitation" included studies where authors claimed and emphasized that their applications were developed to improve communication efficiency or overcome communication barriers, used research methodology techniques such as a pilot study, case study or survey to assess the communication factor directly. In other cases, although the objective of the study was not mainly focused on communication improvement, there was recognizable communication affordance provided by applications, and the research objective was achieved through providing communication channels and improving communication efficiency. Different research methodology techniques such as pilot study, case study or surveys were also used in such projects;

however, the beneficial effect of their applications on facilitating communication was assessed indirectly. As an example, to improve learning efficiency of construction safety knowledge, researchers developed a VR platform to deliver knowledge in immersive hazardous (Le *et al.*, 2015). Such studies were identified under "Indirect Facilitation" category because the main focus of the study was on delivering the safety knowledge and its assessment; however, they used rich communication channels between students and instructors to achieve it. It is noticed that among 41 application that facilitated communication directly or indirectly, 9% of which (4 papers) intend to focus on communication (other alternative terms may be used) as their research objective, whereas 91% of which (37 papers) used and facilitated communication as an approach to achieve their other research objective.

3. Current status of the research

The number of publications per year is illustrated in Figure 3. From 2003 to 2010, relevant articles were published in a series of low and steady numbers with an average of 1 publication per year. In the year 2011, there was a significant and rapid increase in the publication number (7). Publication in 2011–2018 has an average of 4.125 publications per year with two additional local peaks, in 2014 (seven publications) and 2018 (four publications). This increase may suggest that, along with the development and maturity of VR technology, the AEC domain has also seen a more significant implementation of VR for communication purposes.

Furthermore, the number of publications was categorized based on published sources and corresponding year range of publication. Table 2 displays the publication sources with more than one article on VR application to facilitate communication in the AEC domain. *Journal of Information Technology in Construction* contributed most publications (22%) to the research topic with 9 articles in years 2008–2017, followed by *Construction Research Congress* (10%), *The International Conference on Construction Applications of Virtual Reality* (10%), *Journal of Automation in Construction* (5%), *International Journal of Project Management* (5%) and *Journal of Construction Engineering and Management* (5%). These sources suggest that publications relevant to the topic of VR applications in communication are mainly published in technology-related journals and conferences and within the general

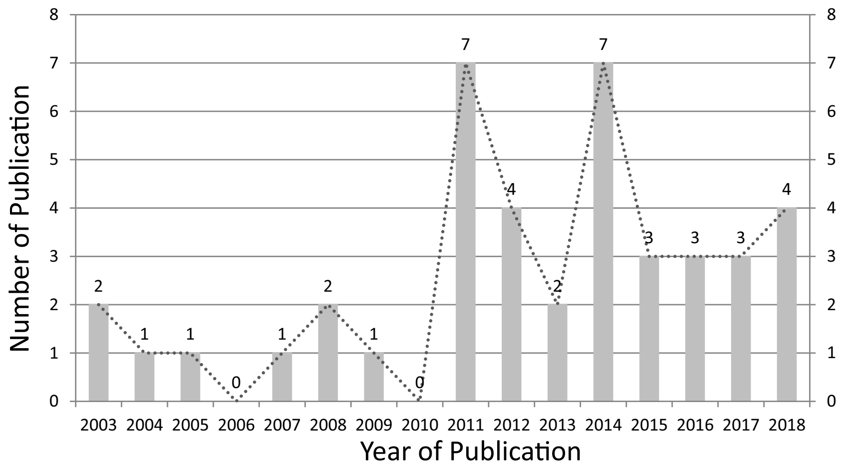

Figure 3.
Publication number 2003–2018

area of construction engineering and management. The remaining publications are distributed among journals and conferences from various design and engineering concentrations, which indicate multidisciplinary research efforts of VR applications in communication within the AEC domain.

Additionally, the obtained publications were analyzed using word clouds. This approach visualizes word frequency and visually weights keywords with higher frequency in a larger font. Publication titles and their authors' last names were assessed using this approach to provide an overview of author publication frequency and title words. In Figure 4(a), it was observed that the most frequent words contained in the publication titles were "Virtual," "Construction," "Design," "Learning" and "Collaborative." "Virtual" was the word with most occurrences, and it showed VR environments were frequently applied for communication purposes in the AEC domain. "Construction" and "Design" showed the fields where VR was frequently applied to improve communication efficiency. "Learning" and "Collaborative" indicated education and collaboration were the main application contexts where VR was applied to facilitate communication within the AEC domain. From Figure 4(b), it was observed that the top authors published are John E. Taylor (Georgia Institute of Technology), Josh Iorio (Virginia Polytechnic Institute and State University), Carrie Sturts Dossick (University of Washington) and Anne Anderson (Washington State University). The author with the most significant number of publications, John E. Taylor, has 13 articles between 2012 and 2018, and his publication focuses on virtual team collaboration in the

Table 2. Number of publications by journal or conference on year range

Journals and conferences	Year range	Publication number (%)
Journal of Information Technology in Construction (ITcon)	2008–2017	9 (22)
ASCE Construction Research Congress (CRC)	2014–2018	4 (10)
The International Conference on Construction Applications of Virtual Reality (CONVR)	2003–2018	4 (10)
Elsevier Journal of Automation in Construction	2011–2013	2 (5)
ASCE Journal of Construction Engineering and Management	2012–2017	2 (5)
Elsevier International Journal of Project Management (IJPM)	2014	2 (5)
Others	2003–2018	18 (43)
Total		41 (100)

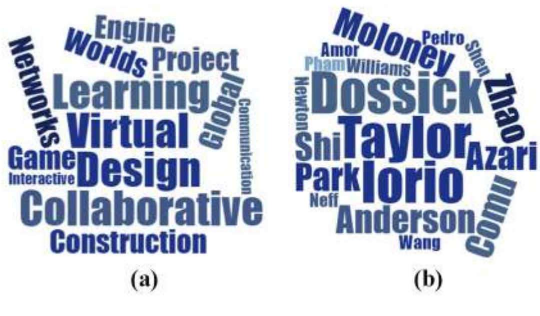

Figure 4. Word clouds

Notes: (a) Articletitles; (b) authors virtual world (CyberGRID). Countries that conducted relevant research were also assessed in this part of the study. The USA has the most research studies with 21 publications between 2011 and 2018, followed by Korea, Australia and New Zealand with four publications.

4. Content analysis-based review

Given the nature of the content analysis-based review, the study needed to deal with a significant number of papers. Therefore, it was essential for the study to identify a review taxonomy that can help direct the review process and concentrate the content analysis on specific research areas. To elicit and report valuable findings logically and systematically, this paper presented a review taxonomy for four specific research scope of this review paper, including *VR Adoption and Challenges*, *Communication Affordance, Context of Application,* and *Communication Assessment Techniques* (Figure 5).

The process of designing and developing an effective application to improve communication under certain contexts in the AEC domain requires several elements to be taken into consideration. What technology should be implemented would be an element to consider at an early stage of the process. *VR Adoption and Challenges* and *Communication Affordance* section reported the content analysis from a technological perspective. The content analysis of *VR Adoption and Challenges* provided basic information about what hardware and software are required for applying VR technology. The challenges and limitations were also discussed to provide a more critical understanding of such technologies. *Communication affordance*, which represents the specific communication-related features provided by such technology, can provide a further introduction on how

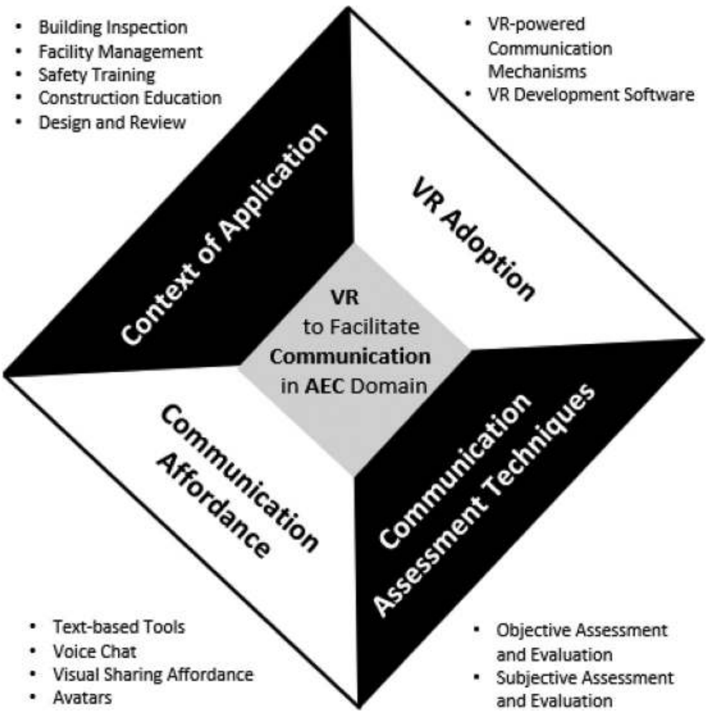

Figure 5.
Review taxonomy

(through what channel) can VR be used to facilitate the communication process. This analysis would present what affordance has been widely developed and used, which may also provide a hint on what other features and functions can be developed in future research studies. *Context of application* was explored to identify the VR applied contexts and their associated phases or activities within the AEC domain. The analysis of application context would help improve our knowledge about what specific situations and contexts have implemented VR technologies for communication-related applications. The analysis of *communication assessment techniques* allowed us to understand how effectively the applications in reviewed publications could improve communication processes.

4.1 Context of applications

Throughout the literature review, tendencies were observed which led to categorizing application contexts of VR into the following groups:

- *Building inspection*: Inspection of a building to ensure building code requirements are met.
- *Facility management*: Maintenance of existing buildings and management of stakeholders.
- *Safety training*: Process of facilitating the learning process of safety and hazard identification and management.
- *Construction Education*: Education on the construction process of a building or infrastructure, excluding safety training; and
- *Design and Review*: Creation of a plan or convention for the construction of a building or infrastructure, and evaluation of a design.

Both industrial and academic contexts were analyzed to obtain an overall understanding of the applications for facilitating communication under the AEC context.

As it was discussed in Section 1, Introduction, the new communication challenges are mainly attributed to such aspects:

- the communication improvement in terms of effectively understanding clients' demand and providing high-quality service accordingly;
- the integration of plan, design and construction processes; and
- globalization of the AEC industry (Dainty *et al.*, 2007).

Because these factors are highly context-relevant, they are investigated in this section based on the discussion of the VR application contexts. In this section, we can have a better understanding on how these VR applications have been used in different contexts, and how can these applications prepare the AEC industry to embrace different aspects of the communication challenges. If a VR application provided a client-focused communication channel between the client (i.e. the owner or the user of the product, such as nurses for a healthcare facility) and other stakeholders, such application would be considered as contributing to the 'communication improvement'. If communication channels were enabled to specifically facilitate the multidisciplinary communication between different stakeholders during the project plan, design and construction processes, this application would be considered as contributing to the "process integration." If a VR application intendedly offered a communication opportunity for members distributed in different locations with various cultural and social backgrounds, this application would be considered as contributing to the "globalization" (Table 3).

Table 3. Distribution of applications in different contexts with different contributions

Application context \ Contribution	Communication improvement	Process integration	Globalization	Other	Sum (%)
Industry					
Building Inspection	–	–	–	2 (Du *et al.*, 2018; Shi *et al.*, 2018)	2 (5)
Facility Management	–	–	–	4 (Arain and Burkle, 2011; Du *et al.*, 2016; Shi *et al.*, 2016; Cheng *et al.*, 2018)	4 (10)
Safety Training	–	–	–	5 (Le and Park, 2012; Le *et al.*, 2015; Le *et al.*, 2016; Eiris and Gheisari, 2018; Pham *et al.*, 2018)	5 (12)
Design and Review	6 (Vosinakis *et al.*, 2008; Christiansson *et al.*, 2011; Koutsabasis *et al.*, 2011; Kumar *et al.*, 2011; Shen *et al.*, 2012; Wu and Kaushik, 2015)	1 (Yamamoto *et al.*, 2018)	–	10 (Moloney and Amor, 2003; Moloney *et al.*, 2003; Moloney and Harvey, 2004; Moloney, 2005; Van Nederveen, 2007; Gül *et al.*, 2008; Gu *et al.*, 2009; Merrick and Gu, 2011; Shiratuddin and Thabet, 2011; Du *et al.*, 2018)	17 (41)
Education					
Construction Education	–	–	13 (Iorio *et al.*, 2011; Comu *et al.*, 2012, 2014, 2017; Dossick *et al.*, 2012, 2014; Alin *et al.*, 2013; Anderson and Dossick, 2014; Anderson *et al.*, 2014, 2017; Iorio and Taylor, 2014a, 2014b; Zelkowicz *et al.*, 2015)	1 (Dib *et al.*, 2014)	14 (34)
Sum (%)	6 (15)	1 (2)	13 (32)	22 (54)	6 (15)

Note: The total sum is not counted because there are overlapping between different contexts

The *Building Inspection* context was found in 5% with two publications (Du *et al.*, 2018; Shi *et al.*, 2018). In both applications, VR environment provided 3D models of a building for participants to practice building inspection process while supporting their communication with voice chat functionality. The inspection performance was mainly tested based on participants' communication frequency. The *Facility Management* context was found in 10% of publications with four studies (Arain and Burkle, 2011; Newton *et al.*, 2013; Du *et al.*, 2016; Shi *et al.*, 2016). These applications enabled real-time interaction between remote stakeholders and provided them with a shared immersive walkthrough experience of the facility, which effectively facilitated the coordination and decision-making process. It was believed that VR applications minimized misunderstanding between facility managers and field workers and reduced communication cost in facility management process, and helped stakeholders achieve sustainable long-term goals. The *Safety Training* context was found in five applications (Le and Park, 2012; Le *et al.*, 2015; Le *et al.*, 2016; Pham *et al.*, 2018; Eris and Gheisari, 2018), and in such applications VR provided trainees hazard scenarios and hazard inspection tasks in digital construction sites and enabled voice chatting among trainees, where trainees were able to acquire safety knowledge by experiencing hazards, and discussing hazard causes and prevention methods with peers. Notably, none of the applications in these three contexts have focused to prepare the AEC industry with the new communication challenges in terms of performance improvement, process integration and globalization.

The *Construction Education* was found in 34% or 14 articles. A total of 13 studies were performed by a research team whose topics focused on the collaboration of geographically distributed student teams on performing construction-related works, including 3D and 4D modeling, cost estimating and scheduling processes. To be specific, research objectives for these studies were classified into distributed team collaboration (Iorio *et al.*, 2011; Dossick *et al.*, 2012; Anderson and Dossick, 2014; Anderson *et al.*, 2014; Dossick *et al.*, 2014; Iorio and Taylor, 2014b; Anderson *et al.*, 2017), boundary spanning (Alin *et al.*, 2013; Iorio and Taylor, 2014a; Zelkowicz *et al.*, 2015; Comu *et al.*, 2017) and project network facilitation (Comu *et al.*, 2012; Comu *et al.*, 2014). In these applications, VR environment provided abundant collaborative functionalities, such as text and voice chat features, thought bubbles and team screen, for virtual teams to share their works in real-time. The specific research focus on global virtual team has ensured their VR applications to be exposed in a global setting and thereafter prepare their users to work with team members with various backgrounds. However, it was noticed that apart from the work from the same research team, none of other applications have contributed to prepare their users with the globalization of the market. In another study for Construction Education category, VR was applied to provide students a platform for practicing leveling and getting familiar with surveyors' communication gestures through avatars (Dib *et al.*, 2014).

The *Design and Review* context was found in 41% with 17 publications of the reviewed articles. Among these 17 applications, 10 studies focused on design collaboration between designers or design reviewers, where VR provided an interactive co-design virtual world with synchronous or asynchronous communication tools and real-time 3D modeling functionality for multiple designers or reviewers to walk through others' design, provide feedback or complete assigned design tasks collaboratively (Du *et al.*, 2018; Gu *et al.*, 2009; Gül *et al.*, 2008; Koutsabasis *et al.*, 2011; Merrick and Gu, 2011, 2011; Moloney *et al.*, 2003; Moloney and Amor, 2003; Shiratuddin and Thabet, 2011; Van Nederveen, 2007). Out of these, six applications stressed the facilitation of communication between designers and owners/clients (Christiansson *et al.*, 2011; Koutsabasis *et al.*, 2011; Kumar *et al.*, 2011; Shen *et al.*, 2012; Vosinakis *et al.*, 2008; Wu and Kaushik, 2015). Rather than co-design, this type of applications was mainly focused on user involvement. These five studies visualized 2D plans into 3D observable models to help owners/clients gain an overall and direct understanding of the design; meanwhile, they enabled owners/clients to leave comments to designers confidently. These applications increased participation of owners/clients during the design process; therefore, their demands and requirements would be satisfied and realized accordingly in higher efficiency. These applications significantly contribute to the performance improvement of the AEC industry from a client-centered perspective. There was one application that focused on a VR-enabled design review teleconference that allowed owners, designers and engineers to work collaboratively to discuss design changes (where the changes would be traced) and point objects in VR environment (Yamamoto *et al.*, 2018).

From the analysis of applications context, it was found that although VR applications have been widely used in the design and construction processes of industrial settings, these applications failed to prepare the AEC industry for the new communication challenges. Only 15% of the reviewed applications were developed with the focus of improving the client-centered communication, and only 2% focused on the process integration of the industry. One study was related to preparing construction students for the globalization of the construction market by exposing them to global collaboration in a semester-long project. However, apart from this study, there was no other application that used VR to provide global collaboration opportunities for the AEC industry.

4.2 Communication affordance

Communication is broken down into the following elements (Riemer, 2007): oral, written, listening, visual and interdisciplinary. Visual literacy is the ability to understand and process image-based information, such as drawings and models, and have the skill to communicate through this type of information (Anderson, 2002). Drawings as well as real and symbolic pictures are one of the most important communication elements in the AEC domain and are frequently exchanged between different parties in this domain. Moreover, it is asserted that among overall time people spend in communication, 75% of which is in the forms of talking and listening (Kline, 1996), which underlines the significant proportions of oral and listening elements and their importance as communication elements.

It was noted in this study that communication affordance provided by VR applications highly corresponds to the specific type of communication element. For example, a text-based tool or voice chat would support oral and listening elements, and a visual sharing affordance might support the visual element of communication. Most observed features provided within the VR environment include communication tools in the following forms: voice, text, shared drawings and files, and avatars. Synchronous voice communication is a high-frequency function provided by the VR environment that directly benefits communication practice from an oral and listening perspective. Text, such as text-based chat and markups, is an auxiliary approach to improve literal communication. VR environment also supports visual communication by providing shared virtual workspace for exchanging drawings, models, and other files synchronously. Avatar is a digital human in a virtual world operated by a live participant (Eiris and Gheisari, 2017). The availability of an avatar's gestures and locations provides other users basic cues of the object discussed by the other avatar and increases the social presence, which possibly results in more efficient communication processes (Anderson and Dossick, 2014). Furthermore, this type of non-verbal behaviors, which usually include eye contact, distance, body orientation, movement, facial expression, gestures and selected features of the spatial environment, can encourage social exchanges and improve interaction efficiency in virtual settings (Tepper and Haase, 1978;

Salem and Earle, 2000). Table 4 illustrates four types of the most popular communication affordance with their usage frequency and percentage.

Text-based tools were the most used communication tools with a usage rate of 74%, followed by voice chat (68%). Text-based communication tools can be divided into two categories: asynchronous commenting and synchronous chat. VR environments providing asynchronous commenting function were generally created for the purpose of architectural design, where clients or design reviewers might select leaving comments or markups if designers were not online to response immediately (Moloney and Amor, 2003; Moloney *et al.*, 2003; Moloney and Harvey, 2004). The comments or markups were placed right next to the associated 3D objects, which provided a direct hint about the discussion topic to designers and reduced coordination latency. The communication affordance of voice chat was found in 28 papers. Compared with traditional flat screen-based teleconference, the combination of

Communication affordance types	Frequency (%)	Reference
Text-based tools		
Asynchronous commenting	6 (15)	Christiansson *et al.* (2011), Kumar *et al.* (2011), Moloney (2005), Moloney *et al.* (2003), Moloney and Amor (2003), Wu and Kaushik (2015)
Synchronous chat	24 (59)	Alin *et al.* (2013), Anderson *et al.* (2014, 2017), Anderson and Dossick (2014), Comu *et al.* (2012, 2014, 2017), Dossick *et al.* (2012, 2014), Du *et al.* (2016), Gu *et al.* (2009), Gül *et al.* (2008), Iorio *et al.* (2011), Iorio and Taylor (2014a, 2014b), Koutsabasis *et al.* (2011), Merrick and Gu (2011), Moloney and Harvey (2004), Pham *et al.*, 2018, Shen *et al.* (2012), Shiratuddin and Thabet (2011), Van Nederveen (2007), Vosinakis *et al.* (2008), Zelkowicz *et al.* (2015)
Voice chat	28 (68)	Alin *et al.* (2013), Anderson *et al.* (2014, 2017), Anderson and Dossick (2014), Arain and Burkle (2011), Christiansson *et al.* (2011), Comu *et al.* (2012, 2014, 2017), Dossick *et al.* (2012, 2014), Du *et al.* (2016, 2018), Gu *et al.* (2009), Iorio *et al.* (2011), Iorio and Taylor (2014a, 2014b), Koutsabasis *et al.* (2011), Le *et al.* (2015, 2016), Le and Park (2012), Moloney and Amor (2003), Newton *et al.* (2013), Shi *et al.* (2018), Shiratuddin and Thabet (2011), Van Nederveen (2007), Yamamoto *et al.* (2018), Zelkowicz *et al.* (2015)
Visual-sharing affordance	18 (44)	Alin *et al.* (2013), Anderson *et al.* (2014, 2014, 2017), Anderson and Dossick (2014), Cheng *et al.* (2018), Comu *et al.* (2012, 2014, 2017), Dossick *et al.* (2012, 2014), Du *et al.* (2016), Iorio *et al.* (2011), Iorio and Taylor (2014a, 2014b), Koutsabasis *et al.* (2011), Park and Kim (2013), Pham *et al.* (2018), Vosinakis *et al.* (2008)
Avatars		
Finger-pointing	1 (2)	Shi *et al.* (2016)
Thought bubbles	13 (32)	Iorio *et al.* (2011), Comu *et al.* (2012, 2014, 2017), Dossick *et al.* (2012, 2014), Alin *et al.* (2013), Anderson and Dossick (2014), Anderson *et al.* (2014, 2017), Iorio and Taylor (2014a, 2014b), Zelkowicz *et al.* (2015)

Table 4. Communication affordance and tools

VR environment and the voice chat function enabled a shared immersive virtual environment between users; thus, this combination avoided limitations of a traditional teleconference, such as the lack of sense of participants' presence and the lack of mutual understanding of pointed objects in building information modeling (BIM) models (Yamamoto *et al.*, 2018). Some researchers took advantage of a rich communicative platform (such as Second Life) that provides built-in tools such as synchronous text-based and voice chat (Le and Park, 2012). In an example, researchers added certain functionality and background on Second Life platform, which was a virtual construction site for students to experience and explore, based on their research objectives of facilitating students' learning process in construction safety class (Le *et al.*, 2015).

The visual sharing affordance, which is the function that allows users to share drawings/viewpoints and to exchange files within the virtual world, was the third common designed affordance in VR applications with a usage rate of 46%. As a built-in feature in the virtual environment, this type of affordance provided users convenience during the communication process. The virtual shared wall allowed users to broadcast and annotate their desktops, and multiple walls were available for users to compare different documents (such as the schedule and cost estimate) side-by-side in the virtual world; meanwhile they were able to explore the building in virtual environment whenever they demanded (Taylor *et al.*, 2018). In this way, coordination of data in different files (i.e. 3D models, drawings, schedule and cost estimate) was facilitated by saving times switching from software to software.

Avatars as the digital representation of humans were used in 15 papers as a medium to facilitate communication. Gestures and position of avatars were the fourth popular type of communication affordance that relied on the application of avatars. Gestures included finger-pointing, thought bubbles and hand signs. The ability to locate the avatar in VR was considered as communication affordance because it provided cues to others as to which object was being discussed, therefore reduced coordination latency and supported more efficient communication (Anderson *et al.*, 2014). Finger-pointing affordance was enabled by a laser gun modeled as an extension of the avatar, which helped the user to draw specific attention from others on the affected items and enhanced their mutual understanding during the construction process (Shi *et al.*, 2016). Thought bubble was designed in five types in the CyberGRID project as a gestural capability appearing on avatars' heads, indicating *I have a comment, I agree, I disagree, I have a question* and *I am away* (Iorio *et al.*, 2011; Comu *et al.*, 2012; Dossick *et al.*, 2012; Alin *et al.*, 2013; Anderson and Dossick, 2014; Anderson *et al.*, 2014; Comu *et al.*, 2014; Dossick *et al.*, 2014; Iorio and Taylor, 2014b; Iorio and Taylor, 2014a; Zelkowicz *et al.*, 2015; Anderson *et al.*, 2017; Comu *et al.*, 2017). It was straightforward to determine whether a team has reached an agreement by simply looking at thought bubbles on avatars' heads. And finally, hand signs were used in a learning-leveling application for surveying students to practice the hand signs with their team members, where hand signs were a unique and practical method for surveyors to communicate at a great distance in a real-world setting (Dib *et al.*, 2014).

The capability of supporting several communication elements at the same time makes VR an advanced and effective tool for communication. The synchronous chat supported by VR and the voice chat tool provide channels to facilitate oral and listening communication. VR environment also supports visual communication by providing shared virtual workspace for exchanging drawings, models, and other files synchronously. In VR environment remote users can observe and discuss details of the same 3D models at the same virtual place, and users can broadcast and annotate their desktops, and multiple virtual walls are available for users to compare different documents (e.g. schedule and cost estimate) side-by-side in the virtual world. Such features significantly facilitate visual communication between remote users (Taylor *et al.*, 2018). Meanwhile, if users are geographically distributed in the virtual environment, VR enables users to locate other users' avatar and provide cues to others about which object is being discussed. These valuable features reduce coordination latency and support more efficient communication (Anderson *et al.*, 2014). Finger-pointing affordance helps the user to draw specific attention from others to the designated items and enhance their mutual understanding during the communication process (Shi *et al.*, 2016). Although communication affordances were popularly implemented and somewhat sufficiently developed, several challenges and limitations were indicated in some publications. It is noted that the asynchronous commenting function was heavily created and used for design reviews; however, Moloney and Harvey (2004) found that the asynchronous communication module was not successful because of the lack of immediacy. There would usually be a time delay of one or two day between designers uploading projects and reviewers reviewing them. This finding indicated that asynchronous commenting might not be suitable for projects and tasks that need to be accomplished promptly. Furthermore, because of technological restrictions, the employment of the avatar as a communication channel was also very limited. Kumar *et al.* (2011) and Merrick *et al.* (2011) stated the lack of available avatar characters and animations that depict the performance of specific tasks, which significantly limited their application. Alin *et al.* (2013) also found that avatars' gestures repertoire was limited.

4.3 Communication assessment techniques

To identify valid applications that could facilitate communication, it is necessary to analyze communication assessment techniques implemented in the reviewed research papers. The assessment techniques for validating the effectiveness of each application were classified and discussed in this section. Notably, though there were 66% of the reviewed publications were developed for industrial contexts (design and review, safety training, facility management and building inspection), majority have not been tested with industrial participants. This suggested an urge demand that a mutual relationship should be established between the industry and academia. Throughout this literature review, it was noticed that communication is a relatively broad notion that is difficult to measure in a uniform method (Lappalainen, 2009). Among 41 applications, 17 manuscripts conducted field-based research or case studies to validate proposed methodologies, yet without implementing any specific assessment and evaluation method. For the remaining 24 publications that implemented specific assessment technique, different forms of evaluation metrics were used such as user feedbacks from interviews or questionnaires, performance time, or number of errors. Although evaluation metrics varied case by case, their assessment techniques could be categorized into two general areas of objective and subjective assessment and evaluation methods (Li *et al.*, 2018). Objective assessment measures the performance time, the numbers of errors, and other quantitative metrics of certain tasks; subjective assessment concerns investigating the users' needs and feedback or expert appraisal (Wang *et al.*, 2013) (Table 5).

The objective assessment method was found in four publications (Newton *et al.*, 2013; Dib *et al.*, 2014; Du *et al.*, 2018; Shi *et al.*, 2018), where evaluation metrics strictly depended on application contexts. As an example, to test the effect of communication during the building inspection process, Du *et al.* (2018) and Shi *et al.* (2018) collected the effective number of discrepancies participants found in the experience. The inspection process was conducted in a VR environment where voice communication was supported; thus, the improved efficiency of communication was considered to be represented by inspection performance. In other words, communication efficiency was assessed indirectly and objectively using the sufficient number of discrepancies identified by participants. Similarly, Newton *et al.* (2013) used assessment tasks on students' understanding of related issues, which was considered as a reflection of communication. In another similar study, Dib *et al.* (2014) assessed communication efficiency indirectly through analyzing scores participants gained from the task of recording the measurements in the surveying practice, after participants had experienced and interacted with VR educational platforms. All these assessments provided findings VR applications improved relevant performances, and associated communication happening during relevant processes was likely to be facilitated.

The subjective assessment method was identified to be used in two specific formats of user-centered interview or questionnaire, and expert appraisal. Interview or questionnaire assessment involved collection and investigation of the users' needs and evaluations on developed platforms from users' perspective (Wang *et al.*, 2013). Interview or questionnaire was used in nine articles, among which four included questions that directly target the effectiveness of communication (Gu *et al.*, 2009; Koutsabasis *et al.*, 2011; Merrick and Gu, 2011; Shen *et al.*, 2012). For instance, to assess efficiency of developed virtual world in improving collaborative design process, Koutsabasis *et al.* (2011) analyzed questionnaires from four dimensions: quality and acceptance of the outcome; participants' use of processes, tools and methods; aspects of design collaboration (e.g. awareness, communication, etc.); and user experience, one of which was the quality of communication between participants with respect of provided tools and available affordances. In all these articles, similar results were found that participants demonstrated positive feedback on the quality of communication in VR world. Interview and questionnaire used in other five articles were not designed to directly assess the communication aspect of the research (Arain and Burkle, 2011; Le and Park, 2012; Le *et al.*, 2015; Le *et al.* (2016); Pham *et al.*, 2018). All these applications were designed for educational purposes; thus, all researchers conducted their surveys mainly focusing on student's learning experience and interest. However, in their data analysis, they indicated that many students agreed virtual world provided channels to interact with instructors and classmates and was a favorable place to learn, which ultimately reflected that communication affordance provided by VR was satisfactory. To summarize, all assessments applying interview or questionnaire provided users' positive feedbacks or satisfactory feelings about communication quality in VR environment directly or indirectly.

An expert appraisal assessment involved collection and investigation of users' conversations and behaviors based on researchers' expertise and knowledge. The expert appraisal was mostly used by a group of researchers, whose topics focused on the collaboration of virtual teams in the virtual world using their developed platform called CyberGRID. Their projects focused on areas such as distributed team collaboration (Iorio *et al.*, 2011; Dossick *et al.*, 2012; Anderson and Dossick, 2014; Anderson *et al.*, 2014;

Evaluation technique	Evaluation criteria	References
Objective assessment	Task performance	Dib *et al.* (2014), Du *et al.* (2018), Newton *et al.*, 2013, Shi *et al.* (2018)
Subjective assessment	Self-evaluation (interview or questionnaire)	Arain and Burkle (2011), Gu *et al.* (2009), Koutsabasis *et al.* (2011), Le *et al.* (2015, 2016), Le and Park (2012), Merrick and Gu (2011), Pham *et al.* (2018), Shen *et al.* (2012)
	Expert appraisal	Iorio *et al.* (2011), Comu *et al.* (2012, 2014, 2017), Dossick *et al.* (2012, 2014), Alin *et al.* (2013), Anderson and Dossick (2014), Anderson *et al.* (2014, 2017), Iorio and Taylor (2014a, 2014b), Zelkowicz *et al.* (2015)

Table 5. Communication evaluation techniques for virtual reality applications

Dossick *et al.*, 2014; Iorio and Taylor, 2014b; Anderson *et al.*, 2017), boundary spanning (Alin *et al.*, 2013; Iorio and Taylor, 2014a; Zelkowicz *et al.*, 2015; Comu *et al.*, 2017) and project network facilitation (Comu *et al.*, 2012; Comu *et al.*, 2014). Although research objectives varied in these papers and not necessarily focused on communication directly, communication was always a metric to further analyze the research objective. For example, Dossick *et al.* (2014) studied the relation between messy talk and the creation of new knowledge. Messy talk was defined as a process of discovery, critically engagement, knowledge exchange and resolving the issue, where communication would happen anytime in this process between team members. Researchers recorded the conversations and behaviors of virtual teams, identified and analyzed time percentage of messy talk and the creation of new knowledge and concluded that new knowledge creation would occur through messy talk in a virtual team. In all these applications, expert appraisal assessments were conducted on the foundation of informative communication and were supported by VR environment. The outcomes of such expert appraisal assessments have suggested that VR environment support adequate communication.

4.4 Virtual reality adoption

This section first discussed types of users and corresponding virtual platforms. Then it was introduced that hardware and software used to develop and support VR environment for communication purposes (Table 6). Hardware includes input and output (display) devices that enable users to experience, interact with the VR environment and communicate with other users with the help of built-in features. The software in this study refers to game engines that are software-development environments where designers can build video games for consoles, mobile devices, and personal computers (Ward, 2008). Specifically, it was found the integration of BIM with the game engines has become predominant since Year 2011 (before 2011 BIM has not been applied, after 2011 more than 20 applications have applied BIM to build virtual construction environment). This founding was also included in the discussion of development software.

4.4.1 Virtual reality-powered communication mechanisms. After reviewing relevant publications, two types of "multi users" and "individual user" platforms were identified (Figure 6). The first type of platforms was developed as online virtual communities for multi-users where users were either co-located or geographically distributed. VR applications enabled various communication channels and could benefit multi users at any distance, as long as they had access to the internet and were at the same virtual environment. Both fully immersed and partially immersed VR systems have been applied to create this type of platform. For example, Taylor *et al.* (2018) applied a partially immersed VR system which enabled users to collaboratively perform different tasks such as scheduling, 3D modeling and cost estimating. The mouse/keyboard allowed users to communicate through text input and annotate the shared computer screen with team members. In this example, the computer screen displayed the virtual environment and other users' avatars. The second type of platform was an individual user-based system where users were exchanging information solely with the platform itself. Two specific studies enabled communication between an individual and a VR platform. Eiris and Gheisari (2018) implemented a conversational virtual human within their proposed VR environment where the user could interact and communicate with virtual safety experts and get relevant information about construction safety of lifting operation. The other VR platform enabled an individual user to practice hand gestures in surveying tasks (Dib *et al.*, 2014). In this application, the user could be trained to efficiently exchange the necessary information with other surveying crewmembers in far distance on the site for successful completion of the surveying task (Dib *et al.*, 2014). Both applications were developed as partially immersed VR

Type of device	Frequency %)	Year range	Reference
Output (display)			
Computer screen	34 (83%)	2003–2018	Alin *et al.* (2013), Anderson *et al.* (2014, 2017), Anderson and Dossick (2014), Arain and Burkle (2011), Comu *et al.* (2012, 2014, 2017), Dib *et al.* (2014), Dossick *et al.* (2012, 2014), Eiris and Gheisari (2018), Gu *et al.* (2009), Gül *et al.* (2008), Iorio *et al.* (2011), Iorio and Taylor (2014a, 2014b), Kumar *et al.* (2011, 2011), Le *et al.* (2015, 2016), Le and Park (2012), Merrick and Gu (2011), Moloney (2005), Moloney *et al.* (2003), Moloney and Amor (2003), Moloney and Harvey, 2004, Pham *et al.* (2018), Shen *et al.* (2012), Shiratuddin and Thabet (2011), Van Nederveen (2007), Vosinakis *et al.* (2008), Wu and Kaushik (2015), Zelkowicz *et al.* (2015)
Head-mounted display	7 (17%)	2011–2018	Christiansson *et al.* (2011), Du *et al.* (2016, 2018), Newton *et al.* (2013), Shi *et al.* (2016, 2016), Yamamoto *et al.* (2018)
Input			
Keyboard/mouse	36 (88%)	2003–2018	Alin *et al.* (2013), Anderson *et al.* (2014, 2017), Anderson and Dossick (2014), Arain and Burkle (2011), Christiansson *et al.* (2011), Comu *et al.* (2012, 2017), Dib *et al.* (2014), Dossick *et al.* (2012, 2014), Du *et al.* (2016), Eiris and Gheisari (2018), Gu *et al.* (2009), Gül *et al.* (2008), Iorio and Taylor (2014a, 2014b), Koutsabasis *et al.* (2011), Kumar *et al.* (2011), Le *et al.* (2015, 2016), Le and Park (2012), Merrick and Gu (2011), Moloney (2005), Moloney *et al.* (2003), Moloney and Amor (2003), Moloney and Harvey, 2004, Pham *et al.* (2018), Shen *et al.* (2012), Shi *et al.* (2016), Shiratuddin and Thabet (2011), Van Nederveen (2007), Vosinakis *et al.* (2008), Wu and Kaushik (2015), Zelkowicz *et al.* (2015)
Game controller/ foystick	3 (7%)	2011–2018	Christiansson *et al.* (2011), Shi *et al.* (2018), Yamamoto *et al.* (2018)
Not specified	4 (10%)	2013–2018	Du *et al.* (2018), Newton *et al.* (2013)

Note: In some applications more than one output/input device was used

Table 6. Output (display) and input devices

systems, which allowed users to be aware of both virtual and real environment while interacting with the VR environment. The input and output information types were the configurations of the information that was delivered by the mechanism, and they were highly corresponding to available communication affordances of the platforms.

The output devices collected from literature review included computer screens, HMDs, and mobile devices. Computer screens were the most frequent applied output device with a usage rate of 83% (34 out of 41 applications). The outstanding supremacy of this device may be explained by its ease of accessibility and supportive conjunction with keyboard and mouse. In all 34 applications, the computer screen was used with keyboard/mouse. As it was indicated earlier in Section 4.2, text-based communication function was the most used affordance provided by VR applications. Therefore, it was expectable that the computer

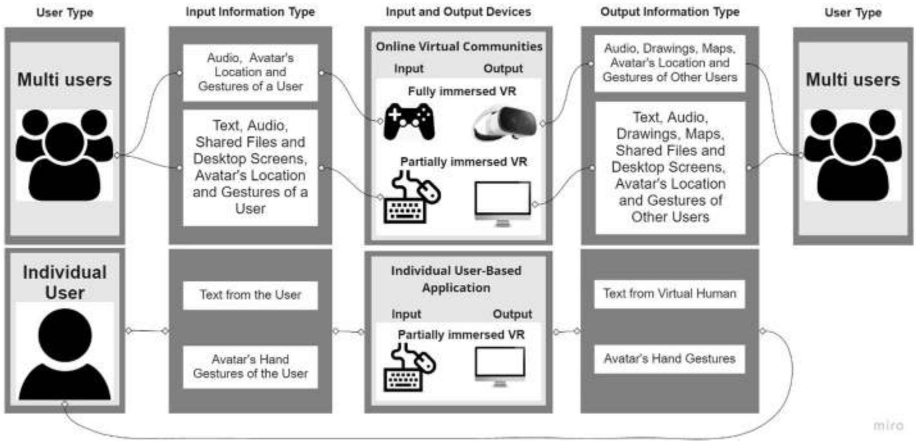

Figure 6.
Communication mechanisms

screen with keyboard/mouse be the most frequent type of display and input devices because this combination provides more convenient text input than other ones. HMDs were used at a rate of 17% (7 papers) and were often used with the application of a game controller or joystick, where it allowed users to navigate and explore building environment and enabled multiple users to communicate through the built-in voice features (Christiansson *et al.*, 2011; Newton *et al.*, 2013; Du *et al.*, 2016; Shi *et al.*, 2016; Du *et al.*, 2018; Shi *et al.*, 2018; Yamamoto *et al.*, 2018).

As for input devices, the most popular type was keyboard and/or mouse (keyboard/mouse), and 36 out of 41 applications were found using this type of device. Specifically, within these 36 applications, 33 were using keyboard/mouse with the use of computer screen. Two applications of keyboard/mouse were combined with the employment of HMD, where players would use mouse click to place green markers to share their location and draw other players' attention for further discussions on specific details (Du *et al.*, 2016; Shi *et al.*, 2016). Game controllers or joysticks were found in three applications to facilitate users' navigation and interaction with VR environment, all of which were used with HMDs (Shi *et al.*, 2016; Atsuhiro *et al.*, 2018; Shi *et al.*, 2018). Four papers provided no specific details on the type of input device.

Based on different hardware packages of two VR systems, the supported communication affordance varied. The partially immersed VR systems mostly used computer screen and mouse/keyboard as output and input hardware. All four types of communication affordance discussed in Section 4.2 can be easily implemented using this combination because this hardware package is widely used and easily compatible with relevant software packages and game engines. For example, in Unity, there are default features added for mouse click and keyboard input, which make it easy and quick to develop partially immersed VR systems. On the contrary, when applying fully immersed VR systems, the types of implemented communication affordance from the reviewed manuscripts were limited. The most frequent affordance provided by fully immersed VR included voice chat affordance, avatar affordance, and limited visual sharing affordance (Christiansson *et al.*, 2011; Newton *et al.*, 2013; Du *et al.*, 2016; Shi *et al.*, 2016; Du *et al.*, 2018; Shi *et al.*, 2018; Chalhoub and Ayer, 2018; Yamamoto *et al.*, 2018). For example, users were wearing the HMD to identify discrepancies of a virtual building in a fully immersive VR (Du *et al.*, 2018). In this specific study, users were able to review floor plans (not freely), communicate orally with other users' avatars and point at virtual objects using a laser beam. However, users were not able to annotate the floor plan or share other necessary files freely in this system. It should be noted that more complex development and coding are required to create fully immersive VR functionalities, mainly when non-typical input devices such as joysticks or game controllers are used.

4.4.2 Virtual reality development software. With the proven effectiveness and increasing industry awareness of BIM technology, it has been more and more popularly applied in the AEC domain (Du *et al.*, 2018). BIM is a digital representation of physical and functional characteristics of a facility and includes shared information of the facility throughout its entire life cycle (National Institute of Building Sciences, 2020). From this review, it was found that the integration of BIM and game engines to develop VR environment has become predominant in the last eight years (2011–2018), where BIM was widely used to create 3-D representations of construction jobsites or facilities in virtual environments (Alin *et al.*, 2013; Anderson *et al.*, 2014, 2017; Anderson and Dossick, 2014; Arain and Burkle, 2011; Christiansson *et al.*, 2011; Comu *et al.*, 2012, 2014, 2017; Dossick *et al.*, 2012, 2014; Du *et al.*, 2016, 2018; Eiris and Gheisari, 2018; Iorio *et al.*, 2011; Iorio and Taylor, 2014a, 2014b; Koutsabasis *et al.*, 2011; Kumar *et al.*, 2011; Shen *et al.*, 2012; Shi *et al.*, 2016, 2018; Shiratuddin and Thabet, 2011; Wu and Kaushik, 2015; Yamamoto *et al.*, 2018; Zelkowicz *et al.*, 2015). It is believed the BIM-based game engine can enhance mutual understanding among users in both industrial and educational settings (Du *et al.*, 2016). In the industrial setting, BIM-based game engine enables the project owners to dive into the simulated virtual building and have an intuitive understanding about their project through self-guided or automated walkthrough at an early phase of the project (Wu and Kaushik, 2015); it also provided a better communication, coordination and conflict resolution for designers and designers reviewers by directly visualizing their design ideas in an immersive and interactive virtual space (Shiratuddin and Thabet, 2011). In the educational setting, BIM-based game engine provided students with a simulated construction jobsite or other virtual space that was filled with construction details for them to explore and gain certain knowledge (Eiris and Gheisari, 2018). However, there were also some limitations of the integration with BIM, which will be discussed in Section 5.1.

In term of game engines used to develop VR environments, Unity 3 D, Havok and Torque 3D were the most ones. Unity 3D was found in 21 papers from year 2011 to 2018, with a utilization rate of 51%. Its wide application might relate to the fact that Unity is compatible with various 3D modeling software packages (such as 3DS MAX, Maya, Softimage, CINEMA and Blender) and operating systems (such as Androids, IOS and Windows) (Wu and Kaushik, 2015). The second most popular game engine Havok found in 10 papers (25 %) from 2007 to 2017 is the game engine used to develop "Second Life" platform, where users can create avatars to walk and communicate using built-in tools such as synchronous text-based or voice chats. Because of these built-in functions, Second Life was an appealing virtual platform for researchers to study communication-related topics. Torque 3D was the other popular engine used in five papers (usage rate of 12% from 2003 to 2011). CryEngine3, 3DVIA Virtools and OpenSimulator were the other game engines that used in the AEC literature, yet not as popular as the above-discussed ones, with only one paper (Table 7).

5. Discussion: challenges and future trends

5.1 Virtual reality challenges and limitations

VR technologies could enable an immersive virtual environment where verbal, nonverbal and visual communication are supported simultaneously. However, there are several challenges and limitations about such technologies and their successful implementation that

Table 7.
Game engines

Game engine	Frequency (%)	Year range	Reference
Unity 3 D	21 (51%)	2011–2018	Alin *et al.* (2013), Anderson *et al.* (2014, 2017), Anderson and Dossick (2014), Comu *et al.* (2012, 2017), Dib *et al.* (2014), Dossick *et al.* (2012, 2014), Du *et al.* (2016), Eiris and Gheisari (2018), Iorio and Taylor (2014a, 2014b, 2014a), Kumar *et al.* (2011), Shi *et al.* (2016, 2018), Wu and Kaushik (2015), Yamamoto *et al.* (2018), Zelkowicz *et al.* (2015)
Havok	10 (25%)	2007–2017	Arain and Burkle (2011), Christiansson *et al.* (2011), Gu *et al.* (2009), Gül *et al.* (2008), Iorio *et al.* (2011), Le *et al.* (2015, 2016), Le and Park (2012), Merrick and Gu (2011), Van Nederveen (2007)
Torque 3 D	5 (12%)	2003–2011	Moloney (2005), Moloney *et al.* (2003), Moloney and Amor (2003), Moloney and Harvey (2004), Shiratuddin and Thabet (2011)
Other engines	3 (7%)	2011–2013	Koutsabasis *et al.* (2011), Newton *et al.* (2013), Shen *et al.* (2012)
Not specified	2 (5%)	2008–2018	Pham *et al.* (2018), Vosinakis *et al.* (2008)

needs to be discussed. First, it is widely reported that the development process for VR applications is very time-consuming (Newton, 2007; Arain and Burkle, 2011; Le and Park, 2012; Le *et al.*, 2015; Le *et al.*, 2016). Arain and Burkle (2011) noted how challenging it was to find a balance between focusing on achieving the research goals of their study and the developing time of their proposed application in terms of creating necessary models and scripting works. If the application provided specific game-like scenarios, the game creation process was not only time-consuming but also required special skills and extra efforts. For instance, Le *et al.* (2016) developed a VR-based defect inspection game and created complicated game scenarios to deliver relevant knowledge. It was reported that the instructors of the course, who also played the developer's role to connect the game with the course content and create specific game scenarios, had to spend the majority of their research time to better understand the technology and the development functions of the game system.

Two other similar challenges were also indicated during the development process of VR applications. The first challenge was the complex scripting process required to build games (Arain and Burkle, 2011; Le *et al.*, 2016). The second challenge was the limited integration of building information models with game engines. For example, Wu and Kaushika (2015) and Shi *et al.* (2016) encountered the problem of losing material information during the BIM conversion process into a game engine environment. Furthermore, if needed, it was challenging to change building components inside the VR environment without going back to the original building information modeling platform (Du *et al.*, 2016). It was mainly because of the interoperability issues and difficulty of dynamical data transfer between game engines and building information models.

Not only developers found it time-consuming to develop the virtual platforms but also users had to spend a significant amount of time in training and practice to learn how to effectively interact with the virtual world (Merrick *et al.*, 2011; Iorio *et al.*, 2011; Shen *et al.*, 2012; Le *et al.*, 2015). Merrick *et al.* (2011) mentioned users needed to develop new and cross-disciplinary skill sets, including computing, design and communication skills, to act smoothly in virtual worlds. Le *et al.* (2015) also indicated the same issue that students, who were the primary users of their developed platform, had to spend extra time and effort to learn new skills to successfully use their platform. Iorio *et al.* (2011) and Shen *et al.* (2012) indicated that because of this significant learning curve; there might be a negative impact for the users to properly use such platforms.

Moreover, because BIM technology only creates digital representations of the real world, the level of realism in the BIM-simulated environment needs to be improved to enhance the sense of presence, or in other words, the sense of being there (Du *et al.*, 2016). For example, modeling the physical appearance, behavior and functionality of an object can be very trivial and far away from realistic (Arain and Burkle, 2011). The simulation of construction activities developed by Le *et al.* (2016) was different from realistic construction works as well in terms of duration and interactions. Furthermore, when the simulated models became large and complex, the juddering issue (low frame per second) was severe, which resulted in even lower realism of the simulations and less satisfactory user experience (Du *et al.*, 2018).

5.2 Future trends

Based on the most recent publications from year 2016 to 2018, along with previously discussed challenges and limitations of VR applications, this section provides some future research trends to develop VR applications so that they can be better used for communication purpose.

5.2.1 Real-time data transfer between building information modeling and the game engines. BIM has been widely integrated with game engines to create VR experiences in the AEC domain to facilitate communication for various applications such as design review (Wu and Kaushik, 2015; Yamamoto *et al.*, 2018), facility management (Du *et al.*, 2018; Shi *et al.*, 2016) and building inspection (Du *et al.*, 2016). All these contexts require a high level of interactions in real-time (i.e. providing users freedom to annotate, manipulate, and change the components of the BIM-generated simulations). For instance, if building inspectors identify a misplacement of a column when they walk through the virtual building, after communicating and reaching a mutual agreement of a location adjustment, the inspectors should be able to manipulate or adjust the column, and such change should be synchronized with the associated BIM contents. The studies conducted by Wu and Kaushik (2015), Du *et al.* (2016), Shi *et al.* (2016), Du *et al.* (2018) and Yamamoto *et al.* (2018) have stressed the significance of the real-time data transfer process yet significant amount of research needs to be conducted to propose a direct and automatic approach to enable this process. Therefore, it is necessary for future efforts to focus on the real-time model information transfer between BIM software and the game engines. Meanwhile, when multiple users, either co-located or remote, are involved, tracking the changes made by different users should also be taken into consideration for proper communication purposes (Yamamoto *et al.*, 2018).

5.2.2 Virtual reality integration with augmented reality approaches. Mixed reality is defined as a "reality spectrum" ranging between pure reality, where the environment is as seen by the user without any computer-generated object, and virtuality, where the environment is entirely computer generated (Milgram and Kishino, 1994). Within this range, augmented reality (AR0 is one of the most dominant areas. AR is an innovate visualization technology that can overlay virtual information (e.g. 3D models, images, animations and audios) on the real world to provide users a more informative environment without moving them to an entirely virtual world (Cheng *et al.*, 2017). From this review study, it was noticed that AR applications provide limited communication channels compared to VR, which is a more mature approach for communication-related applications. AR communication-relevant applications are mainly about enabling a shared visualization for users, which is a basic feature for most VR applications. On the contrary, VR applications can potentially offer various communication channels, which are theoretically and technically impracticable or challenging to create in AR. Therefore, to effectively exact communication-relevant papers and obtained more informative outcomes with the focus of communication, we decided to focus only on the applications of VR technology in the review phase.

However, the unique advantages of AR cannot be overlooked. The unique advantages of AR are that it would not block the users' view of reality and add layers of information to their real-world view of the environment, which could be significantly beneficial for onsite users to use (Cheng *et al.*, 2018). Because of these advantages, AR technology has a significant potential to be integrated with VR technology and facilitate the communication between the users offsite and the ones onsite (Cheng *et al.*, 2018; Le *et al.*, 2015). For instance, in a context of facility management, a site inspector could use the AR medium to scan the real facility and use the contents superimposed in the real-world view to do the inspection while sharing the view with the offsite facility manager in a remote office who could access the inspected facility through a VR medium. This way, the onsite inspector and offsite facility manager share the same viewpoint, they can both interact with the virtual objects, and the interactions will be updated through both AR and VR mediums immediately. Future research on VR integration with AR would facilitate communication between remote offices and project jobsites.

5.2.3 Enhancing the level of realism in virtual reality. Previous research has shown that a more realistic virtual environment may induce a better sense of presence, which possibly results in more efficient communication processes (Anderson and Dossick, 2014; Shi *et al.*, 2016). Therefore, several studies have stressed the realism improvement of virtual environments (Du *et al.*, 2016; Shi *et al.*, 2016). The most common ways to create the virtual environment in the VR applications include 1) creating the virtual construction sites in BIM and integrating BIM models with the game engines (Du *et al.*, 2018; Eiris and Gheisari, 2018; Yamamoto *et al.*, 2018) or 2) creating the virtual environment in Second Life (Dib *et al.*, 2014; Le *et al.*, 2015, 2016). However, modeling a close-to-reality setting requires significant time, and the rendering of such models necessitates high computational cost (Eiris *et al.*, 2018). Furthermore, when the models or the virtual environments become more complex, expensive hardware for higher frames per second experience is necessary to avoid the juddering issue, which will introduce an additional cost for most construction users (Du *et al.*, 2018). Further research is required on creating more realistic VR environments that are not computationally expensive to develop or might use different reality capturing techniques (e.g. 360-degree panoramic VR, point cloud data) to reduce the time and cost to create realistic VR experiences.

5.2.4 Integration of avatars with enhanced emotional and physical behaviors. Non-verbal (e.g. physical behaviors) and emotional cues play a major role in the communication process (Dainty *et al.*, 2007). Research shows that more than 60% of all communication is non-verbal (Riggenbach 1986). Because AEC projects are based on a significant amount of both formal and informal interactions between different human parties involved in the project, it is essential to use non-verbal cues so that all parties can exchange their messages effectively and provide feedback to each other correctly (Dainty *et al.*, 2007). The emotional and physical behaviors reflect the inner attitude of the communication parties, thus simulating such non-verbal cues through avatars in the VR environment can assist users to better interpret each other's implied meaning. Therefore, it is suggested for future researches to implement and evaluate the impact of the integration of avatars with enhanced emotional and physical behaviors in facilitating communication in VR settings (Anderson *et al.*, 2017; Comu *et al.*, 2017; Yamamoto *et al.*, 2018).

6. Summary and Conclusion

In complex AEC domain that requires a continuous collaboration of various stakeholders, communication is a fundamental and necessary component to ensure to reach a satisfied performance of a project. With different communication methods and technology having been used in this domain, this study focused on an emerging and promising technology which has been identified as one of the central technologies in Industry 4.0 relevant literatures: VR. This study aimed to explore the potential of VR technology in improving and digitizing communication processes in the AEC domain. Considering one of the ultimate goals of Industry 4.0 is to enable digital information exchange and communication between stakeholders, the focus of this study can be considered as a sub-topic of implementing Industry 4.0 in the AEC domain. Content analysis-based review was conducted to achieve the goal of this study; similar to many other reviews, the main limitation of this research is the specific keywords and criteria generated to evaluate the findings and the chosen databases. Another limitation of this study is that the manual search (supplementary) process played an essential role in the literature search stage because the database searching was not able to locate some publications that are communication related; this process were subjective compared with the database searching. Because evaluation standards were relatively subjective, variations existed on the selection of papers and analysis of applications. Furthermore, although many efforts have been made to explore the applications of VR applications in facilitating communication, it is acknowledged that this review is not comprehensive and limited to solely publications in English within the AEC domain. Communication in this study is limited to the interpersonal level, i.e. communication between individuals. Team and organizational communication are higher-level communication aspects that should be explored in future studies. To deepen the understanding on how VR technology has been applied for facilitating communication and how to improve such applications to better fulfill the requirements, future research should explore such applications in other sectors as well.

In this study, 41 papers from peer-reviewed journal publications and conference proceedings were included and assessed and provide an in-depth insight for scholars and professionals on VR technology that facilitated communication in the AEC domain. The covering range of this study included both industrial and educational areas. Through the publications analyzed, applications of VR in communication improvement were mainly found in five categories: *Building inspection, Facility management, Safety Training, Construction Education* and *Design and Review*. Based on respective research objectives, different communication tools and affordance were provided or built in these applications in several forms: text-based tools including asynchronous commenting tool and synchronous chat function, voice chat tool, visual sharing affordance, and avatars. In terms of the validation of applications' effect in communication facilitation, assessment techniques of communication were analyzed in this study. Objective (task performance) and subjective (interview and questionnaire, expert appraisal) methods were observed from those publications, and most outcomes have successfully provided supportive evidence that VR applications have the capability of improving communication efficiency in the AEC domain. This research also studied the process of developing VR applications and summarized the type of hardware (input and output devices) and software (game engine) used. Computer screen, mouse and keyboard were the most commonly found hardware, which might relate to the ease of accessibility, navigation, and typing in the VR environment. As for software (game engine), Unity 3D, Havok, and Torque 3D were the most popular game engines used by researchers to design their platforms. It was found that BIM technology has been significantly integrated with the game engine to create the virtual construction environment in recent eight years (2011–2018). From academic respect, four future research directions of VR applications for communication purpose were identified:

(1) real-time data transfer between BIM and the game engine;

(2) conjunction with AR applications;

(3) improvement of the realism of VR; and

(4) simulations of avatars' emotions and physical behaviors. To better implement the Industry 4.0 and prepare the AEC industry for the new communication challenges, it is encouraged to adopt VR in the following fields:

- using VR to improve communication in terms of effectively understanding clients' demand and providing high-quality service accordingly, which can avoid misunderstanding and reduce reworks;
- using VR to support smooth and opportune information flow between different stakeholders to integrate the plan, design, and construction processes, which can prompt the horizontal and vertical integrations of IT systems, processes and data flow between different stakeholders in Industry 4.0; and
- using VR to expose industrial participants in the global collaboration setting and prepare for the globalization of the AEC industry.

With the advancement of VR technology, their applications in the AEC domain are becoming promising. This research explored current VR applications from the perspective of communication facilitation, provided insights to the future research directions in improving communication efficiency and helped AEC domain to integrate these promising technologies in the coming Fourth industrial revolution. The outcome of this review can benefit both industry professionals and researchers by helping them recognize the potentials of such applications and understand the requirements and challenges of VR implementation to facilitate communication in the AEC domain. For the AEC industry, its dynamic nature requires efficient, accurate and frequent information exchange throughout the entire project life cycle. With the continuous integration of emerging VR technology in the AEC industry, the outcome of this review will help the industry make informed decisions on the successful adoption of VR technologies as communication tools. This study also contributes to the research field by providing a detailed review of the current state and future research directions of VR applications in communication-relevant AEC scenarios. A better understanding of the requirements, challenges and future research directions of VR implementation to facilitate communication in the more frequently identified areas will optimize current research efforts in those areas and also can promote future research on other applications that have not integrated VR yet but might have the potential to benefit from it. Ultimately, this paper can contribute to the implementation of Industry 4.0 in AEC domain by exploring the potential of VR in digitalizing communication processes for construction projects. VR provides a shared visualization of information and immersive environment for users to explore, communicate and meet with others. These attributes will particularly benefit international projects or other ones with geographically distributed team members where it is not practical to hold regular in-person meetings and inspect constructed facilities in the real world. To further integrate VR technologies with the AEC domain, more affordances in VR platforms should be developed and implemented to meet specific communication requirements in the AEC domain.

References

Accreditation Board for Engineering and Technology (2016), "Criteria for accrediting engineering programs", Accreditation Board for Engineering and Technology.

Alin, P., Iorio, J. and Taylor, J.E. (2013), "Digital boundary objects as negotiation facilitators: spanning boundaries in virtual engineering project networks", *Project Management Journal*, Vol. 44 No. 3, pp. 48-63.

American Council for Construction Education (2014), "Standards and criteria for accreditation of postsecondary construction education degree programs".

Anderson, E. (2002), "Enhancing visual literacy through cognitive activities", *Proceedings of the 2002 ASEE/SEF/TUB Colloquium*.

Anderson, A. and Dossick, C.S. (2014), "Avatar-model interaction in virtual worlds improves distributed team collaboration through issue discovery", *Computing in Civil and Building Engineering (2014)*, pp. 793-800.

Anderson, A., Dossick, C.S., Iorio, J. and Taylor, J.E. (2017), "The impact of avatars, social norms and copresence on the collaboration effectiveness of AEC virtual teams", *Journal of Information Technology in Construction (ITcon)*, Vol. 22 No. 15, pp. 287-304.

Anderson, A., Dossick, C.S., Azari, R., Taylor, J.E., Hartmann, T. and Mahalingham, A. (2014), "Exploring BIMs as avatars: using 3D virtual worlds to improve collaboration with models", *Construction Research Congress 2014: Construction in a Global Network*, pp. 179-188.

Arain, F.M. and Burkle, M. (2011), "Learning construction project management in the virtual world: leveraging on second life", *Journal of Information Technology in Construction (ITcon)*, Vol. 16 No. 16, pp. 243-258.

"Are books peer reviewed?" (2015), available at: https://onesearch.library.utoronto.ca/faq/are-books-peer-reviewed (accessed 6 April 2020).

Bhoir, S. and Esmaeili, B. (2015), "State-of-the-art review of virtual reality environment applications in construction safety", *AEI 2015*, pp. 457-468.

Bowden, S., Dorr, A., Thorpe, A. and Anumba, C.J. (2004), "Mapping site processes for the introduction of mobile IT", *Proceedings of ECPPM 2004 EWork and EBusiness in Architecture, Engineering and Construction*, pp. 491-498.

Bowman, D.A. and McMahan, R.P. (2007), "Virtual reality: how much immersion is enough?", *Computer, presented at the Computer*, Vol. 40 No. 7, pp. 36-43.

Carlsson, C. and Hagsand, O. (1993), "DIVE A multi-user virtual reality system", *Proceedings of IEEE Virtual Reality Annual International Symposium, IEEE*, pp. 394-400.

Chalhoub, J. and Ayer, S.K. (2018), "Using Mixed Reality for electrical construction design communication", *Automation in Construction*, Elsevier, Vol. 86, pp. 1-10.

Chen, Y. and Kamara, J. (2008), "The mechanisms of information communication on construction sites", *Forum Ejournal*, Vol. 8, pp. 1-32.

Cheng, J.C., Chen, K. and Chen, W. (2017), "Comparison of marker-based AR and marker-less AR: a case study on indoor decoration system", Lean and Computing in Construction Congress (LC3): Proceedings of the Joint Conference on Computing in Construction (JC3), pp. 483-490.

Cheng, E.W., Li, H., Love, P.E. and Irani, Z. (2001), "Network communication in the construction industry", *Corporate Communications: An International Journal*.

Cheng, J., Chen, K., Chen, W. and Li, C. (2018), "A location aware augmented reality collaborative system framework for facility maintenance management", *Proceedings of the 18th International Conference on Construction Applications of Virtual Reality (CONVR2018)*, pp. 30-39.

Christiansson, P., Svidt, K., Pedersen, K. and Dybro, U. (2011), "User participation in the building process", *Journal of Information Technology in Construction*, Vol. 16, pp. 309-334.

Clement, A. and Murugavel, T. (2015), "English for employability: a case study of the English language training need analysis for engineering students in India", *English Language Teaching*, Vol. 8 No. 2, pp. 116-125.

Comu, S., Taylor, J.E. and Dossick, C.S. (2014), "Comparing global versus domestic project network facilitation in virtual workspaces", *Construction Research Congress 2014: Construction in a Global Network*, pp. 2175-2184.

Comu, S., Iorio, J., Taylor, J.E. and Dossick, C.S. (2012), "Quantifying the impact of facilitation on transactive memory system formation in global virtual project networks", *Journal of Construction Engineering and Management*, Vol. 139 No. 3, pp. 294-303.

Comu, S., Taylor, J.E., Dossick, C.S., Iorio, J., Anderson, A. and Shealy, T. (2017), "Examining the Effect of Boundary Spanning Technologies in Virtual Project Teams", *Lean and Computing in Construction Congress – Volume 1: Proceedings of the Joint Conference on Computing in Construction, presented at the Lean and Computing in Construction Congress – Joint Conference on Computing in Construction*, *Heriot-Watt University*, *Heraklion, Crete*, pp. 593-600.

Coulter, R., Saland, L., Caudell, T., Goldsmith, T.E. and Alverson, D. (2007), "The effect of degree of immersion upon learning performance in virtual reality simulations for medical education", *InMedicine Meets Virtual Reality*, Vol. 15, p. 155.

Dainty, A., Moore, D. and Murray, M. (2007), *Communication in Construction: Theory and Practice*, Routledge.

Dib, H. and Adamo-Villani, N. (2014), "An interactive virtual environment for learning d ifferential leveling: development and initial findings", *Advances in Engineering Education*, pp. 1-17.

Dossick, C., Anderson, A., Iorio, J., Neff, G. and Taylor, J. (2012), "Messy talk and mutual discovery: exploring the necessary conditions for synthesis in virtual teams", *Proceedings Engineering Project Organizations Conference*.

Dossick, C.S. and Neff, G. (2011), "Messy talk and clean technology: communication, problem-solving and collaboration using building information modelling", *The Engineering Project Organization Journal*, Vol. 1 No. 2, pp. 83-93.

Dossick, C.S., Anderson, A., Azari, R., Iorio, J., Neff, G. and Taylor, J.E. (2014), "Messy talk in virtual teams: achieving knowledge synthesis through shared visualizations", *Journal of Management in Engineering*, Vol. 31 No. 1, available at: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000301

Du, J., Shi, Y., Zou, Z. and Zhao, D. (2018), "CoVR: cloud-based multiuser virtual reality headset system for project communication of remote users", *Journal of Construction Engineering and Management*, Vol. 144 No. 2, p. 04017109.

Du, J., Shi, Y., Mei, C., Quarles, J. and Yan, W. (2016), "Communication by interaction: a multiplayer VR environment for building walkthroughs", *Construction Research Congress 2016*, pp. 2281-2290.

Dutra, A., Ripoll-Feliu, V.M., Fillol, A.G., Ensslin, S.R. and Ensslin, L. (2015), "The construction of knowledge from the scientific literature about the theme seaport performance evaluation", *International Journal of Productivity and Performance Management*, Vol. 64 No. 2, pp. 243-269.

Eiris, R. and Gheisari, M. (2017), "Research trends of virtual human applications in architecture, engineering and construction", *Journal of Information Technology in Construction (ITcon)*, Vol. 22 No. 9, pp. 168-184.

Eiris, R. and Gheisari, M. (2018), "Building intelligent virtual agents as conversational partners in digital construction sites", *Construction Research Congress 2018, presented at the Construction Research Congress* 2018, *American Society of Civil Engineers*, *New Orleans*, pp. 200-209.

Eiris, R., Gheisari, M. and Esmaeili, B. (2018), "PARS: using augmented 360-degree panoramas of reality for construction safety training", *International Journal of Environmental Research and Public Health*, Vol. 15 No. 11, p. 2452.

Falagas, M.E., Pitsouni, E.I., Malietzis, G.A. and Pappas, G. (2008), "Comparison of PubMed, Scopus, web of science, and Google scholar: strengths and weaknesses", *The FASEB Journal*, Federation of American Societies for Experimental Biology, Vol. 22 No. 2, pp. 338-342.

Gamil, Y. and Rahman, I.A. (2017), "Identification of causes and effects of poor communication in construction industry: a theoretical review", *Emerging Science Journal*, Vol. 1 No. 4, pp. 239-247.

Gautier, G., Piddington, C. and Fernando, T. (2008), "Understanding the collaborative workspaces", *Enterprise Interoperability III*, Springer, pp. 99-111.

Gu, N., Nakapan, W., Williams, A. and Gul, L. (2009), "Evaluating the use of 3D virtual worlds in collaborative design learning", *The 13th International Conference on Computer Aided Architectural Design (CAADFutures)*.

Gül, L.F., Gu, N. and Williams, A. (2008), "Virtual worlds as a constructivist learning platform: evaluations of 3D virtual worlds on design teaching and learning", *Journal of Information Technology in Construction (ITcon)*, Vol. 13 No. 36, pp. 578-593.

Harzing, A.-W. (2010), "Advantages of Thomsons ISI web of science", available at: https://harzing.com/popbook/ch14_1.htm (accessed 13 April 2020).

Iorio, J. and Taylor, J.E. (2014a), "Boundary object efficacy: The mediating role of boundary objects on task conflict in global virtual project networks", *International Journal of Project Management*, Vol. 32 No. 1, pp. 7-17.

Iorio, J. and Taylor, J.E. (2014b), "Precursors to engaged leaders in virtual project teams", *International Journal of Project Management*, Vol. 33 No. 2, pp. 395-405.

Iorio, J., Peschiera, G., Taylor, J.E. and Korpela, L. (2011), "Factors impacting usage patterns of collaborative tools designed to support global virtual design project networks", *Journal of Information Technology in Construction (ITcon)*, Vol. 16 No. 14, pp. 209-230.

Jackson, P.C. (1987), *Corporate Communication for Managers*, Trans-Atlantic Publications.

Kim, M., Wang, X., Love, P., Li, H. and Kang, S.-C. (2013), "Virtual reality for the built environment: a critical review of recent advances", *Journal of Information Technology in Construction*, Vol. 18, pp. 279-305. No. 2013.

Koutsabasis, P., Vosinakis, S., Malisova, K. and Paparounas, N. (2011), "On the value of virtual worlds for collaborative design", *Design Studies*, Vol. 33 No. 4, pp. 357-390.

Kumar, S., Hedrick, M., Wiacek, C. and Messner, J.I. (2011), "Developing an experienced-based design review application for healthcare facilities using a 3D game engine", *Journal of Information Technology in Construction (ITcon)*, Vol. 16 No. 6, pp. 85-104.

Lappalainen, P. (2009), "Communication as part of the engineering skills set", *European Journal of Engineering Education*, Taylor & Francis, Vol. 34 No. 2, pp. 123-129.

Lasi, H., Fettke, P., Kemper, H.G., Feld, T. and Hoffmann, M. (2014), "Industry 4.0", *Business & Information Systems Engineering*, Vol. 6 No. 4, pp. 239-242.

Laufer, A. and Tucker, R.L. (1987), "Is construction project planning really doing its job? A critical examination of focus, role and process", *Construction Management and Economics*, Taylor & Francis, Vol. 5 No. 3, pp. 243-266.

Le, Q.T. and Park, C.S. (2012), "Construction safety education model based on second life", *Proceedings of IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE) 2012*, IEEE, pp. H2C-1.

Le, Q.T., Pedro, A. and Park, C.S. (2015), "A social virtual reality based construction safety education system for experiential learning", *Journal of Intelligent & Robotic Systems*, Vol. 79 No. 3, pp. 487-506.

Le, Q.T., Pedro, A., Pham, H.C. and Park, C.S. (2016), "A virtual world based construction defect game for interactive and experiential learning", *International Journal of Engineering Education*, Vol. 32, pp. 457-467.

Li, X., Yi, W., Chi, H.-L., Wang, X. and Chan, A.P. (2018), "A critical review of virtual and augmented reality (VR/AR) applications in construction safety", *Automation in Construction*, Vol. 86, pp. 150-162.

Liang, C., Lu, W., Rowlinson, S. and Zhang, X. (2016), "Development of a multifunctional BIM maturity model", *Journal of Construction Engineering and Management*, American Society of Civil Engineers, Vol. 142 No. 11, p. 06016003.

Manning, R. and Messner, J. (2008), "Case studies in BIM implementation for programming of healthcare facilities", *Electronic Journal of Information Technology in Construction*, Kungliga Tenkniska Hoegskolan/Royal Institute of technology, Vol. 13, pp. 446-457.

Mansoori, S. (2013), "Which is better, a conference paper or journal publication?", ResearchGate, available at: www.researchgate.net/post/Which_is_better_a_conference_paper_or_journal_publication (accessed 6 April 2020).

Merrick, K.E. and Gu, N. (2011), "Case studies using multiuser virtual worlds as an innovative platform for collaborative design", *Journal of Information Technology in Construction (ITcon)*, Vol. 16 No. 12, pp. 165-188.

Merrick, K.E., Gu, N. and Wang, X. (2011), "Case studies using multiuser virtual worlds as an innovative platform for collaborative design", International Council for Research and Innovation in Building and Construction, available at: https://nova.newcastle.edu.au/vital/access/manager/Repository/uon:15297 (accessed 22 May 2020).

Milgram, P. and Kishino, F. (1994), "A taxonomy of mixed reality visual displays", *IEICE TRANSACTIONS on Information and Systems*, The Institute of Electronics, Information and Communication Engineers, Vol. 77 No. 12, pp. 1321-1329.

Mok, K.Y., Shen, G.Q. and Yang, J. (2015), "Stakeholder management studies in mega construction projects: a review and future directions", *International Journal of Project Management*, Elsevier, Vol. 33 No. 2, pp. 446-457.

Moloney, J. (2005), "Game engines and virtual design studios", Digital Design: The Quest for New Paradigms [23nd ECAADe Conference Proceedings, pp. 55-62.

Moloney, J. and Amor, R. (2003), "StringCVE: advances in a game engine-based collaborative virtual environment for architectural design", *Proceedings of CONVR 2003 Conference on Construction Applications of Virtual Reality*, *Citeseer*, pp. 156-168.

Moloney, J. and Harvey, L. (2004), "Visualization and'auralization'of architectural design in a game engine based collaborative virtual environment", *Proceedings. Eighth International Conference on Information Visualisation, 2004. IV 2004*, IEEE, pp. 827-832.

Moloney, J., Amor, R., Furness, J. and Moores, B. (2003), "Design critique inside a multi-player game engine", *CIB REPORT*, Vol. 284, p. 255.

Mongeon, P. and Paul-Hus, A. (2016), "The journal coverage of Web of Science and Scopus: a comparative analysis", *Scientometrics*, Vol. 106 No. 1, pp. 213-228.

National Institute of Building Sciences (2020), "What is a BIM", available at: www.nationalbimstandard.org/faqs (accessed 16 January 2020).

Newton, S., Lowe, R., Kember, R., Wang, R. and Davey, S. (2013), "The situation engine: a hyper-immersive platform for construction workplace simulation and learning", *Proceedings of the 13th International Conference on Construction Applications of Virtual Reality*, pp. 30-31.

O'Donnell, K., Hecsh, J., Underwood, T., Loker, W., Trechter, S.A., David, D. and White, A. (2011), "Putting high-impact practices and inclusive excellence at the center of GE reform: lessons from the California State University LEAP initiative", *Peer Review, Association of American Colleges and Universities*, Vol. 13 No. 2, p. 22.

Oesterreich, T.D. and Teuteberg, F. (2016), "Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry", *Computers in Industry*, Vol. 83, pp. 121-139.

Oraee, M., Hosseini, M.R., Papadonikolaki, E., Palliyaguru, R. and Arashpour, M. (2017), "Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review", *International Journal of Project Management*, Elsevier, Vol. 35 No. 7, pp. 1288-1301.

Park, C.-S. and Kim, H.-J. (2013), "A framework for construction safety management and visualization system", *Automation in Construction*, Vol. 33, pp. 95-103.

Pham, H., Dao, N.N., Kim, J.U., Cho, S. and Park, C.S. (2018), "Energy-efficient learning system using web-based panoramic virtual photoreality for interactive construction safety education", *Sustainability*, Vol. 10 No. 7, p. 2262.

Regenbrecht, H. and Donath, D. (1997), "Architectural education and virtual reality aided design (VRAD)", Designing Digital Space-An Architects Guide to Virtual Reality, pp. 155-176.

Rheingold, H. (1991), *Virtual Reality: Exploring the Brave New Technologies*, Simon & Schuster Adult Publishing Group.

Riemer, M.J. (2002), "English and communication skills for the global engineer", *Global Journal of Engineering Education (GJEE)*, Vol. 6 No. 1, pp. 91-100.

Riemer, M.J. (2007), "Communication skills for the 21st century engineer", *Global Journal of Engineering Education (GJEE)*, Vol. 11 No. 1, pp. 89-100.

Salem, B. and Earle, N. (2000), "Designing a non-verbal language for expressive avatars", *Proceedings of the Third International Conference on Collaborative Virtual Environments*, pp. 93-101.

Shen, W., Shen, Q. and Sun, Q. (2012), "Building information modeling-based user activity simulation and evaluation method for improving designer–user communications", *Automation in Construction*, Vol. 21, pp. 148-160.

Sheth, T.D. (2015), "Communication skill: A prerequisite for engineers", *International Journal on Studies in English Language and Literature*, Vol. 3 No. 7, pp. 51-54.

Shi, Y., Du, J., Lavy, S. and Zhao, D. (2016), "A multiuser shared virtual environment for facility management", *Procedia Engineering*, Vol. 145, pp. 120-127.

Shi, Y., Du, J., Tang, P. and Zhao, D. (2018), "Characterizing the role of communications in teams carrying out building inspection", *Construction Research Congress 2018, presented at the Construction Research Congress 2018, American Society of Civil Engineers, New Orleans*, pp. 554-564.

Shiratuddin, M.F. and Thabet, W. (2011), "Utilizing a 3D game engine to develop a virtual design review system", *Journal of Information Technology in Construction–ITcon*, Vol. 16, pp. 39-68.

Siddaway, A. (2014), "What is a systematic literature review and how do I do one", *University of Stirling*, Vol. 1, pp. 1-13.

Singhvi, V. and Terk, M. (2003), "Prophet: a contextual information system framework", *CIB REPORT*, Vol. 284, p. 318.

Sun, C., Jiang, S., Skibniewski, M., Man, Q. and Shen, L. (2015), "A literature review of the factors limiting the application of BIM in the construction industry", *Technological and Economic Development of Economy*, Vol. 23 No. 5, pp. 1-14.

Taroun, A. (2014), "Towards a better modelling and assessment of construction risk: insights from a literature review", *International Journal of Project Management*, Vol. 32 No. 1, pp. 101-115.

Taylor, J.E., Alin, P., Anderson, A., Çomu, S., Dossick, C.S., Hartmann, T., Iorio, J. *et al.* (2018), "CyberGRID: A Virtual Workspace for Architecture, Engineering, and Construction", *Transforming Engineering Education: Innovative Computer-Mediated Learning Technologies*, pp. 291-321.

Tepper, D.T. and Haase, R.F. (1978), "Verbal and nonverbal communication of facilitative conditions", *Journal of Counseling Psychology*, Vol. 25 No. 1, p. 35.

Van Nederveen, S. (2007), "Collaborative design in second life", *Proceedings of the Second International Conference World of Construction Project Management*.

Van Riel, C.B. and Fombrun, C.J. (2007), *Essentials of Corporate Communication: Implementing Practices for Effective Reputation Management*, Routledge.

Vosinakis, S., Koutsabasis, P., Stavrakis, M., Viorres, N. and Darzentas, J. (2008), "Virtual environments for collaborative design: requirements and guidelines from a social action perspective", *Co-Design*, Vol. 4 No. 3, pp. 133-150.

Wang, X., Kim, M.J., Love, P.E. and Kang, S.C. (2013), "Augmented reality in built environment: classification and implications for future research", *Automation in Construction*, Vol. 32, pp. 1-13.

Wang, P., Wu, P., Wang, J., Chi, H.-L. and Wang, X. (2018), "A critical review of the use of virtual reality in construction engineering education and training", *International Journal of Environmental Research and Public Health*, Vol. 15 No. 6, p. 1204.

Warwick, K., Gray, J. and Roberts, D. (1993), "Virtual reality in engineering", Institution of Electrical Engineers.

Wu, W. and Kaushik, I. (2015), "Design for sustainable aging: improving design communication through building information modeling and game engine integration", *Procedia Engineering*, Vol. 118, pp. 926-933.

Yamamoto, A., Yabuki, N. and Fukuda, T. (2018), "Immersive virtual reality teleconferencing system with design change tracking and 3D editing", *Proceedings of the 18th International Conference on Construction Applications of Virtual Reality (CONVR2018)*, pp. 302-310.

Zelkowicz, A., Iorio, J., Taylor, J.E. and Via, C.E. (2015), "Exploring the role of cultural boundary spanners at complex boundaries in global virtual AEC networks", *Journal of Information Technology in Construction (ITcon)*, Vol. 20 No. 24, pp. 385-398.

Zhang, J. and El-Diraby, T.E. (2012), "Social semantic approach to support communication in AEC", *Journal of Computing in Civil Engineering*, Vol. 26 No. 1, pp. 90-104.

Zhou, W., Whyte, J. and Sacks, R. (2012), "Construction safety and digital design: a review", *Automation in Construction*, Vol. 22, pp. 102-111.

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