VIRTUAL REALITY FOR THE BUILT ENVIRONMENT: A CRITICAL REVIEW OF RECENT ADVANCES

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Abstract: This paper reviews the current state of the art for Virtual Reality (VR) and Virtual Environment (VE) applications in the field of the built environment. The review begins with a brief overview of technological components involved in enabling VR technology. A classification framework is developed to classify 150 journal papers in order to reveal the scholarly coverage of VR and VE from 2005 to 2011, inclusive. The classification framework summarizes achievements, established knowledge, research issues and challenges in the area. The framework is based on four layers of VR: concept and theory, implementation, evaluation and industrial adoption. These layers encompass architecture and design, urban planning and landscape, engineering, construction, facility management, lifecycle integration, training and education. This paper also discusses various representative VR research work in line with the classification framework. Finally the paper predicts future research trends in this area.

KEYWORDS: Virtual Reality, Virtual Environment, Built Environment, Critical Review, Framework

1. INTRODUCTION

Virtual Reality (VR) has different meanings for different people. It is defined as "the computer-generated simulation of three-dimensional images of an environment or sequence of events that someone using special

electronic equipment may view, as on a video screen, and interact with in a seemingly physical way" [1]. It is also defined as the "computer simulation of a real or imaginary system that enables a user to perform operations on the simulated system and shows the effects in real time" [2] During the past two decades, practical applications of VR technology have spanned many fields including pilot training [3-5], driving and military applications [6-8], industrial applications [9, 10] and medical visualization [11-15]. As an area that heavily relies on visual communication, the Architecture, Engineering, Construction and facility management (AEC/FM) industry benefits significantly from advances in VR technology. In the past seven years there has been a transition from describing potential benefits of adopting VR technology and the experimental and simulation testing of prototypes to the development of actual VR applications in pilot testing and industry. This paper reviews the majority of the literature covering recent advances in VR work in various areas of the built environment from 2005 to 2011, inclusive. The purpose of this review is to identify and classify the major areas of research in the field. This review identifies the areas in which significant research has been concentrated, using statistics. It also reveals areas of research paucity. Such reviews enable the consolidation of knowledge, allowing researchers to take stock of accomplishments and trends [16-18]. This paper also identifies major research questions and issues that need to be addressed. As another contribution, implications of this review for human factors and pure VR technical disciplines are discussed.

It was approximately two decades ago that applications of VR visualization technology were brought to the attention of architects (McMillan 1994). This opened the door for numerous disciplines to interact with architects who were already looking at the possibilities of VR. The exciting visualization opportunities presented by VR technologies have captured the attention of a growing number of researchers from the architecture, engineering, construction and facilities management (AEC/FM) domain. Researchers in computer science and computer engineering—where VR concepts and technology were born—initially studied VR from the perspective of technology development, without deeply incorporating knowledge of application domains. In contrast the AEC/FM area requires that a user perspective be considered, in order to realize the ultimate goal of practical VR adoption. There are many opportunities for improving the efficiencies of VR in practice, and these require changes in the way work is carried out. This review paper summarizes how applied VR confronts technical challenges and also suggests how future objectives in this area might be pursued.

The organization of the paper is as follows: Section 2 explains the current status of VR and its enabling technologies. In Section 3 the research methodology used to search, screen, review and categorize the literature is illustrated. Section 4 presents the features of each category and subcategory within the classification framework. Section 5 interprets and discusses the results of this review and predicts future trends; this section also includes representative work examples and recommendations. Finally, Section 6 emphasizes the main insights gained from research and development related to VR in the built environment.

2. ENABLING TECHNOLOGIES OF VR IN THE BUILT ENVIRONMENT

Since 1995, using the concept of the "hype cycles", Gartner has characterized the over-enthusiasm and subsequent disappointment that typically occur when new technologies are introduced. Hype cycles [19] can also be used to show how and when technologies move beyond hype, to offer practical benefits and become widely accepted. Public virtual world technologies have recently sat at the bottom of Gartner's "trough of disillusionment", during which virtual worlds had become unfashionable. However, some virtual world technologies have now matured beyond this stage to become productive in practical contexts. Throughout 2008 the corporate world was exposed to virtual world technologies, and such technologies are exerting a growing influence on how companies train, market, advertise and communicate [19].

VR is a simulation of a real world environment, generated through computer software and experienced by the user through a human–machine interface. A huge variety of VR devices can be utilized to create virtual environments with different capabilities and purposes. Depending on budget, needs and desired complexity, a wide range of hardware and software is available for creation of VR simulations. The basic technological components of VR systems are feedback displays and interaction devices. Numerous VR simulation software toolkits and engines are available for developing VR prototypes; these include Virtools, Secondlife, Visualization Toolkit (VTK) and Open Graphics Library (OpenGL). Many AEC/FM VR applications have been prototyped based on such software [20-23].

The simplest visual display device is a desktop computer monitor, sometimes with a 3D stereoscopic effect. Many such displays are not as realistic as true-stereo 3D; however, the sense of depth can be enhanced through the use of depth cues such as perspective, relative motion, occlusion and aerial perspective [24-26]. To create an immersive virtual environment, one needs a display that can provide true-stereo 3D. This can be achieved by using a head-mounted display (HMD) which allows stereo viewing via small monitors mounted in front of each eye and linking of the VR viewpoint using head tracking [27-29]. Large screen stereo projection systems, which provide compelling stereo that involves the use of lightweight polarizing glasses, are an alternative option [30, 31]. A very high end example of this type of setup is the cave automatic virtual environment (the CAVE™ system), which provides a multi-person, room-sized, high-resolution, 3D audio and video virtual environment [20]. Most work in VR has focused on the visual sense, employing virtual graphic objects and overlays. However, virtualization might apply to all other senses as well. For example haptic displays, based on tactile information, are typically presented by means of a hand held master manipulator [32] or glove-type devices [33].

Human interact with their environment through five senses—vision, hearing, touch, proprioception and smell. VR can mimic these senses, through devices employed in human- computer interactions, with various degrees of fidelity. For example, a haptic interface can impose a force feedback on a user's hand when he/she is "punching" an object in a virtual environment. There are a number of ways that six dimensional (three translational and three rotational) controlling signals can be generated. For more detailed description of these input paradigms, readers are referred to [34].

3. RESEARCH METHODOLOGY

Recently a large quantity of work has been produced on VR for the built environment, although the idea of using VR in the built environment dates back several decades. The nature of this work has migrated from early conceptual frameworks and lab-based proofs of concept to sophisticated implementation that incorporates knowledge of application domains and theories concerning human factors. It is necessary to have a comprehensive review of recent significant VR work and its application to the built environment. The main objectives of this review are:

•to provide a framework for the integration and classification of state of the art work on research concerning VR in the built environment

•to reveal areas of research concentration and paucity in this field

•to summarize issues and challenges related to VR in the built environment, and suggest how these can be pursued

•to forecast future research and development trends in this area

The selection criteria:

Papers were reviewed to determine eligibility for this study based on the following criteria:

•To ensure currency, only articles published from 2005 to 2011 were considered.

•Selected papers were required to deal with VR work in the built environment. Articles that concentrated solely on VR, as opposed to its applications in the built environment, were excluded. For example, VR papers primarily covering product design or product assembly were outside the scope of this review.

•For purposes of quality assurance, only articles from relevant leading international journals were searched to ensure that only rigorously peer reviewed material was included. Conference papers, book chapters and articles in non-leading or non-international journals were not considered.

Data sources:

Leading international journals in AEC/FM, as listed in Table 1, were identified and searched. In order to include relevant journals from other domains, for example pure VR technical journals that have papers dealing with VR for the built environment, we searched the following six online databases listed in order of the numbers of articles obtained: Science Direct, IEEE Xplore, Springer Link Online Libraries, ACM Digital Library, Wiley InterScience, Ingenta Journals, and EBSCO (Electronic Journal Service). Journals that are more computer science focused, or otherwise narrow in focus, were excluded from the list. Relevant journals identified from this search include Expert systems with applications, Presence, International Journal of Virtual Reality and Virtual Reality. Relevant articles from these journals studied VR in the built environment from the perspective of technical development. The total number of articles from this search is 23.

Table 1 Journal list searched and the associated number of articles

Journal Title	Number of articles
Advanced Engineering Informatics	5
American Society of Civil Engineers (ASCE) Journals	19
Architectural engineering and design management	5
Architectural science review	4
Artificial Intelligence for Engineering Design, Analysis and Manufacturing	2
Automation in Construction	21
Building and Environment	1
CoDesign	2
Construction management and economics	3
Design Studies	4
Environment and Planning B: Planning and Design	3
Expert system with applications	1
International Journal of Architectural Computing	27
Journal of information technology in construction	31
Presence : Teleoperators and virtual environments	5
The International Journal of Virtual Reality	9
Virtual Reality	8
Total	150

Procedures for extracting articles:

Research reviews of specific paradigms are an established form of enquiry within the information systems discipline [35]. For example, Hong et al. [36] used this approach to conduct a research review in the area of context-aware computing. Identification of articles within the journals listed in Table 1 involved keyword searches and an exhaustive search of journal titles. The keywords used were "virtual", "virtual reality, "visualization" and "virtual environment". Abstracts of all articles that appeared to fit our review criteria were read, followed by reading of full articles in order to extract the main findings and emphasis of each article. Many articles that were initially identified via their titles or keywords were discarded if either the abstract or the article itself did not primarily focus on VR. For example, although containing the keyword "virtual", virtual organization papers are not eligible because such papers contain no contents concerning VR. More than 200 papers were initially identified and, following screening, only 150 articles were determined to be suitable for content analysis.

Two independent researchers proposed their classification frameworks. Both of these researchers conducted an analysis based on their own classification frameworks. Then a matching process was used to resolve inconsistencies between the two systems and form a single classification framework. Once each category in the classification framework was finalized one of the original researchers, along with a third researcher who was not involved in developing the classification system, allocated each of the selected articles to the appropriate section of the framework. Cohen's kappa statistic was used to analyse correspondence between the researchers' allocation of articles to the categories in the classification framework. The result shows that there was a high degree of reliability between the different researchers' classifications (0.95). This is well above the recommended level of 0.80 [37].

A longitudinal perspective is also taken in this review in order to identify patterns, trends and themes in relation to quantities of publications in various research sub-areas. Table 2 lists the numbers of articles published in each selected journal from 2005 to 2011, inclusive. This time frame does not cover the early stages of work on VR in the built environment, but is extensive enough to identify the emergence of literature on a wide range of research themes according to the classification framework.

Table 2 Number of articles published in each journal between 2005 and 2011

Journal Title	2005	2006	2007	2008	2009	2010	2011	Total
Advanced Engineering Informatics			2		1	1	1	5
American Society of Civil Engineers (ASCE) Journals	5	1	3	3	4	2	1	19
Architectural engineering and design management	1	1		2	1			5
Architectural science review	1				2		1	4
Artificial Intelligence for Engineering Design, Analysis and Manufacturing			2					2
Automation in Construction	3	3	3	2	3	3	4	21
Building and Environment							1	1
CoDesign				1	1			2
Construction management and economics			1	1	1			3
Design Studies		2				1	1	4
Environment and Planning B: Planning and Design	1			1			1	3
Expert system with applications							1	1
International Journal of Architectural Computing	5	2	10	1	7	1	1	27
Journal of information technology in construction	2	6		8	3	3	9	31
Presence : Teleprators and virtual environments		2	1	1	1			5
The International Journal of Virtual Reality		1	1	2	3	1	1	9
Virtual Reality		5	1			2	0	8
Total	18	23	24	22	27	14	22	150

Framework for classifying literature on VR in the built environment:

The classification framework used for VR and VE applications in the field of the built environment consists of the following three parts. The first part includes specific application areas in the built environment where the second part describes four layers of VR which encompass the application areas. The third part involves technological components in enabling VR technology:

1. *Application to the built environment involving*: architecture and design, landscape and urban planning, engineering-related issues, construction, facility management, lifecycle integration and training and education.

2. *The architecture layers of built environment VR systems*, as shown in Figure 1, based on standard architecture layer criteria for emerging information technology concepts or tools [36], for example context-aware computing, mobile computing and pervasive computing. This architecture consists of four layers:

   a) concept and theory, consisting of algorithms, development specifications, conceptual frameworks, evaluation frameworks and technology transfer

   b) implementation including hardware display, input, computing and trackers and software. involving agent-, intelligence- and knowledge-based issues, information design and interaction design

   c) evaluation, divided into effectiveness and usability categories

   d) industry adoption, specifically concerning whether a prototype has been industry-tested.

3. *Other technical criteria:*

   •Theory of human factors: is theory on human factors involved?

•Built environment domain knowledge: is there considerable reliance on knowledge of VR work in the built environment domain?

•Single-user VR system vs. Collaborative VR system

•Type of display is used: head-mounted display (HMD), window on the world, or projection

•Self-developed vs. Commercially-developed software

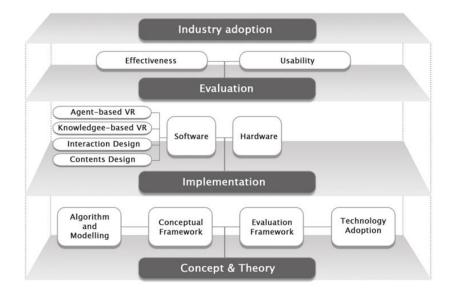•Self-evaluation vs. Comparative evaluation

Figure 1 Architecture layer framework of VR systems in the built environment

4. RESULTS OF ARTICLE CLASSIFICATION

Classification of articles by publication year:

The number of articles by publication year is depicted in Figure 2. VR article numbers grew steadily from 2005 to 2009, inclusive, whereas the numbers of such articles from 2006 to 2008, inclusive, remained static. Surprisingly, there was a significant drop in article numbers in 2010, compared with 2009, but this was followed by a marked increase in 2011. It seemed that effort and interest concerning VR in the built environment have increased in recent years.
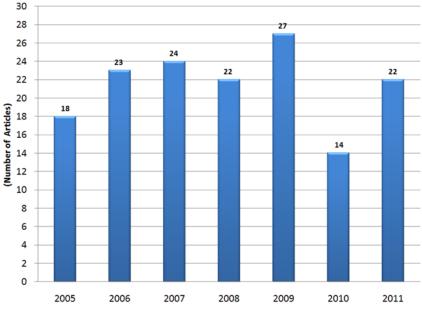
Figure 2 Number of VR in built environment publications from 2005 to 2011

Classification of articles by journal:

The journals searched are categorized in Table 1. Over 17 journals containing articles related to VR in the built environment were searched; (all journals produced by the American Society of Civil Engineers (ASCE) are grouped together as "ASCE Journals"). Most of them were related to the Architecture, Design, Engineering, Construction, and Facility Management. As Table 1 shows, the Journal of Information Technology in Construction published the most articles on VR systems (31 articles, 21%). The International Journal of Architectural Computing published 27 articles (18%). Automation in Construction published 21 articles (14%), which is close to the 19 articles (13%) published collectively in all ASCE journals. This distribution reveals that most articles on VR in the built environment were published in computer or IT-related journals in the AEC areas. The spread of remaining articles across journals in other areas highlights that there are many facets of VR in built environment research, relevant to a wide cross section of disciplines.
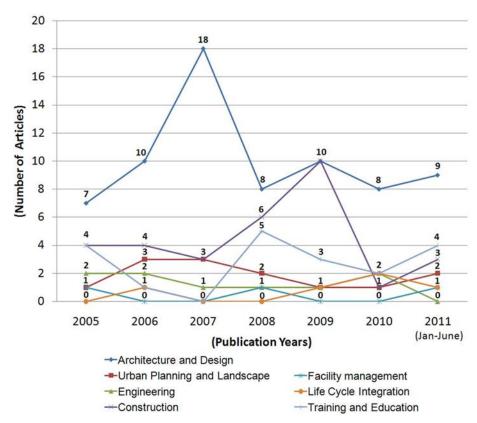
Figure 3 Number of articles in each application area from year 2005 to 2011

Classification of articles by application area:

The number of publications within each of discipline area over the seven-year period analysed is shown in Figure 3. In terms of built environment disciplines, architecture has been the area with greatest interest in VR (71 articles, 47.3%). It is likely that architecture was the first built environment discipline to embrace VR, because architects are visually oriented and appreciate the need for visual aids. The door was then opened for other inquirers to join with architects who were already looking at possibilities for virtual visualization.

While the number of articles on VR published in construction journals was smaller than the number of publications in the area of architecture and design, construction journals contained the second greatest number of VR articles (30 articles, 20%). The concept of Virtual Construction has been substantially explored in construction journals, due to offering opportunities for identifying potential problems prior to actual construction. Interestingly, many Virtual Construction systems are related to Building Information Modelling (BIM) and 4D CAD, both of which extensively visualize construction information and processes in the current standard approach to building design. For example, Staub-French et al. [38] proposed a 4D visualization approach to multiple product models by integrating 3D CAD software with linear planning software to define a project model in association with a process model. In this approach, construction sequences can be modified and the consequences of this examined using 4D CAD, facilitating a two-way flow of communication with scheduling software.

Training and education journals contained 19 articles (12.7%) which is not surprising, as virtual training is becoming increasingly important in a variety of areas. VR offers a unique capacity for real time feedback to be provided in a very intuitive form. Wang et al. [39] developed a virtual training system based on Unity3D for use in heavy equipment operations. In this system, novice trainees can see their own operation attempts in the same spatial frame of reference as that of a "virtual coach". Training tasks were simplified during the early stages of learning, assisting trainees to focus on key elements. In contrast, a real world situation may include potential accidents and this can slow down learning if trainees' focus is fragmented as a result.

Engineering-related journals contained 9 articles on VR applications (6%). For example, Hutchinson et al. [40] described their development of an interactive hybrid environment, termed VizClass, integrating both 2D and 3D spatial activities by coupling a series of touch-sensitive whiteboards with a semi-immersive 3D wall display. This environment was developed for studying complex engineering problems involving time-varying movement. Simple interpolation schemes are applied here to visualize time-varying building deformation, study 3D displacement history (using 3D traces) and rapidly assess maxima values (using bounding boxes). Interaction paradigms including spatially tracked gloves and whiteboards with keyboard and mouse are integrated into this system, allowing users to manipulate models and data.

Urban planning and landscape journals contained 13 VR articles (8.7%). There were very few papers in the areas of facility management (3 articles, 2%) and life cycle integration (5 articles, 3.3%). Although there has been relatively little research in the area of facilities management (FM) it is envisaged that VR, especially combined with BIM, will become a very effective tool for assisting with early design conception in the area of FM.

VR is still at an early exploration stage in the field of lifecycle integration and, consequently, there has not been much recent focus on VR in this domain. However, there has been some preliminary conceptual and exploratory work in this area. For example, as part of "the IntUBE project—Intelligent Use of Buildings' Energy Information", Crosbie et al. [41] proposed a conceptual framework for virtual collaborative lifecycle tools in order to improve the energy performance of built environment features including building design, operation and retrofitting via the intelligent use of buildings' energy information. They conducted a case study in which three different design alternatives developed for a school were assessed against relevant sustainability standards and building regulations. Guo et al. [42] proposed a conceptual framework of a virtual prototyping-based information sharing platform based on analysis of the information flow in lifecycle management (LCM). VR-based LCM of projects was analysed via its application to a real-life construction project. This analysis demonstrated that VR-based LCM is an effective tool to support construction in terms of reducing duration, risks and costs of projects and improving levels of service to owners and tenants.

Classification of articles by architecture layer:

Figure 4 shows the number of articles dealing with various architecture layers from 2005 to 2011, inclusive. The numbers of articles, relative percentages within subject and global percentage of all subjects by each category of the classification framework are listed in Table 3. It is important to state that an article might fall into multiple categories. For example, an article might make both a significant "contents design" contribution and also have significance for evaluation of effectiveness and usability. Thus, the sum in the "number of articles" column in Table 3 is greater than 150, the total number of the articles. The numbers of articles in Table 3 tallies the number of articles in each category. It shows the percentage within subject indicates the percentage of papers within one category. The global percentage means that the number of papers in total number. Tables 4–7 represent all references of the VR articles. With respect to layer 1, 36.7% (55 articles) of reviewed articles concerned concept and theory. Such contributions provide researchers with a conceptual map for conducting future research. Layer 2, the implementation layer, contained the highest percentage of VR articles (81 articles, 54%). This implies that VR technology has matured sufficiently to enable implementation, either of off-the-shelf commercial packages or through user development via lower level software infrastructure. 39.3% of the review articles (59 articles, 39.3%) contained significant evaluation (Layer 3) of the effectiveness and/or usability, through scientific and formal approaches. Unfortunately, only 7.3% (11) of the published articles dealt significantly with industrial adoption or piloting. These figures suggest that VR is being used in the built environment and that this has attracted formal evaluation to quantitatively demonstrate its usefulness. Wide-spread industrial adoption of VR has not yet been realized, but this potential area of VR application is beginning to attract attention.
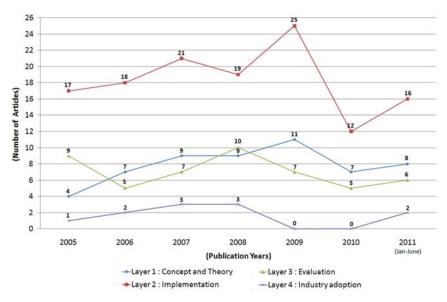
Figure 4 Number of articles at each architecture layer from year 2005 to 2011

The following subsection explores representative and significant work identified at each architectural layer and also discusses research issues, challenges and future trends in this field

Table 3 Number of articles by each subject of the classification framework from 2005 to 2011

Classification criteria	Number of articles	Relative Percentage of subject (%)	Global Percentage of all subject (%)
Application Areas	150	100	100
Architecture and Design	71	47.3	47.3
Urban Planning and Landscape	13	8.7	8.7
Engineering	9	6.0	6.0
Construction	30	20.0	20.0
Facility management	3	2.0	2.0
Lifecycle Integration	5	3.3	3.3
Training and Education	19	12.7	12.7
Layer 1. Concept and Theory	55	100	36.7
1.1 Algorithm and Modelling	25	45.5	16.7
1.2 Conceptual Framework	23	41.8	15.3
1.3 Evaluation Framework	0	0.0	0.0
1.4 Technology Adoption	7	12.7	4.7
Layer 2. Implementation	128	100	85.3
2.1 Software	126	98.4	84.0
2.1.1 Contents design	84	65.6	56.0
2.1.2 Agent-based VR	8	6.3	5.3
2.1.3 Knowledge-based VR	5	3.9	3.3
2.1.4 Interaction design	29	22.7	19.3
2.2 Hardware	16	12.5	10.7
Layer 3. Evaluation	49	100	32.7
3.1 Effectiveness	32	65.3	21.3
3.2 Usability	3	6.1	2.0
3.3 Effectiveness+ Usability	14	43.8	9.3

Layer 4. Industry adoption	11	7.3	7.3
Display			
HMD	2	1.4	1.3
Monitor	120	85.1	80.0
Projector	19	13.5	12.7
VR System			
Single-user system	103	74.1	68.7
Collaborative system	36	25.9	24.0
VR Toolkit			
Prototype	53	39.6	35.3
Commercial	81	60.4	54.0
Evaluation Method			
Self-evaluation	30	61.2	20.0
Comparative evaluation	19	38.8	12.7
Case study	23	28.4	15.3
Human Factors	45	30.0	30.0
Domain Knowledge	85	56.7	56.7
TOTAL	150		100.0

a. Layer 1: Concept and theory layer

This layer 1 represents the references according to the detailed categories in concept and research layer in Table 3. The concept and theory layer involves ideas about how VR should/can be adopted to solve a problem in the built environment. Within this layer, algorithms are essential to developing VR systems and research in this area includes work on artificial intelligence methodology to provide the foundations for VR to become part of intelligent systems. Conceptual framework material gives users a general idea of what VR systems will look like and how they will function; this pertains, for example to general system capabilities, user interfaces, data flow and system management. Implementation of VR systems can be built upon such conceptual roadmapping.

Layer 1, concept and theory, has been divided into four categories. Most of the articles in this layer relate to algorithms and modelling based on engineering principles (25 articles; 16.7%) and sophisticated conceptual frameworks (23 articles, 15.3%). Interestingly, no article in this layer concerned the development of a built environment VR evaluation framework or heuristic guidelines for usability evaluation, though such guidelines are well established in the pure VR area [43]. Certainly, pure VR evaluation guidelines can be adapted and customized for use in the context of the built environment. 4.7% (7 articles) of the articles reviewed examined issues and potentials of technology transfer and adoption in industry. This number is reasonable and not surprising, considering the nature of this VR study. Strategies and business models for gaining revenue by using VR systems are very few.

Table 4 Articles on the concept and theory layer

Classification criteria		References
Concept and Theory	Algorithm and Modelling	Lai and Kang[54], Rezazadeh et al.[55], Kang and Miranda[56], Alves and Bártolo[57], Toraño et al.[58], Rosenman et al.[59], Rekapalli et al.[60], Kang et al.[61], Kamat and Martinez[62], Li and Zhu[63], Zhang et al.[64], Lai et al.[65], Gursel et al.[66], Kamat and Martinez[67], Liu and You[68], Mallasi[47], Thalmann et al.[69], Edward et al.[70], Xu et al.[71], Rodriguez and Amato[72], Gu and Tsai[73], Yu et al.[74], Moustakas et al.[75], Popov et al.[76], Timm and Kamat[77]
	Conceptual Framework	Li et al.[78], Maher et al.[79], Crosbie et al.[41], Guo et al.[42], Sacks et al.[80], Staub-French et al.[38], Nimr and Mohamed [81], McMeel and Cockeram[82], Okeil[83], Isaacs et al.[84],Ku and Mahabaleshwarkar[85], Toro et al.[86], Jachna et al.[87], Maher et

Technology Adoption	al.[88], Russell et al.[89], Sher et al.[90], Cerovšek et al.[91], Calderón et al.[92], Woksepp and Olofsson[93], Lucas and Thabet[94], Obonyo[95], Fruchter et al.[96], Naji[97] Taylor[98], Woksepp and Olofsson[53], Goulding et al.[99], Li et al.[100], Li et al.[101], Greenwood et al.[102], Johnsson et al.[103]

Algorithms and modelling methods are fundamental to visualizing the built environment in the virtual world. Such algorithms need to consider engineering needs in order to properly develop simulation or analysis methods. Algorithms also need to be based on a balance between computational efficiencies and awareness of constraints imposed by the existing hardware and software environments.

This review paper extracted and summarized high priority research issues and questions that need to be addressed by future researchers. It should be noted that the research issues and questions presented below and in other sections are not the ones addressed in the review paper here.

Research issues and questions:

•How can real world information be visualized efficiently and effectively?

•How can the ever-changing, complex geometry of the real construction site be handled?

•How can VR models and information be effectively organized for large engineering projects?

•How can an efficient scene graph management for large models in VR systems be realized?

b. Layer 2: implementation

As shown in Table 3, we divide this layer into software and hardware. Software is further divided into contents design, interaction design, agent-based VR and knowledge-based VR. Agent-based VR refers to VR systems that heavily rely on the concept and approach of the agent in order to gain certain levels of intelligence and autonomy. Agent-based VR combines conventional VR with an agent-related system. Knowledge-based VR is similar to knowledge-based system in definition, but it is more geared towards its application in VR system. Certain VR system might be very complicated involving massive knowledge to be managed. Combining knowledge-based system with VR concept is an innovation. Projection-based VR system is the VR rendering and visualization with a projector and its screen.

In terms of layer 2, implementation, many more articles deal with VR software (42 articles, 28%) than with hardware (16 articles, 10.7%). Looking further into the technical details of each VR system shown in Table 3, showed that most systems (65.6%) used "contents design" software. Eight VR systems (6.3%) used "agent-based VR". Five VR systems (3.9%) used "knowledge-based VR", 29 systems (22.7%) used "interaction design" and 16 VR systems (12.5%) used "hardware". Many built environment VR systems have not integrated interactive visualization with advanced 3D display components. This is confirmed by the low percentages of VR systems that have adopted the HMD (1.3%) and projection-based arrangements (12.7%).

A significant amount of the available literature focuses on technical issues such as agent architecture, multi-agent systems (MAS) learning and negotiation protocols, yet gives limited information on lessons learnt from agent-based applications. Surprisingly, only 8 articles (5.3%) involved incorporation of an agent into the virtual environment. The agent approach is one way to make VR intelligent; this is an essential component for VR, especially in collaborative systems. In the small number of articles dealing with an agent approach, this approach was generally used to support collaboration in a 3D virtual world.

Research issues and questions:

•Simulation of human behavior remains a challenging issue especially when real-time animation, such as virtual character facial modelling and locomotion, must be supported.

•There is a need for better integration of knowledge in the agent-based environment, through letting the

agent learn or by introducing features to assist memory.

•How can the agent-augmented ontology approach used to automate information extraction and document annotation? Answering this question could help users to easily track the logic behind decisions made during the virtual design and construction processes.

•How can semantics implemented to enable VR systems to support most of the commonly used data types and to store massive datasets?

•How can the collaborative possibilities of semantics architecture be explored?

Table 5 Articles on the implementation layer

Classification criteria			References
Implementation	Software	Contents design	Lai and Kang[54], Laing et al.[45], Huang et al.[46], Kang et al.[104], Kang and Miranda[56], Sampaio et al.[105], Alves and Bártolo[57], Li et al.[52], Korkmaz et al.[106], Rekapalli and Martinez[60], Kang et al.[61], Howard and Gaborit[24], Kamat and Martinez[62], Jáuregui et al.[25], Li and Zhu[63], Li et al.[26], Zhang et al.[64], Lai et al.[65], Gursel et al.[66], Aspin[30], Zhou et al.[107], Kamat and Martinez[67], Kang et al.[44], Liu and You[68], Iorio et al.[108], Dawood and Sikka[109], Xie et al.[110], Dawood et al.[22], Khanzode et al.[31], Shiratuddin and Thabet[111], Sørensen et al.[112], Merrick et al.[113], Jason et al.[114], Peng[115], Heldal[116], Stuerzlinger et al.[117], Stock and Bishop[118], Griffon et al.[119], Badni[120], Thalmann et al.[69], Lim et al.[121], Sunar et al.[122], Kang and Kim[123], Drettakis et al.[124], Wittkopf [125], Gu and Tsai[73],Ham and Schnabel[126], Yu et al.[74], Ch'ng and Stone[127], Forte and Pietroni[128], Hannibal et al.[129], Barros et al.[130], Wyeld et al.[131], Fukuda et al.[132], Chevrier et al.[133], Kalay and Grabowicz[134], Foni et al.[135], Stahre et al.[136], Kersten[137], Tost and Economou [138], Vecchia et al.[139], Massera[140], Mullins and Strojan[141], Walczak[142], Vosinakis et al.[143], Gül and Maher[144], Greenwood et al.[102], Johnsson et al.[103], Franz et al.[145], Westerdahl et al.[146], Rafi et al.[147], Russell et al.[89], Gül et al.[148], Timm and Kamat[77], Muramoto et al.[149], Sher et al.[90], Horne and Hamza[150], Lucas and Thabet[94], Breland et al.[151], Franz and Wiener[152], Cubukcu and Nasar[153], Stamps[154], Gül[155], Ibrahim et al.[156]
		Agent-based VR	Maher et al.[79], Toraño et al.[58], Rosenman et al.[59], Wang et al.[157], Edward et al.[70], Rodriguez and Amato[72], Calderón et al.[92], Obonyo[95]
		Knowledge-based VR	Mallasi[47], Toro et al.[86], Kleinermann et al.[158], Xu et al.[71], Popov et al.[76]
		Interaction design	Gu et al.[159], Setareh et al.[28], Setareh et al.[160], Shen and Grafe[27], Calderón et al.[161], Conniff et al.[162], Rahimiana and Ibrahimb[163], Wahlström et al.[164], Champion et al.[165], Hutchinson et al.[40], Chen and Bowman [166], Schroeder et al.[167], Bartolo and Wang[168], Interrante et al.[29], Vries et al.[169], Ioannidis et al.[170], Kieferle et al.[171], Paterson[172], Pechlivanidou et al.[173], Fischer[174], Calderon et al.[175], Hernández et al.[176], Moustakas et al.[75], Crotch et al.[177], Rahaman and Tan[178], Reffat[179], Sampaio et al.[180], Arain and Burkle[181], Fruchter et al.[96]
	Hardware		Fumarola and Poelman[182], Gu et al.[159], Setareh et al.[28], Setareh et al.[160], Xie et al.[110], Sørensen et al.[112], Ye et al.[183], Wahlström et al.[164], Hutchinson et al.[40], Vries et al.[169], Kieferle et al.[171], Kersten[137], Fischer[174], Hernández et al.[176], Moustakas et al.[75], Muramoto et al.[149]

c. Layer 3: evaluation

Evaluation is classified as either effectiveness evaluation or usability evaluation. Effectiveness evaluation concerns productivity improvement, performance time, number of errors and other quantitative indicators of how effectively a VR system can facilitate a certain activity. Usability evaluation involves investigating user needs

based on user interviews, field studies of users and expert appraisal of VR systems. Emerging VR devices and services introduce a new level of complexity to usability evaluation. Some researchers in this area have investigated general guidelines for evaluating VR systems, while others have evaluated novel VR interfaces and ways of interacting. It was suggested that a hybrid evaluation method, comprised of cognitive walkthrough and heuristic evaluation, would be useful for evaluating VR interfaces.

74.6% of the articles surveyed on built environment VR evaluation related to effectiveness evaluation. 25.4% of the articles surveyed focused on usability evaluation. The remainder of literature on evaluation (9.3%) concerns both effectiveness and usability evaluation. More extensive usability evaluation literature, to augment the material covering effectiveness evaluation, would be of value. Further, an evaluation subcategory is to look at if self-evaluation or comparative evaluation is involved. Self-evaluation means to evaluate the effectiveness and system performance itself. Comparative evaluation refers to comparison of a VR tool with a well-established benchmark (e.g. a typical work method/tool, or CAD software). Comparative evaluation is likely to be more reliable than self-evaluation, as comparisons can introduce an element of more objective appraisal [44-46]. 30 articles (61.2%) concerned self-evaluation, while 19 articles (38.8%) involved comparative evaluation.

Table 6 Articles at the evaluation layer

Classification criteria		References
Evaluation	Effectiveness	Lai and Kang[54], Laing et al.[45], Rezazadeh et al.[55], Gu et al.[159], Kang and Miranda[56], Li et al.[26], Zhang et al.[64], Woksepp and Olofsson[53], Kang et al.[44], Iorio et al.[108], Dawood and Sikka[109], Khanzode et al.[31], Rahimiana and Ibrahimb[163], Rodriguez and Amato[72], Wittkopf[125], Bartolo and Wang[168], Yu et al.[74], Hannibal et al.[129], Pechlivanidou et al.[173], Tost and Economou[138], Vecchia et al.[139], Mullins and Strojan[141], Gül and Maher[144], Franz et al.[145], Rafi et al.[147], Gül et al.[148], Sher et al.[90], Cerovšek et al.[91], Breland et al.[151], Franz and Wiener[152], Stamps[154], Fruchter et al.[96]
	Usability	Westerdahl et al.[146], Lucas and Thabet[94], Cubukcu and Nasar[153]
	Effectiveness+Usability	Howard and Gaborit[24], Setareh et al.[28], Dawood et al.[22], Conniff et al.[162], Wahlström et al.[164], Champion et al.[165], Hutchinson et al.[40], Heldal[116], Stuerzlinger et al.[117], Drettakis et al.[124], Schroeder et al.[167], Interrante et al.[29], Muramoto et al.[149], Gül[155]

Research issues and questions:

•How can usability evaluation guidelines specifically pertaining to VR in the built environment take domain knowledge into account?

•How can the usability of shared collaborative virtual environments (CVEs) be improved—by improving the systems and features of the environment, or by improving user awareness of their activities and setting?

•How can designers of virtual working environments most effectively leverage the collaborative potential of virtual tools to increase these tools' performance in complex design tasks?

•There are needs of evaluation methods for evaluating the factors at the low end – communication and awareness of each other's actions.

d. Layer 4: industrial adoption

With respect to layer 4, only 11 of the articles reviewed (7.3%) significantly involved an industrial practitioner testing their VR system in an actual project. This shows a need for establishment of stronger ties between industry and academia. Demonstration of benefits gained through using VR tools in practical projects has the

potential to convince industry to adopt such tools as part of daily routines. It should be noted that case studies were excluded from this review if these studies only collected practitioners' opinions of a particular VR system, asked practitioners to participate in a study, or used information from a practical industrial project as the basis for VR prototyping and implementation. In order to qualify for this review, studies were required to primarily involve testing of VR systems in practical industrial circumstances.

Table 7 Articles on the industry adoption layer

Classification criteria	References
Industry adoption	Li et al.[78], Huang et al.[46], Howard and Gaborit[24], Setareh et al.[160], Lai et al.[65], Xie et al.[110], Khanzode et al.[31], Li et al.[101], Hernández et al.[176], Messner et al.[184], Woksepp and Olofsson[93]

Other Technical Criteria:

In terms of VR displays, 80% of the reviewed articles (120 articles) featured standard monitoring, 12.7 % (19 articles) used projection-based displays such as interactive walls or CAVE and only 1.3% (2 articles) used head-mounted displays (HMD)

Most of the VR systems described in the literature are single-user-based (103 articles, 74.1%) with almost three times as much use as collaborative VR systems (36 articles, 25.9%). Therefore, more attention should be spent on collaborative system, because multidisciplinary collaboration is a trend that we predict will become a standard. There is also a trend to break down silo work. Figure 5 shows the number of articles involving collaborative VR systems from 2005-2011, inclusive.

39.6% of the articles reviewed (53 articles) covered self-developed VR systems. This relates to the modelling described in the first layer of VR architecture, described above. 60.4% of the articles reviewed (81 articles) were based on customization of off-the-shelf commercial software. This is unsurprising, as the work-readiness and sophistication of commercial software are attractive in terms of built environment VR applications. Furthermore, technologies and tools related to VR are standardized due to the large amount of commercial software used as a basis for prototyping.

Surprisingly, only 30% of the articles reviewed (45 articles) substantially involved human factors, models, theories and practices. 56.7% of the articles reviewed (85 articles) were serious domain knowledge studies, involving extraction and application of VR systems in the built environment. This percentage is low but is expected to be higher. Otherwise, it will be simply proof-of-concept application. Opportunities exist for improving practices through new efficiencies and through devising new ways of executing work tasks. Attention to human resource capabilities and other attendant human factors have the potential to yield successful technology development decisions and integration.
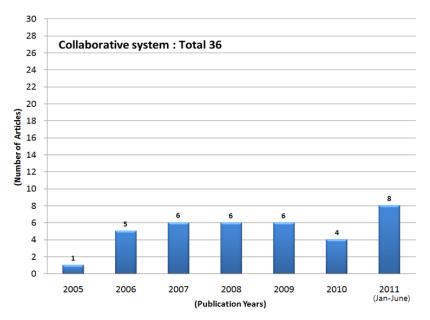
Figure 5 Number of articles involving collaborative VR system from 2005 to 2011

5. DISCUSSION

With respect to VR architecture work at the concept and theory level, technologies and tools have been standardized due to a high percentage of commercial software being used as a basis for prototyping. However, more efforts are needed for standardizing VR architecture to enable easier implementation of VR systems in the built environment. Consideration of concepts and theory underpinning this prototyping—such as context modelling methodology, inference algorithms, agents and interactions between agents—has been improving over the period from 2005 to 2011. Due to the added value, there is greater demand for integrating CAD with VR technology [47].

In terms of the implementation level, there is insufficient VR in the built environment with respect to interaction and devices. This lack of VR richness in the built environment is due to a lack of VR integration into the real environment. For example, on-site sensors can be used for office-based VR, this might be specific useful for construction monitoring and new paradigm of design and communicating design in architecture [48-51]. A standard for interactions between VR and real environments has not yet been achieved, therefore greater research focus on integration between the real and the virtual is required. The immediate future of VR may increasingly lie in the built environment, therefore VR has to catch up with the real world need for VR technology. However, researchers are now beginning to realize the impossibility of developing VR systems and applications solely in indoor and lab environments.

Feedback from project planners [52] indicates that it would be helpful if construction planning schedules could be developed together with site planning in VR systems. Good site layout planning can increase the productivity of construction activities, improve safety and avoid obstructive material and equipment movements on-site. Hence, a computer-aided environment can support site layout design.

In terms of VR at the evaluation level, most work is related to the evaluation of VR effectiveness for tasks in the built environments. Only about a quarter of the reviewed work focused on usability evaluation. Usability evaluation or human-computer interaction (HCI) research is critical, as past research has shown that there may be differences between the manner in which real and virtual spaces are evaluated and that these differences may be additionally influenced by delivery and viewing methods [45]. HCI needs to be used to facilitate interactions between users and VR systems. HCI design needs to be conducted through iterative prototyping and testing to

figure out the best way to build user-friendly interfaces [53]. Surprisingly, less than 10% of the work reviewed concerns both effectiveness and usability evaluation together. Increased work on usability evaluation would enhance the worth of effectiveness evaluation. Furthermore, comparative evaluation should be encouraged, to promote fairness and objectivity [44-46].

In terms of VR work at the industry adoption level, only 7.3% of the articles reviewed significantly involved an industrial practitioner and tested their system in a practical project. This shows a need to establish stronger ties between industry and academia. The results/ benefits gained from using the implemented VR tools in practical projects can educate or convince industrial to accept and even widely adopt the tool into their daily practice routines. Furthermore, there are very few strategic business models for gaining the revenue by adopting VR technologies in industry.

Published studies on VR in the built environment are, for the most part, small-scale and do not involve industry. These studies are primarily geared toward proof of concept testing or examination of feasibility. However, such studies are appropriate for testing new technologies in the early stages of application. VR systems, no matter how sophisticated they are, might fail if appropriate consideration is not given to user requirements. However, the viability of VR systems will depend very much on how familiar VR developers and users are with the scientific rationale behind VR applications in the built environment; such understanding will be key to designing appropriate system features and successful VR support. Additionally, considerable domain knowledge is required to understand the potential capabilities of various VR technologies and which functions are necessary for various applications. Thus, scientific evaluation of VR systems is required to ensure their success. Small-scale experiments can give some answers regarding the use of VR in the built environment, but collaboration between built environment practitioners, human factor researchers, computer engineers and others is need to fully realise the potential in this area. Organising collaboration on this scale is not a trivial task. In terms of the types of AEC/FM problems that have been investigated in studies of VR applications, VR architecture has received most of the attention. The record of success in applying VR to the built environment has been good to date, and there is promise for further success in this area.

6. SUMMARY

This review details the wide variety of built environment applications for which VR systems are now being developed and tested. It was found that a total of 150 articles were published in the normative built environment literature from 2005 to 2011, inclusive. Published studies in this area, for the most part, still consist of small studies without industrial practitioners-based control groups, geared toward feasibility or proof of concept testing. Journal articles were classified according to concept and theory, implementation, evaluation of effectiveness and usability and industrial adoption. This classification has enabled identification of gaps in the VR literature and the proposal of future research directions. The use of VR for facilities management and lifecycle integration is in its infancy, but has great potential. Much work remains to be done to identify which types of practices will benefit most from VR, and which system features are critical in this context.

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