Vision Network

Augmented Reality and Virtual Reality for
Digital Built Britain

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Centre for Digital Built Britain

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Contents

The Vision Network

Lead	Manuel Davila	UWE Bristol
Core Members	Tom Beach	Cardiff University
	Stéphane Côté	Bentley Systems
	Peter Demian	Loughborough University
	Andrew Gamblen	Willmott Dixon
	Amer Hijazi	A&H Group
	Andrew Jordaan	Mott MacDonald
	Mac Muzvimwe	Arcadis
	Hasan Omar	A&H Group
	Hadeel Saadoon	Coventry University Estates
	Mohammad Samie	Cranfield University
	Zakwan Skaf	Cranfield University

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Executive Summary

The Vision Network, a mix of academics and industry experts, conducted a study into the levels of adoption of Augmented Reality (AR) and Virtual Reality (VR) technologies in the UK's Architecture, Engineering, and Construction (AEC) sectors. A mixed research method was used to analyse the collected data, and to identify and prioritise R&D opportunities. The results of this study are presented in this report; which intends to inform a future research agenda.

AR and VR, or "immersive technologies" as they are also referred, have the potential to change all types of visual communications dramatically. Immersive technologies are of great and broad interest in the UK. In 2018, Innovate UK, Digital Catapult and the MTC have published a series of reports on the influence of AR&VR technologies for the UK economy. The reports indicate that immersive technologies are fuelling a nascent and dynamic economic sector focused primarily in the entertainment sector. Huge benefits can be gained in the manufacturing and construction sectors, but the levels of adoption and commercial solutions are not as developed. The Vision Network conducted a more granular study to obtain a defined picture of the current landscape and to identify R&D opportunities that will accelerate the adoption of immersive technologies in the AEC sectors. The main findings of this report are:

- The level of adoption of immersive technologies in the UK's AEC sector is low. A level of adoption index was defined to provide a quantitative indication of adoption levels. The adoption index for VR in the UK AEC sector is 2.5 out of 5, and for AR is 1.5 out of 5. Five represents full adoption and 1 not used.
- Most of the companies have tested immersive technologies at some capacity, but they have not integrated the technologies into their regular workflow.
- The level of adoption, research, development, and maturity of VR is higher than AR. Around 90% of the research projects on immersive technologies are focused on VR. AR should be given priority in a future research agenda.
- There is no research centre focused primarily on the development of AR&VR technologies for construction, civil engineering, and infrastructure.
- Six main use-cases were identified for the use of immersive technologies in the AEC sector: (1) Client/Public Engagement, (2) Design Support, (3) Design Review, (4) Construction Support/Progress Monitoring, (5) Operations and Management, (6) Training.
- Client/Public Engagement, Design Support, Design Review are the use-cases that have been tested the most, that have fewer difficulties to implement, and that represent more appeal for implementation.
- Particularly for VR, there have been many advancements that facilitate its implementation for Client/Public Engagement without the need for a specialist or programmer in the subject.
- The need for programmers and specialists from other industries (i.e., gaming sector and entertainment) represents an obstacle for companies to start using immersive technologies.
- There are several technical, social and economic factors that limit the adoption of immersive technologies. They are regarded as an untested, expensive technology that requires specialised high-processing equipment. It has a branding problem. In general, workers will not adopt it enthusiastically.
- The results of the study indicate that technical limitations might be the more relevant ones. However, a future research agenda should take a holistic approach and address the three types of limitations.

- The major perceived benefit for adoption is that immersive technologies will improve communication and reduce ambiguities. They are not perceived as technologies that will greatly improve productivity.
- A comprehensive list of required capabilities and R&D opportunities for each identify use-case have been compiled. Two tables summarising the most relevant capabilities are presented in section 5.

Immersive technologies are still in the early stages of adoption in the construction industry in comparison with the manufacturing and aerospace sectors. The rate of adoption is slower as well. Part of the problem is that the percentage of investment in R&D in the construction sector is deficient. In the construction sector, R&D and IT spending are far behind other industries. For example, R&D spending in construction represents less than 1% of the revenues, compared to 3.5-4.5% in the automotive and aerospace sectors, and 8% in the telecom sector (Welsh et al., 2018). A substantial increase in the percentage of investment on R&D is required. More importantly, an R&D roadmap must be developed to drive market adoption of immersive technologies. The R&D activities should focus on developing the identified hardware and software capabilities, the required standards to ensure interoperability, and developing the new skills required for market adoption. In addition, the R&D activities should bridge the gaps between the current state of using immersive technologies in the construction sector and the new vision of the future built environment in short-term and long-term frameworks.

Immersive technologies are a reality and have been adopted in other sectors. Independently of their level of maturity, industry stakeholders recognise the potential benefits. But stakeholders also are aware of the risks. Immersive technologies can represent significant investments, and their benefits have not been demonstrated satisfactorily. Consequently, all future research for construction applications should be preferably accompanied by a technology demonstration with actual data and in an actual site. Clear evaluations of cost and benefits should be carried out. Construction industry research projects should focus on demonstrating that the technology can be trusted for actual work and not just for laboratory experiments. Particular attention should be given to technology acceptability, particularly regarding their impact on a number of jobs. Users and stakeholders should be presented with the specific advantages for them, such as fewer mistakes, a better understanding of design intent, reduction of risks, and better collaboration with their colleagues. Research projects that advance the integration of various other technologies with immersive technologies are required as well. The most significant potential benefits reside in integrating immersive technologies with new sensing technologies and IoT devices, computer vision, simulations, predictive analytics, and optimisation techniques.

Lastly, the construction sector has a low productivity problem. Productivity has increased by only 1% annually over the past two decades (Mckinsey Global Institute, 2015), which represents one-quarter of the rate experienced in the manufacturing sector. There is strong evidence of the link between the level of digitisation in a sector and its productivity growth (Oesterreich and Teuteberg, 2016). Thus, the low productivity problem can be partially attributed to the low application of innovative technologies and their poor implementation into work routines. Immersive technologies have the potential to contribute to improving productivity levels. However, industry stakeholders consider immersive technologies only as a way to improve communication. Studies must be carried out that quantify the improvements in productivity achieved due to the use of immersive technologies.

1. Introduction

Augmented Reality (AR) and Virtual Reality (VR) are visualisation technologies that are dramatically changing the meaning of visual communication. AR & VR technologies are becoming widespread, and every industry will be affected by the rapid adoption of these technologies. So far, they have been mainly used for: (1) gaming and entertainment, (2) tourism, (3) marketing, and (4) education and training.

AR and VR technologies are of utmost importance for the Digital Built Britain (DBB) vision as the architecture, construction and engineering industries rely heavily on imagery for communication. The Data for the Public Good report (National Infrastructure Commission, 2017) considered AR and VR as key new technologies to increase the productivity of infrastructure and support decision-making. Immersive technologies have been developed over the last few decades. However, as with other digital technologies, their adoption in the Architecture, Engineering, and Construction (AEC) sectors is still low. For example, The McKinsey Global Institute (2016) reported that the level of digitalization index for the construction industry was the lowest out of 22 industries.

This report presents the results of the Vision Network's investigation into the levels of adoption of immersive technologies in the UK's AEC sectors, and the capabilities that should be developed to achieve the DBB vision. This report is the result of a mixed research methodology that combined qualitative (focus group discussions) and quantitative (questionnaire) data collection and analysis. The objective of the report is to identify gaps in R&D that a future research agenda should consider accelerating the uptake of immersive technologies in the AEC sectors.

The report is structured as follows: section 2 presents a brief description of the objectives and methodology of this study, section 3 presents the levels of adoption and research landscape in the UK, section 4 presents the challenges, limitations, and drivers for the adoption of immersive technologies, and section 5, *Research agenda*, presents use-cases and demonstrators and what capabilities to develop.

Virtual Reality

Virtual Reality (VR) is the technology that enables the creation of entirely computer-generated environments that give the user the sensation of being completely immersed within a virtual environment. It provides a way to replace the perception of the surrounding world with a computer-generated artificial 3D environment. The virtual experience is provided usually through a head-mounted display (HMD).

Augmented Reality

Augmented Reality (AR) is the technology that enables to overlay digital information onto the real environment –in real-time and in the correct spatial position– to augment or enhance the real environment. In other words, AR enables digital objects and/or information to be overlaid either through a head-mounted display or via a handheld device with a camera such as a smartphone or a tablet.

Immersive Technologies

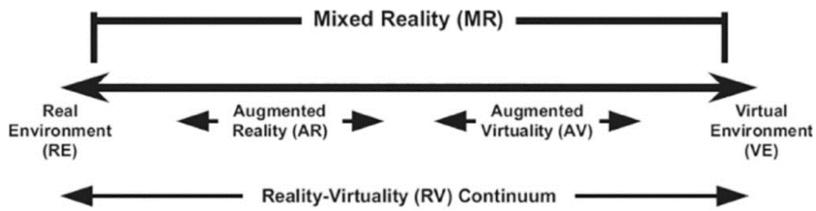
The term "Immersive Technologies" is used to refer to both AR and VR technologies even though the term immersive characterises the main feature of VR. In strict terms, not all AR technologies are immersive, but "immersive technologies" has been adopted because it is easier to understand and provides more information than "Augmented Reality".

Mixed Reality

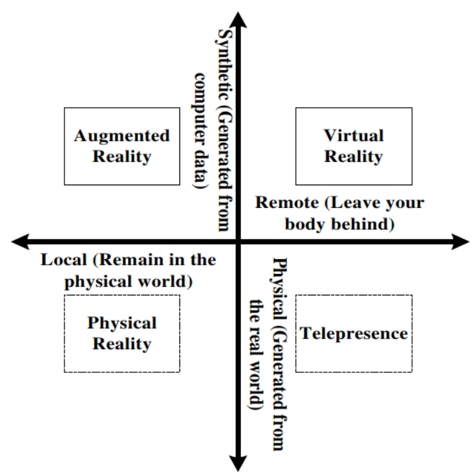
The term "Mixed Reality" originally referred to the spectrum or "virtual continuum" in which different technologies exist based on how much of the real environment is displayed. Milgram (1994) introduced a taxonomy and a diagram to map technologies within a "Reality-Virtuality" spectrum (see Fig. 1-1) in which Virtual Reality is closer to one end of the spectrum while Augmented Reality is closer to the other end.

Benford et al. (1998) presented a similar taxonomy to explain the difference between AR and VR. In this case, the technologies are mapped in a four-region space (see Fig. 1-1), in which two spectrums range from the *physical world* to *virtual world* (horizontal scale) and from *computer-generated* data to *physical data* (vertical scale).

There is no an entirely agreed definition of mixed reality yet, and its definition may evolve in the coming years influenced by the big players developing the technologies, e.g., Microsoft (Bray and Zeller, 2018).



Milgram's taxonomy (1994).



Benford's taxonomy (1998).

Figure 1-1. Milgram's and Benford's taxonomies.

2. Objectives and Methodology

The main objectives of the Vision Network reflect the CDBB requirements to answer the following questions:

1. *What are the existing AR&VR capabilities in the UK's industry and academia to support the DBB vision?*
2. *What AR&VR capabilities should be developed to achieve the DBB vision?*

The Vision Network used a mixed research methodology to address the questions above. Table 2-1 presents the activities carried out to answer the questions above. The mixed research methodology consisted of three components: (1) Literature Review, (2) Qualitative data collection and analysis through focus group discussions, and (3) Quantitative data collection and analysis through a targeted questionnaire.

Table 2-1. Research activities and sections dedicated to answering the two main questions.

Questions	Sections	Activities
Question 1	Section 3. Levels of adoption and research landscape in the UK	• Literature review • Targeted questionnaire
	Section 3.1. Existing level of adoption in UK companies Section 3.2. Existing research in the UK	
Question 2	Section 4. Challenges, limitations and drivers	• Literature review • Exploratory workshops (focus discussion groups) • Targeted questionnaire
	Section 5.1. Use-cases / demonstrators	
	Section 5.2. Capabilities to develop	• Qualitative and quantitative analysis

2.1. Exploratory Workshops

The main activities conducted by the Vision Network were exploratory workshops in which focus group discussions were carried out. Four exploratory workshops were conducted. Appendix A1 presents a table with detailed information about the workshops. In total 12 focus group discussions were held. Each discussion group lasted 45 minutes. Sixty-four experts from 36 organisations, companies and academic institutions participated in the focus group discussions.

The primary objective of the first two exploratory workshops (W1 and W2) was to identify: (1) use-cases, (2) limitations, (3) drivers, (4) capabilities and (5) existing case-studies relevant to the use of AR&VR technologies in the UK's context. In these two workshops, participants from Bentley Systems, WSP, and Site Lense, presented how these organisations are using and developing immersive technologies. In the second part of the workshop, 3 focus group discussions where conducted (Fig. 2.1-1) to address the following topics: (i) use-cases at the different DBB phases (Delivery, Operations, Integration), (ii) drivers and capabilities and (iii) challenges and limitations. In Appendix A2 are presented tables that summarise the findings of the first two workshops (W1 and W2).

The objective of the other two workshops (W3 and W4) was to acquire more granular knowledge about the same topics. For example: to rank and qualify the identified use-cases, to identify the relevant stakeholders and scale of the use-cases, and to identify the benefits and limitations of specific use cases. During these workshops, Bentley Systems, KPF, and the MTC presented how their organisations are using immersive technologies. Appendix A3 presents tables that summarise the findings of workshops 4 and 5.

2.2. Targeted Questionnaire

Based on the findings of the first three workshops and the literature review, lists of use-cases, challenges and drivers were compiled. Using these lists, a questionnaire was prepared. The questionnaire was administered to targeted experts in relevant organisations. Between 3 to 5 experts were selected from the following 7 categories: (1) top 10 UK construction companies (based on revenue), (2) SMEs UK construction companies, (3) top 10 UK engineering consulting companies (based on number of staff), (4) SMEs UK engineering consulting companies, (5) top 10 architecture firms (based on number of staff), (5) SMEs UK architecture firms, (6) Start-ups and technology companies, and (7) academics and researchers. In total, 45 experts were contacted, from which 34 responses were received representing a 75% response rate. A Likert scale ranging from 1-5 was used to rank the importance of the studied factors.

2.3. Literature Review

A literature review was conducted to identify the scale and impact of AR&VR research conducted by academia in the UK. The review was carried out by compiling a list of research centres and research projects in the UK. An analysis of the results will help to identify gaps in the research efforts and how they correlate with the interests of industry stakeholders.

Figure 2.1-1. Demonstration of AR applications and breakout sessions.

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3. Levels of adoption and research landscape in the UK

This section presents the results of the levels of adoption of immersive technologies in UK companies and the research landscape.

3.1. Existing level of adoption in UK companies

One of the objectives of the targeted questionnaire was to obtain an idea of the levels of adoption of immersive technologies in the UK. The following points are derived from the findings of the workshops and the results of the targeted questionnaire (see Appendix B1 for figures of the questionnaire results):

- **The level of adoption of immersive technologies in the UK's AEC sector is low**. 88.3% of the companies indicated that they had used immersive technologies in less than 25% of the projects, of which 61.8% have used it in less than 5% of the projects. 8.8% of the companies have not used VR at all, and 23.5% have not used AR.
- **VR has been used more than AR**. 61.8 % of the surveyed companies indicate that they have tested VR or have a basic implementation (i.e., used in pilot projects); whereas for AR, the figure is 52.9%. 2.9% of the companies claim to have a full implementation of VR; while no company has fully implemented AR.
- **Immersive technologies are a new topic for AEC companies**. 58.8% of the companies have started using them in the last 3 years.
- **There is a high motivation for companies to adopt immersive technologies**. 73.5% of the companies indicate that it is likely or very likely that they will invest in VR in the next 3 years; while the figure is 61.8% for AR.
- **The most important motivation for immersive technologies adoption is: "to find ways to be more efficient and productive".** The second most important motivations are: "research curiosity" and "client requirement"; followed by: "to obtain a differentiation advantage in the market", "strategic decision from top management", and "to be part of the trend".
- **The most important source of value is that it "enables the provision of new or better services"**. The second most important source of value is that it "reduces risk"; followed by "increases productivity".
- **Six main use-cases for the use of immersive technologies were identified** in the delivery and operations of infrastructure and built assets:
    1. Client/Public Engagement
    2. Design Support
    3. Design Review
    4. Construction Support/Progress Monitoring
    5. Operations and Management
    6. Training
- All surveyed companies have used all the identified use-cases in varying levels of implementation. A detailed explanation of the identified use-cases and their level of implementation in practice is presented in section 5.1.

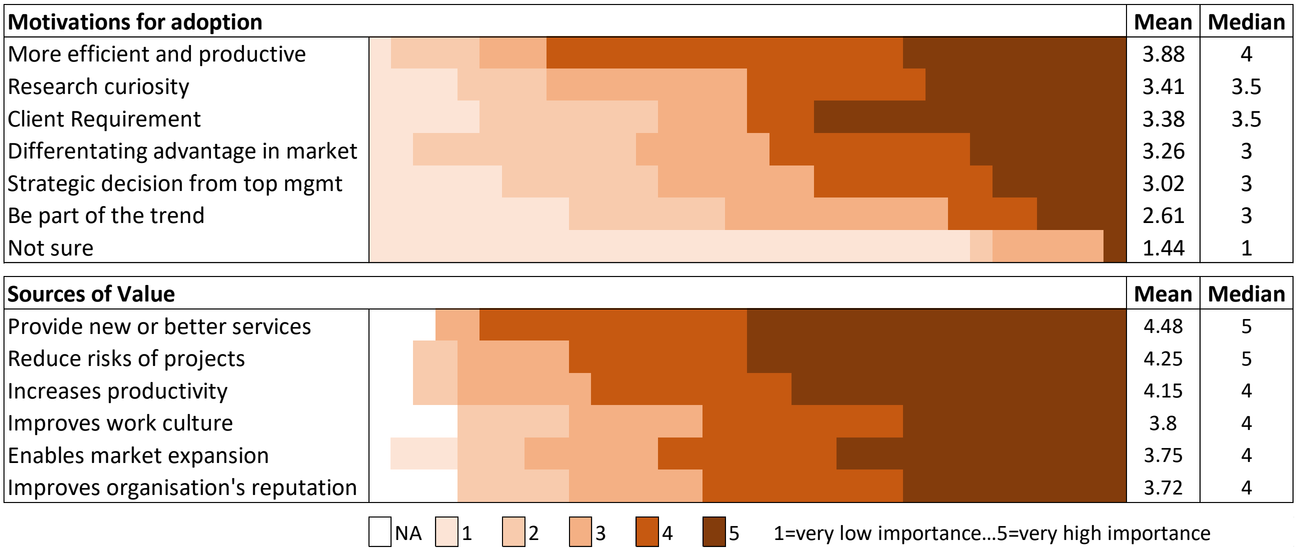

Figure 3.2-1. Motivations and sources of value of implementing immersive technologies

Innovate UK, Digital Catapult and the MTC have published a series of reports on the influence of AR&VR technologies for the UK economy. Findings from the reports that are more relevant to the Vision Network work are briefly discussed below.

MTC findings

The Manufacturing Technology Centre (MTC) in collaboration with i3P, a consortium of large construction companies and infrastructure providers, carried out exploratory research into the maturity and applicability of immersive technologies in construction companies in 2017 (http://www.the-mtc.org/our-projects/i3p-programme). They found that 37% of the companies have some experience with VR and AR. This result is somewhat aligned with our findings in which 32.4% of the companies indicated that they had used immersive technologies in 5% to 50% of their projects.

Immerse UK findings

Immerse UK, an initiative funded by Innovate UK and managed by a Knowledge Transfer Network (KTN), published the report “The immersive economy in the UK” in 2018 (https://goo.gl/tEsMtf) (Mateos-Garcia et al., 2018). The report provides an overview of the levels of adoption of immersive technologies in all sectors of the UK economy. The main conclusion of the report is that the immerse economy in the UK is already a reality and that it has vast potential for growth and could be an export-intensive sector. The following findings can be useful to describe the current adoption levels of immersive technologies in the construction industry.

- There are around one thousand companies in the UK developing immersive solutions in all sectors.
- Approximately 20% of companies developing immersive solutions work in the Architecture and Engineering sectors.
- 38% of the companies are located in London. Other cities with a significant number of companies include Bristol, Manchester, Brighton, Birmingham, Newcastle, Liverpool, Cambridge, Oxford, and Edinburgh.
- There have been 253 research projects on immersive technologies, from 2006 to 2017, funded by Innovate UK, Research Councils and the European Union (H2020) representing an investment of £160 million.

- Funding for R&D has been increasing in recent years. Innovate UK provided in 2017 approximately 60% of the funding (~30 projects); while Research Councils and the European Union (H2020) provide 20% each (~10 projects each).
- The total R&D funding for immersive technologies in the UK is ~£70 million in 2017.
- The highest concentration of R&D funding is located in London with ~70% of the research projects, followed by Bristol with ~15% of the projects.
- The main limitation for adoption is that there is no substantial justification for the initial investment (Allcoat et al., 2018).

Immerse UK, Digital Catapult and the High Value Manufacturing Catapult commissioned another report (Growing VR/AR companies in the UK, https://goo.gl/q3sG1G), (PwC, 2018). They have also produced an interactive map (https://goo.gl/9Nm57P). Findings from both documents include (Figure 3.2-2):

- There are approximately 500 companies developing immersive solutions in the UK. Approximately 250 are located in London, 20 in Bristol and the rest are mainly located in Manchester, Brighton, Birmingham, Newcastle, and Liverpool (Include table in Appendix).
- The venture capital funding attracted by these companies totals $68.44 million. The main cities attracting funding are London ($64.7 million) and Bristol ($2.24 million).

City	No of companies	VC funding
London	244	$64.7 million
Bristol	20	$2.24 million
Manchester	16	$0.90 million
Brighton	16	$0.47 million
Birmingham	16	$0.01 million
Newcastle	14	$0.04 million
Liverpool	11	$0.08 million
Total	463	$68.44 million

Figure 3.2-2. AR&VR companies in the UK and corresponding venture capital funding (Dalton, 2018).

*Cities conducting AR&VR research according (Dalton, 2018): Paisley, Glasgow, Edinburgh, Newcastle, York, Bradford, Ormskirk, Salford, Manchester, Sheffield, Stoke-on-Trent, Nothing ham, Loughborough, Sheffield, Leister, Birmingham, Norwich, Milton-Keynes, Oxford, Colchester, Cardiff, Bristol, Reading, Guildford, Portsmouth, Southampton, and London (This list is not exhaustive).

3.2. Existing research in the UK

The Vision Network complemented the existing work presented in the recently published reports by developing a more granular research landscape of AR&VR in the UK with a special focus on sectors involved in the DBB vision. The presented research landscape consists of two levels of granularity: (1) research groups and centres and (2) research projects. A list of research groups, research centres, and technology enabling centres in the UK dedicated to immersive technologies has been compiled. Table 3.2-1 presents a list of selected research and academic centres (see Appendix B2 for a more comprehensive list). An important conclusion is that there are very few centres focused primarily to the development of AR&VR technologies for construction, civil engineering, and infrastructure. Immersive technologies are being used to support teaching activities as well. Table B2-2 in Appendix B2 presents the universities providing immersive technologies courses.

Regarding the second level of granularity, Table 3.2-2 presents the main research projects in the UK in the last few years related to immersive technologies and the built environment. A more comprehensive list is presented in Appendix B2 in Table B2-3. A number of findings of this review include:

- Around 90% of the research projects are related to VR.
- Only 4% of the research projects are specifically related to AR.
- Only 4% of the projects are related to the built environment.
- Approximately 33% of the projects have been conducted in London.

Table 3.2-1. List of selected research and academic centres in the UK dedicated to AR&VR technologies

Name	University	Characteristics
Bristol VR Lab	UWE Bristol & University of Bristol	Platform to support start-ups and links with research
https://bristolvrlab.com/		
Advanced VR Research Centre (AVRRC)	Loughborough University	Research centre focused on manufacturing
http://www.lboro.ac.uk/research/avrrc/		
The MSk Lab	Imperial College London	Research centre focused on medical and surgical training
http://www.imperial.ac.uk/msk-lab/research/surgical-technology/augmented-and-virtual-reality/		
Virtual Reality Research Group	University of Salford	Research group focused on mental health and social interaction
https://www.salford.ac.uk/research/health-sciences/research-groups/virtual-reality		
Creative AR & VR Hub	Manchester Metropolitan University	Research centre focused on creative industries
https://www2.mmu.ac.uk/creativear/		
Centre for the Study of Perceptual Experience	Glasgow University	Research centre focus on fundamental research regarding perceptual experience
https://www.gla.ac.uk/research/az/cspe/projects/vrar/		
VR and AR Oxford Hub	University of Oxford	Platform to facilitate networking, training and showcasing of immersive technologies
https://vraroxfordhub.co.uk/		
The Manufacturing Technology Centre (MTC)	NA	Research centre focus on advanced manufacturing
http://thearea.org/area-members/manufacturing-technology-centre-mtc/		

Table 3.2-2. List of the main research projects in the UK concerning to AR&VR technologies

Examples of research projects	
1	Loughborough University (VR/MR) 'Thinking Inside the Box': A Mixed Reality Development Platform for co-creating energy efficient retail spaces Loughborough University, Civil and Building Engineering 01 September 2017, Value (£): 197,902 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P033911/1
2	University of Exeter (VR) VSimulators: Human factors simulation for motion and serviceability in the built environment 01 May 2017, Value (£): 3,246,099 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P020690/1
3	University of Leeds (VR) Multi-Disciplinary Pedestrian-in-the-Loop Simulator 01 November 2017, Value (£): 653,011 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R008833/1

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4. Challenges, limitations and drivers

This section has two sub-sections that discuss the challenges and limitations for the adoption of immersive technologies in the DBB context, and the benefits and drivers that contribute to their adoption.

4.1. Challenges and limitations

This section discusses the main challenges limiting the adoption of immersive technologies in the built environment. Three types of challenges were investigated: technical, economic and social challenges. For each type of challenge, a number of limitations were identified during the workshops. Then, the limitations were ranked using the targeted questionnaire. The complete list of identified technical, economic and social limitations is presented in Appendix C1. According to findings from the workshops and the targeted questionnaire, the most relevant type of challenges is technical. Around 41% of the survey respondents believe that technical challenges are the most relevant (Fig. 4.1-1). However, this is not a very significant difference. A quantitative analysis of all the investigated limitations was carried out to obtain a quantitative metric on the difference of their importance. The aggregated median of all the technical, economic and social limitations is the same (i.e., 3 out of 5), and their mean is very similar (i.e., 3.25, 3.37, 3.28 respectively) (see figures 4.1-2, 4.1-3, and 4.1-4). These results indicate that the importance of research requirements is very similar for the three types of challenges.

Note that in the targeted questionnaire respondents could identify additional limitations. The most relevant include:

- Immersive technologies need to be automated and remove the need for programmers/developers.
- Software for making AR&VR environments is difficult to use and needs a better transition from CAD software
- Clients often are not interested in long-term gains, as they are looking for an immediate advantage which can be easily identified and highlighted. (Identify short-term advantages for adopting immersive technologies)

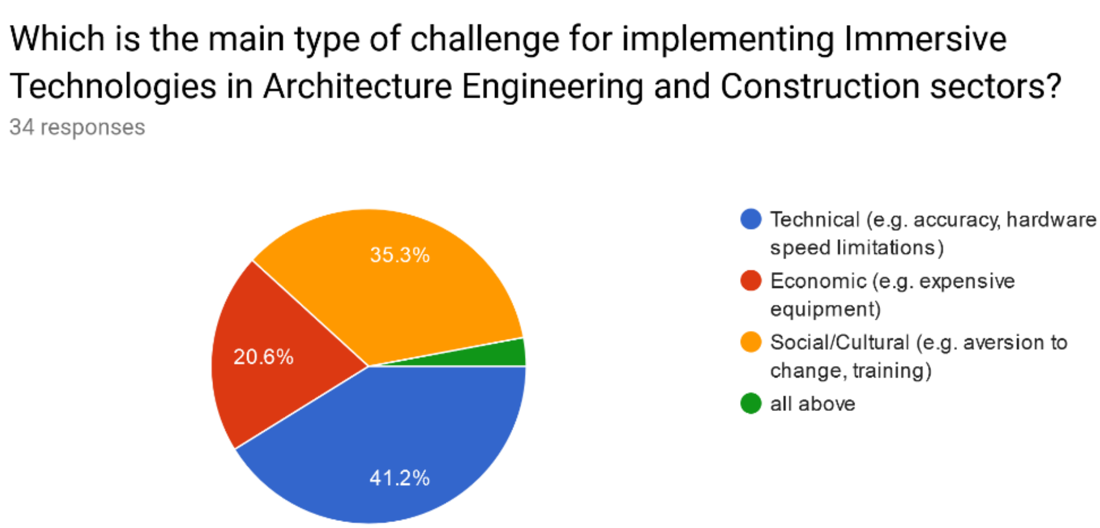

Figure 4.1-1. Importance of the types of challenges for adoption.

4.1.1. Technical limitations

Technical limitations refer to the gaps in research and development regarding hardware, software, processes, standards, etc. that limit the use of immersive technologies in the AEC sectors. The identified limitations were ranked using the mean and median of the survey scores. The results from the quantitative analysis of the targeted questionnaire show that the limitations can be grouped in two categories, i.e.: important (median value = 4 out of 5) and somewhat important (median value = 3 out of 5), see figure 4.1-2. The most significant technical limitations in the "important" category are (1) ''Lack of standards for data exchange (interoperability)", (2) "Need of specialised high-processing equipment'', and (3) ''Limited size of 3D models to be displayed''. The "somewhat important" category groups all the remaining limitations. Note that all the other identified limitations have very similar means and medians and thus can be considered as equally important.

Note that the "lack of standards" was identified as a limiting factor for several use-cases, i.e., design review, construction support, and operations and maintenance support. Therefore, in addition, to being ranked as the most relevant limitation, addressing it will benefit the majority of use-cases. Note as well that the importance of having common data standards to increase the training efficiency and to facilitate the generalisation of the customer/public engagement experience were also discussed during some of the workshops.

Technical limitations	Mean	Median
Lack of standards for data exchange	3.72	4
Need of high-processing power equipment	3.69	4
Limited size of 3D models to be displayed	3.50	4
Lack of multi-user capabilities	3.45	3
Power and battery limitations	3.19	3
Uncomfortable and heavy HMDs	3.09	3
Low resolution of displays	3.06	3
Large space requirements	2.94	3
Data security and ownership	2.94	3
Narrow Field of View (FOV)	2.93	3
	3.25	**3**

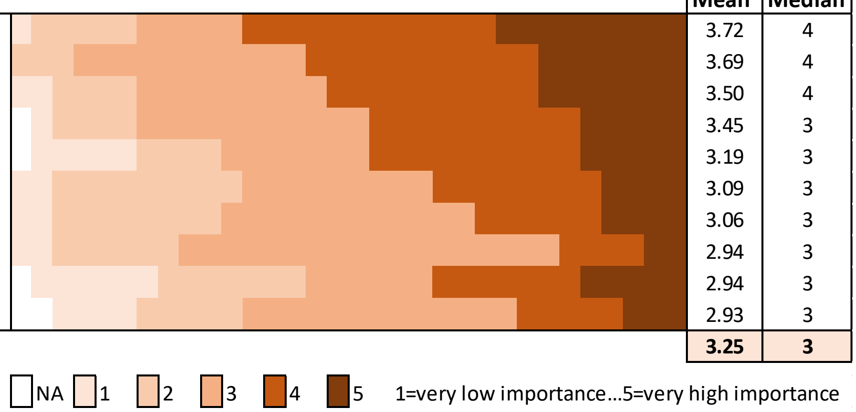

Figure 4.1-2. Technical Limitations for using Immersive Technologies

4.1.2. Social limitations

Social limitations refer to the social factors that act as barriers to the adoption of immersive technologies. The results from the targeted questionnaire show that the highest ranked social limitations are: (1) ''Aversion to the adoption of new technologies and (2) ''Skill shortages and difficulty to access skills from education" with a median value of 4 out of 5. While the lowest ranked is: "job security" (where employees may think they will lose their jobs) with a median value of 2.5 out of 5 (Figure 4.1-3). In this respect, during the workshops, it was noted that better adoption results were obtained with bottom-up approaches rather than top-down. For example, it is better than a group of enthusiastic workers start testing and using immersive technologies and disseminate the advantages than the top management mandates their use.

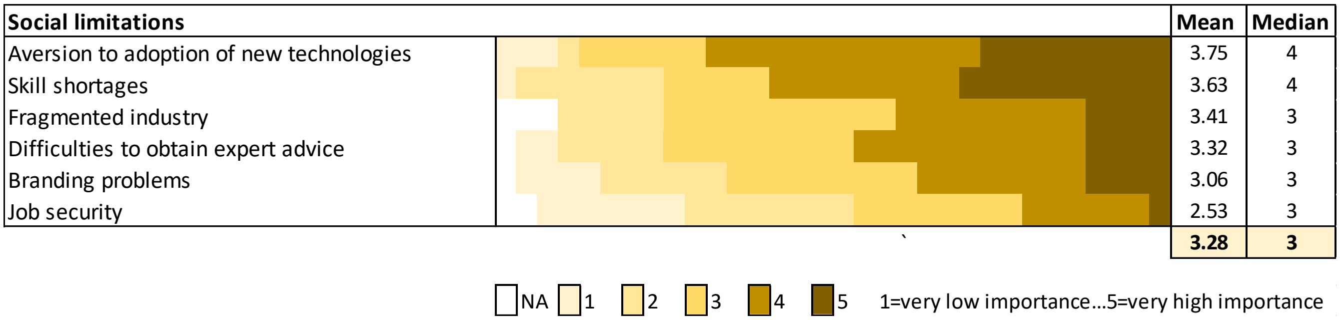

Figure 4.1-3. Social Limitations for using Immersive Technologies

4.1.3. Economic limitations

Economic limitations refer to the financial aspects of implementing immersive technologies. The results from the quantitative analysis of the targeted questionnaire show that the economic limitations can be grouped in two categories, i.e.: important (median value = 4 out of 5) and somewhat important (median value = 3 out of 5), see Figure 4.1-4. In the important group the following limitations are included: ''Expensive hardware and training'' and ''Lack of time to explore immersive technologies''. In the somewhat important group, the following limitations are included: "Limited access to finance", "Lack of client's interest'' and "Lack of market knowledge''. Note that while a few pieces of equipment can be easily acquired, for broad implementation a substantial investment is required. In addition, the cost of hiring specialist and training is also relatively high.

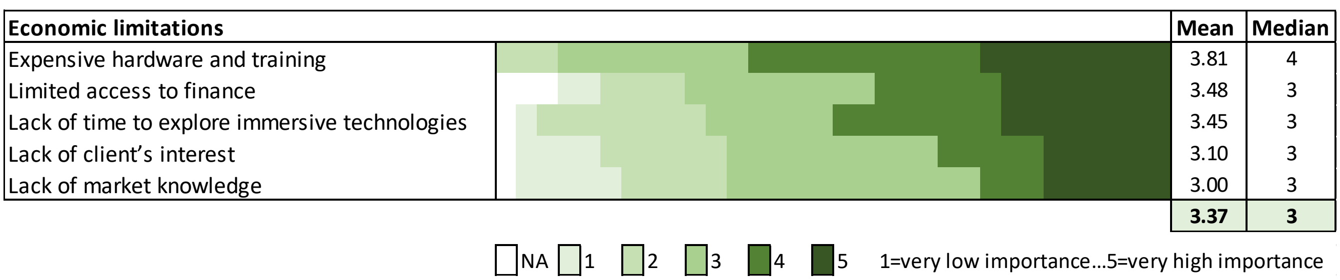

Figure 4.1-4. Economic Limitations for using Immersive Technologies

4.2. Benefits and drivers

This section discusses the main benefits and drivers for the adoption of immersive technologies in the built environment. According to the targeted questionnaire, the most relevant benefits for adopting immersive technologies are: that it improves project understanding and reduces ambiguities and that it improves collaboration between stakeholders (Figure 4.2-1). The least relevant benefits are: that it reduces overall spending on projects and that it contributes to delivering projects within scope, quality, time and budget. This indicates that, at the moment, immersive technologies are seen primarily as a way to improve communication. Immersive technologies are not considered as technologies that will improve productivity or save money.

Benefits for using immersive technologies	Mean	Median
Improves project understanding and reduces ambiguities	4.13	4
Improves collaboration between stakeholders during the project lifecycle	3.91	4
Improves greatly health & safety during construction	3.75	4
Contributes to deliver projects within scope, quality, time and budget	3.44	3
Reduces the overall spending on projects	3.06	3

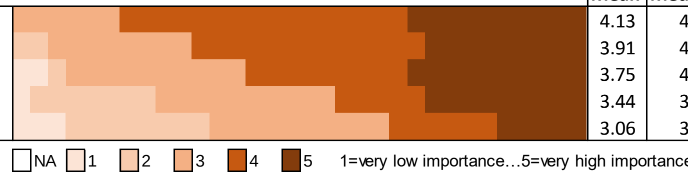

Figure 4.2-1. Benefits of using Immersive Technologies

Figure 4.2-2 shows the results of the targeted questionnaire regarding the importance of the drivers for adopting immersive technologies. All the identified drivers are considered as important (median = 4) or somewhat important (median = 3.5). The most important driver is the increasing R&D investment in the construction industry; while the decreasing budgets for public infrastructure are considered the least important.

Drivers for adopting Immersive Technologies	Mean	Median
Increasing R&D investment in the construction sector	4.00	4
The need to increase labour productivity	3.94	4
Risk reduction	3.88	4
Adequate marketing	3.66	4
Government incentives	3.59	4
Increasing difficulties to access labour	3.34	3.5
Decreasing public infrastructure budgets	3.31	3.5

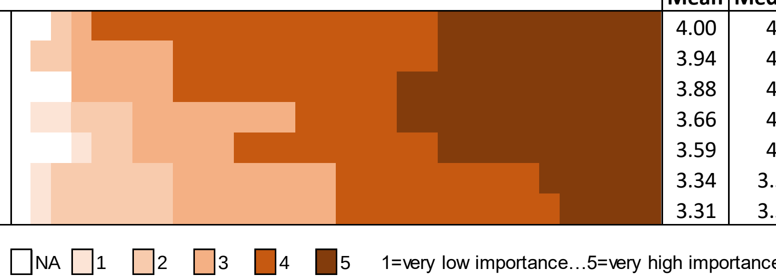

Figure 4.2-2. Drivers of using Immersive Technologies

5. Research Agenda

This section discusses the levels of adoption of AR and VR for specific use-cases, examples of real-life demonstrators, and the capabilities required to enable the adoption of immersive technologies in the AEC sectors.

5.1. Use-cases

Six main use-cases were identified in which immersive technologies can be applied in the DBB vision:

1. **Client/Public Engagement**. Immersive technologies can be used to engage with potential clients or with the public to show how a built-asset will look like and to get more relevant feedback. The expectations of the clients and the public will be more in line with the actual design.
2. **Design Support**. Immersive technologies can support designers to identify the consequences of their design decisions and to have a better understanding of the final results.
3. **Design Review.** Immersive technologies facilitate the communication of design intent. Designs can be reviewed in a more efficient way. Issues can be identified more easily and sign off can be done more efficiently.
4. **Construction Support/Progress Monitoring**. Immersive technologies can support various construction tasks including progress monitoring (identify what parts have been built and what is missing in a visual manner), safety (identify hazards and risks), worker support (provide the required information to carry out a task).
5. **Operations and Management**. Immersive technologies can support maintenance, repair, and inspection tasks by directing technicians to the specific equipment, showing the tasks to be completed and providing technical information in context.
6. **Training**. Immersive technologies provide realistic scenarios for situated learning. Immersive technologies can reduce the cost of training, by simulating the use of expensive equipment, simulate dangerous environments, reducing travel costs, as well as improving health and safety.

Figure 5.1-1 shows the results of the targeted questionnaire concerning the levels of adoption of AR and VR per specific use-case and the appeal that each use-case represent for future adoption. Note that darker colours represent higher levels of adoption or higher appeal. The following inputs can be deduced from these results:

- Immersive technologies have a low level of adoption in the UK construction sector.
- VR has a higher level of adoption than AR. The aggregated median for the level of adoption for VR is 2.5 out of 5, and for AR is 1.5 out of 5.
- Both AR and VR have been used primarily for the customer and public engagement. The use-cases with the least level of adoption are Operations and Maintenance Support and Construction support for AR&VR.
- Customer/Public Engagement, Design Review, and Design Support are the use-cases with the highest appeal for organisations to adopt in the future.

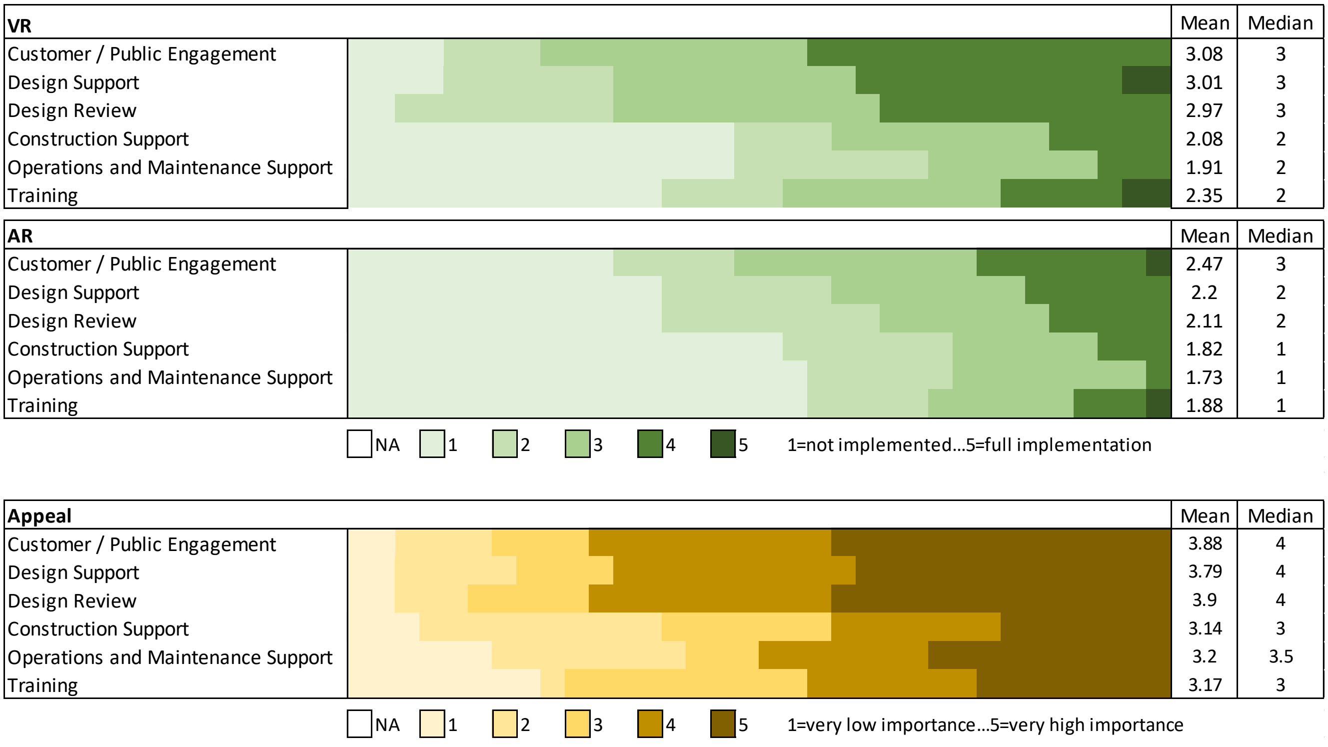

Figure 5.1-1. Level of adoption per specific use-cases and appeal for future adoption

5.2. Demonstrators

In the past few years, there has been a notable increase in the number of real-life demonstrations of adoption and use of AR and VR on projects. Below is a sample list of the type of demonstrators being carried out in the UK. This is not a comprehensive list. The intention is to exemplify different types of demonstrators that are being carried out in industry.

1) A VR model, developed by Arcadis, was used to explore multiple spatial possibilities for upgrading and restoring Eindhoven Station. With the challenge of fitting various functional spaces together to meet the needs of end users, Arcadis created a VR model to visualize various spatial orientations which ultimately aided in the decision-making, permit and execution procedures. Using VR, Arcadis provided value engineering services by helping the client realise the benefits of implementing solar harvesting panels in the project although this was not the original intent. The model paved a way to prove that the Client's goal of a contemporary historic station could be realised through the combination of a restored existing building and a modern sustainable architectural approach. The three added-value outcomes were:

    a) VR helped visualise various spatial configurations, which was critical to decision making. Arcadis successfully implemented these configurations into an interactive web-based platform. It gave the Client the trust and level of confidence with the work prior to actual execution.

    b) Through the VR, the Client realised the hidden potential of using solar panels, which added sustainable value to the project.

    c) The ability to visualise project components right from the planning stage helped identify potential risks, which reduced costs and time.

2) Anglian Water's @One Alliance reported in November 2018 (BIM+ online magazine)[1] that they had incorporated VR into their workflows, which in turn was enabling smarter design thinking and aiding better collaboration. The alliance is using the VR models to engage with the construction and operations staff to obtain user feedback and also to undertake key procedures such as Safe to Operate reviews. The next target for the alliance is using VR to conduct site safety training. In March 2018, BIM+ reported that hire firm Nationwide were using VR for Mobile Elevating Work Platform training[2]. Overall, the adoption and use of VR has given the better visibility of designs and better ways of engaging with the stakeholders throughout the design process.

   [1] http://www.bimplus.co.uk/projects/case-study-virtual-reality-improves-collaboration-/

   [2] http://www.bimplus.co.uk/technology/hire-firm-nationwide-use-vr-work-platform-training/

3) There is also an update in the use of Mixed Reality, in particular, VisuaLive3D with HoloLens, which provides the users and designers with an array of tools such as visualisation, measurement, turning off layers, etc.

4) Use of QR codes linked to online panoramic renders of finished rooms has been utilised to enable site operatives on multiple Willmott Dixon Construction sites to view the finished room and understand the level of finish and details required to deliver a quality product. This use of VR resulted in:

   a) Reduced number of snags on projects where this was employed

   b) Reduced cost of error due to a greater understanding of the room by the Supply Chain

5) Multiple Willmott Dixon Construction projects now utilise the design models to help with the Customer journey, aiding in visualisation of the asset through small engagement sessions with key stakeholders at specific milestones on a project. This engagement is typically held within a VR environment to ensure the asset is effectively communicated and all parties understand what is going to be constructed. These sessions typically provide the following outcomes:

   a) Brings the asset to life for those who usually struggle with understanding a 2D drawing

   b) Refinement of the design; sight lines, size of spaces, and "feel" of the environment are tweaked following these sessions

6) Heriot Watt University, Immersive Virtual Reality. The Immersive and Controlled Environment (ICE) is a research project funded 100% by the construction industry that is developing a new kind of immersive virtual reality (VR) technology that the team calls iHR. The project focuses on the value of VR for public engagement, particularly when engaging with young people about a sector like construction. A mobile version of out iHR system has been developed that this is used to immerse visitors in challenging construction work environments, in particular, work at height. Users can walk on a steel beam 100m above ground, or experience is navigating on the top of the nacelle of a wind turbine, sit in the cabin of a crane operator for high-rise construction. (https://www.hw.ac.uk/research/engage/case-studies/immersive-virtual-reality.htm).

5.3. Capabilities to develop

Comprehensive list of capabilities to develop were compiled during the four exploratory workshops (see Appendix D1). From that list, 11 capabilities were selected, and participants in the questionnaire were asked to rank them according to their importance for successful adoption in practice. Figure 5.2-1 shows the ranking of the key immersive technologies capabilities to be developed. The most important capability to be developed according to the targeted questionnaire results is “adequate usability” with a median score of 4.5 out of 5. This capability refers to the ease-of-use of certain technologies. In the case of immersive technologies, the head-mounted displays are often heavy and bulky, not comfortable to wear, they cannot be used for long periods of time and can cause motion sickness. The lowest ranked capabilities are “multisensory capabilities” and “rugged equipment and water resistance” with a median score of 3 out of 5. The rest of the capabilities have the same median score (4 out of 5). Fats mobile data connectivity, multi-user capabilities and interoperability among different devices were also regarded as important capabilities to be developed.

The importance of the development of these capabilities for Immersive Technologies	Mean	Median
Adequate usability (e.g. avoid motion sickness)	4.05	4.5
Fast mobile data connectivity	4.11	4
Multi-user capabilities	3.99	4
Interoperability among different devices	3.97	4
Object recognition (powered by AI algorithms)	3.94	4
Higher display resolution	3.94	4
Accurate tracking	3.91	4
Integration with enterprise data sources	3.85	4
Adequate battery capacity	3.76	4
Rugged equipment and water resistance	3.44	3
Multisensor capabilities (capture users emotions)	3.23	3

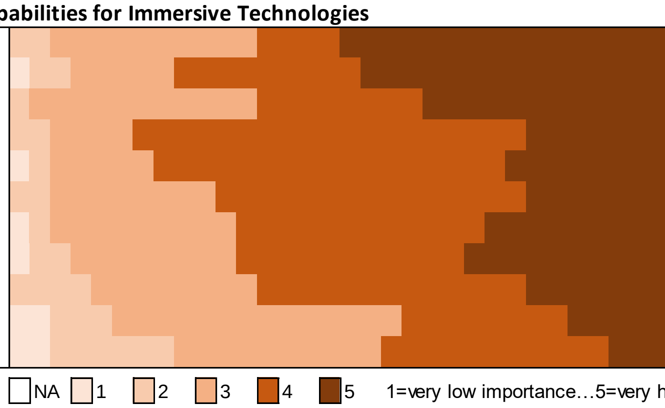

Figure 5.2-1. Ranking of the capabilities to be developed

5.4. Summary tables

Table 5.4-1. Table summarising the capabilities to develop for VR

Capability	Rationale and Drivers	Applicable Use Cases	Timescale to realise	Enabling Technologies and Behaviours	Barriers to development or adoption	Supports and Case Studies	Suggested Research Needs
➢ **Technical**							
Increased tracking and mapping accuracy	Increasing the tracking accuracy of VR's user-movements. This will allow for a more immersive feel for users navigating built environment assets	All	3 years	Requires incremental improvements in current technologies. Combine various tracking technologies (e.g., infrared, accelerometers, gyroscope, etc.) with machine learning algorithms for better performance.	Achieving performance improvements without dramatically increasing the cost of devices.	A demo that shows high-accurate tracking using various combined technologies (hardware and software)	Low power high accuracy tracking technologies. Investigate the benefits of using machine learning models to improve tracking accuracy.
*Reduction in capital cost of VR hardware	High required investment in adopting VR prevents many smaller organisations from adopting this technology	All	7 years	Increased levels of production in current VR devices. Increased adoption required to bring down unit price. Develop a VR device for the built environment.	Challenges surrounding reducing in price while maintaining specification of devices.	NA	Studies to identify the specific needs of VR devices for the built environment. This will enable to remove unneeded features.
*Increased Battery Capacity	Short battery life impedes the application of VR in "on-location" settings.	Progress Monitoring, Operations, and Maintenance Support	5 years	New battery technologies under development for next-generation mobile devices.	Achieving an increase in battery life without making devices significantly heavier or costlier	Demo is showing a VR device being used for several hours.	Higher powered battery devices. More power efficient VR device operation.
*Increased User Comfort	VR devices are often described as uncomfortable. Many built environment applications require significant use of these devices - thus, increase comfort to increase the level of adoption.	All	5 years	Investigate the use of VR in other fields, i.e. military or gaming use - where long device usage is a requirement	Increasing comfort without significantly increase device cost.	NA	User Studies to identify sources of discomfort. Studies to define the characteristics of more comfortable devices

*Increasing maximum model size	Build environment data models tend to be large and complex. Limitation on VR devices prevents the use of these large models. This results in only sections of models being utilised at any one time	All	3 years	Current rendering technologies deployed on conventional computing devices	Connectivity, bandwidth, and processing limitations of VR devices	Operation use cases where access to large part of a model is required without the opportunity to "return to base" to load a new part of the model.	Streaming of models from base computer to VR device or increasing storage capacity of devices. Investigate the benefits and capabilities of cloud-based rendering.
Improved Multi User Capabilities	VR technologies are mainly single user environment, in the design stages there is a key requirement for multi-user use of VR or design review etc.	Design Support Design Review	3 years	Technology from gaming sector	Complexity of built environment models Bandwidth limitations	Design review case study: where designers need to review, together, in a VR setting current state of design.	There are some preliminary solutions that enable multi user capabilities but have not been thoroughly tested. Define features required for different use cases
*Increased embedded processing for mobile VR	Mobile VR devices have limited on board processing capabilities. Increasing these capabilities will open up new use cases when away from base.	Progress Monitoring Operations and Maintenance Support	5 years	Mobile CPU chipsets	Balancing processing power, battery life and cost.	On site case studies i.e. mobile VR on site for understanding the 3D model, simulations for installation procedures, etc.	Investigate various encoding methods (including machine learning) to reduce the data required to process for mobile VR.
*Decreased reliance on connectivity	Connectivity to either a computing device or internet connectivity is a requirement of many devices. This presents limitation when using VR in an "on-location" setting	Progress Monitoring Operations and Maintenance Support	5 years	Increased storage/processing on VR devices	Balancing battery life and cost.	On site case studies i.e. VR on site for understanding the 3D model, simulations for installation procedures, etc.	Investigate methods for off-line operations of VR devices
➢ **Integration**							
*Increased adoption of built environment data exchange standards	Current VR technologies do not easily interoperate with built environment data standards either limiting adoption or requiring intervention of programmers to bridge the gap, thus incurring extra costs	All	3 Years	Current built environment data models (i.e. IFC)	Limited data storage available on VR devices	Design Review applications, where manual translation from BIM model to 3D model is required.	Automating interoperability between BIM data and 3D modelling standards used by VR devices
*Increased integration with other built environment systems	Integration with build environment software/hardware systems (i.e. Building Management Systems) to open new use cases without need for programmer intervention.	Progress Monitoring Operations and Maintenance Support	5 years	Existing BMS system protocols (i.e. SCADA systems)	Limited data storage on VR devices. Closed Protocols used by built environment systems. Connectivity issues.	Operational use cases, where data from BMS systems is fused with building model data.	Real time integration of VR systems with APIs of build environment systems

*Increase compliance of VR software with corporate systems	VR software (installed on computer) tend to have compatibility issues with corporate systems	All	3 years	None	Restrictions in corporate systems to connect to other applications.	Demo of showing the integration of a corporate system that shares data with a VR application.	Develop a best-practice guide on how to integrate corporate systems with VR applications
*Creation of robust technology ecosystem	Different VR technologies often will not interoperate and are based on differing software systems. Create a robust ecosystems of VR tools to aid adoption and reduce vendor lock in	All	10 years	Methods to integrate various applications and data sources.	Commercial barriers - lack of open standards - lack of engagement from device manufacturers	Applications where AR/VR technologies or differing technologies are used together	Development of standardised data formats/APIs to allow AR/VR devices to work together
➢ **Processes, workflow and management**							
*Achieving a reduction in adoption aversion within the industry and dispelling myth that technology is immature	Engaging in dissemination and demonstration of VR technologies to motivate uptake and reduce the aversion to adoption in the industry. Convince users that devices are not "novelty" and will enable them to do their jobs more efficiently, not replace them.	All	3 years	Approaches to facilitate technology adoption	Lack of interest from stakeholders	Develop an interactive course for technology adoption	Devise best-practices for technology adoption and training
*Development of evidence based built environment business cases for use of VR	Development of business cases to aid organisations in understanding the advantages/opportunities in adopting VR technologies.	All	3 years	None	Difficulty to find suitable case studies. Stakeholders may not want to share data regarding cost/benefit	Develop a case-study that identifies clearly the cost/benefits of using AR/VR	Business modelling and market research/analysis activities
*Increasing level of expert advice and training available within the industry	A lack of VR expertise with understanding of the built environment restricts the availability of credible training opportunities	All	5 years	None	Aversion to change in adoption devices	Map the places in the UK, where expert advice can be obtained.	Development of exemplar training material, collection of use case information to inform training needs.
*Wider advertisement of VR opportunities and increased management understanding	Many smaller organisations are un-aware of the benefits of VR technologies and unsure how to begin adoption. Work is required to convince management of the benefits in adoption	All	5 years	Reduction in aversion to change and evidence-based business case.	Resistance to change and lack of awareness about the business benefits	Adoption campaign focused on SMEs	Research on technology acceptability.

*Explicit clarification of data security and ownership issues	Many organisations have concerns regarding security issues of VR. This is largely an issue of perception rather than a technology issue. Overcome these by providing explicit guidance and clarification to debunk security concerns	All	3 years	All enabling technologies need to be involved: hardware, UI, conversations with device, accuracy, reliability, etc.	Aversion to change & belief that technology is immature or is not suitable for professional work.	User studies on acceptability for VR technology	Research on technology acceptability.
*This capability applies for both AR and VR							

Table 5.4-2. Table summarising the capabilities to develop for AR

Capability	Rationale and Drivers	Applicable Use Cases	Timescale to realise	Enabling Technologies and Behaviours	Barriers to development or adoption	Supports and Case Studies	Suggested Research Needs
➢ **Technical**							
Capacity to augment dynamic scenes, such as construction sites	Construction would benefit greatly from AR. The challenge of building sites is that it is a dynamic environment that changes constantly in two manners: 1-New components are included constantly (new walls are built, windows are installed, etc.) 2- The scene is highly dynamic. Workers walk around, material is transported, machinery and equipment move around, etc. All of which affects the quality of the tracking and the processing of occlusion.	Indicating the location of components to be installed, propose alternatives when clashes occur in real-time, confirm things were installed at the right location, and show what component needs to be installed next.	5 years	Robust tracking in dynamic scenes, and real-time capture of 3D scene topography.	Currently, tracking technology is not sufficiently robust and accurate in such adverse conditions. Builders need accurate, non-ambiguous & robust augmentation that they can rely on. A system is required that constantly captures and updates the physical world, to enable augmentation in dynamic environments.	A demonstrator that shows AR is possible in dynamic construction scenes, and that provides reliable & accurate augmentations with good occlusion processing.	1- Robust tracking in adverse dynamic conditions, outdoor & indoor, both for dynamic events and short-term changes in the environment. 2- Real-time reconstruction and update of environment for live calculation of occlusion. 3- Live processing of captured data for model creation. 4- Fast tracking initialisation method (whether automatic or semi-automatic (user-assisted)

Anywhere augmentation in all cities	AR can be useful to many actors in cities: infrastructure planners and workers, safety & security, insurance, traffic monitoring & planning, tourism, for citizen, etc.	-City planning support that shows new infrastructure in the context of the existing city. -Gather citizen's support. -Evaluating modifications required to a house for insurance purposes. -Third person augmentation viewing system for security services operations.	5 years	Anywhere localisation and tracking. Augmentation database.	-Lack of robust anywhere localisation and tracking system. -Difficult access to all augmentation data under one format. -Difficulties to enable all actors to provide an updated version of their data available online. -Some data does not exist or is not geo-localised in 3D or is not accurate.	Many demonstrators have already been presented, for various city applications. A demonstration that shows the anywhere augmentation in a small city, merging various data sources, and being useful to many levels of stakeholders would be a step forward.	Anywhere augmentation support (city modelling, robustness to illumination / traffic / weather / seasons conditions), potential necessity to develop / enforce use of standards for data storage.
Easy and transparent system for capture and update of reality model	Accurate augmented reality tracking, proper projections and fine occlusion requires accurate knowledge of the shape and size of the environment. This is also true for dynamic environments such as building sites, which must be constantly scanned as they keep changing.	-Accurate topography of the environment can be used to project pipe models onto the surface of the ground. Cables hidden behind walls, which properly show assembly instructions through occlusion with real world objects, etc. -Capturing the physical world for creating as-built models, as those will be required later for building augmentation.	3 years	A variety of environment capture technology, including active sensors, SLAM, wide angle cameras, meshing technology, etc.	The development of this technology requires the integration of many other technologies (sensing, computer vision, automated 3d modelling, etc.).	A demonstrator that shows (both initial and update) scene capture and 3D meshing in industrial environments, on a variety of surfaces (uniform, reflective, textured, etc.)	Fusion of 3D sensing devices to create robust meshing in a variety of situations. Automatic update of complex meshes when a small zone is re-captured after changed in the physical world.
Robust building-wide indoor localisation in industrial and buildings contexts	Indoor augmented reality would have major benefits in industrial and buildings contexts. This requires accurate localisation of the user anywhere within a building, in spite of the complexity of the building or similarities between rooms.	Maintenance, operation, problem solving, escape routes, etc.	5 years	Various tracking technologies, including SLAM, cameras, but others might also be required, such as Wi-Fi and inertial.	Tracking works well for small zones, but larger zones with lots of similarities between rooms or large industrial areas are challenging, especially if the AR device is turned on in one of those areas, without context.	A real case showing successful tracking in large and complex industrial areas, or in a building with many very similar rooms.	Fusion of tracking technologies to enable such building-wide accurate tracking.

Have a clear indication of the accuracy of the augmentation, and a clear graphical representation of that accuracy	AR will not take off in the built environment if the technology cannot provide some value of certainty on the augmentations. Engineers tell us they would not use an AR tool that is inaccurate and that therefore leads them into making mistakes.	All applications that require some level of accuracy, or for which making a mistake has serious consequences.	7 years	A good knowledge of the quality of the tracking will be required, but also the quality of the data, and the knowledge of the physical world. AR augmentation accuracy is a combination of the error of all sources.	The level of quality of the various data sources is not known. There is no unified graphical representations for uncertainty.	A demonstration that shows augmentation error is visually clear to understand, and statistically proven to be correct with an appropriate confidence level.	Propose ways to graphically represent and display augmentation uncertainty; Find ways to calculate augmentation uncertainty in real-time.
*Capacity to modify models on site, based on observations	AR relies on the availability of 3D models. Such models may not accurately or completely represent the physical object. There should be ways for the AR user to propose modifications to the model in situations in which he is able to see a clear discrepancy between how the model is and how it should be.	Industrial maintenance (modified part), indoor building augmentation (new furniture added, new door installed), etc.	3 years	In addition to typical augmentation tools, ways to display and edit the model to enable such modifications would be required.	Models used for AR visualisation and BIM models used for construction are not the same and are not linked.	A demo that shows a real-time modification, for a variety of uses cases, including a plant and an office / residential building.	Tools that link AR models and BIM models for real-time modification in both directions.
Diminished reality	Augmented reality is a useful tool, but physical objects are often in the way of augmentations. For instance, when displaying a building model in the environment where it is going to be built, trees and land topography may be in the way. Diminished reality could be used to make those objects disappear, making the augmentation more perceptually clear.	Construction planning, clash detection, Visualisation of hidden infrastructure, etc.	5 years	3D capture, inpainting techniques	More research is required in this field. 3D inpainting is difficult. Some problems are tricky, such as finding where the object starts and where it ends, and what to replace it with.	A demo that shows successful diminished reality in a complex infrastructure scene.	Diminished reality in built environment scenes.

Device operation though AR	Devices have their user interface: a door has a handle, a microwave oven has buttons, and cabinets have knobs. Augmented reality opens the door to unified interfaces, where everything would be controllable through an AR interface - this way all the microwave ovens in the world would work based on your preferred way of operating one.	This could advantageously be used in industry, where complex plants could be operated without risk by operators who are not necessarily familiar with the specifics of a given plant.	10 years	IoT, motors on handles / buttons, or programmable interfaces	Development of many new types of hardware. New standards will be required.	A successful demo showing operation of two different industrial devices using the same AR interface.	Standards for AR user interface for various devices, complexity of making every device AR-enabled.
AR Assistant	The built environment involves a multitude of trades. Not all workers have all the knowledge to do everything, and AR virtual assistants could help compensate lack of knowledge or experience of some workers, and facilitate knowledge sharing in a working population getting older.	All applications of AR that involve specialised knowledge.	15 years	AI, knowledge encoding and sharing, virtual humans showing interest and emotions.	Lack of availability of intelligent agents	A working prototype. A study of the acceptability of such technology would be very important.	Conversational AI, AI in the field of infrastructure, virtual humans that can be trusted.
Augmented Reality applications that are linked with measurement tools	Workers use measurement tools daily (e.g. measuring tapes, laser scanners, levels & angle measurement devices, etc.). Augmented Reality could be used to display the measurement, in a variety of measurement systems, directly in AR, and link with previous and future measurements.	All applications in which measurements have to be taken, such as design, building, and operations.	5 years	Connection with measurement hardware	Lack of availability of connected measurement tools.	Prototype showing AR displaying measurement of tools, on a construction site, and highlighting the benefits of the technique.	Evaluate each type of measurement in the built environment, and find advantages of displaying the results in AR.

Multi-User Augmented Reality	Multi-user experiences with multi viewports can facilitate clients, designers and multiple stakeholders’ engagement	Customer and Public Engagement, Design Review, Training and O&M	5 years	Two-way, multi-user connections between office workers and site workers	Slow mobile connections. Low processing performance of mobile devices.	A demonstrator that shows the communication between one office worker with many site workers.	Investigate the bandwidth required to transmit the necessary information for two-way multi-user communication.
Object recognition	Object recognition of assets without the need of tags or RFID for progress monitoring or inventory checks.	Operations and Maintenance	5 years	Integrate object recognition algorithms into AR devices. Create the necessary data to train object recognition algorithms.	Lack of labelled data to train algorithms.	A demo that identifies different types of components without tags or RFID.	Quantify the amount of labelled data required to train models. Investigate the possibility of using synthetic data to train the algorithms.
➢ **Processes, workflow and management**							
Safety approved equipment that frees workers hands	Construction & industry work has strict safety requirements. AR equipment may not be appropriate, safe or even approved for use on site.	All industry / construction work that have safety regulations with which AR equipment could interfere.	5 years	Robust equipment that can withstand industry environments, and that does not cause threat to user or that does not prevent other safety equipment or user senses from operating normally.	Availability of necessary hardware, industry & regulation organizations slow to evaluate / adopt new equipment.	Equipment that satisfies the safety requirements, which would be approved, and successfully tested in a variety of environments. If the equipment would contribute in lowering casualties, for instance by warning the worker of risky situations, it would be even better.	Ways AR devices could be worn in combination with clothing and other safety equipment, demonstrations of safety. Use of AR for improvement of safety in industry. Evaluations of risks and mitigation methods, comparisons benefits vs risks.
*Ensure data quality	Accurate and reliable augmented reality requires quality data. Unfortunately, data sources vary greatly in terms of quality, reliability, and accuracy. It is imperative that AR applications in the built environment consider data quality in the augmentation phase, for instance by adapting the display, but also data managers to upgrade and maintain their data to be AR quality.	Any application in the infrastructure world - this includes building maintenance (e.g. As-built models availability and quality), sub surface utilities (quality of data), etc.	15 years	All necessary technologies exist. A systems integration approach should be taken to ensure the quality of data from various sources.	Lack of legislation, Laborious and costly tasks	A city-wide example of highly accurate and reliable data, showing all the benefits of good data for augmentation quality.	Evaluate the impact of accurate data on augmentation quality and other advantages for the built environment.

*Innovative ways to display data, both spatially and temporally, for decision making, that go much beyond paper or tablets	Augmented reality shows lots of potential but is often seen as an extension of the desktop environment. There should be new ways to display the data, which would enhance its value, and facilitate its use and interpretation.	All fields in design, construction, maintenance, and operation.	10 years	New visualisation technologies methods and approaches. Systems integration: technologies that can transfer information from multiple data sources	There is a very established tradition on how to represent data in 2D. A change to 3D representations can potentially face many obstacles.	Prototypes showing many different manners of representing the same datasets	New user interface paradigms, that go beyond current use of 2D and 3D data.
AR Virtual notes	Workers communicate to each other via paper notes, text messages, and phone calls. Virtual Notes left on site could enhance workers productivity by lowering the need for live communication.	Construction and maintenance would benefit from such technology, by allowing workers to leave virtual notes, animations and video messages to their fellow workers.	5 years	Accurate tracking and user positioning. Ways of recording animations / creating virtual notes.	Anywhere augmentation is not available, and AR devices are not widespread on construction sites.	A working prototype showing virtual notes left behind and read.	Anywhere augmentation support on a building site, easy to use creation tools for notes
*Acceptable / trustable AR technology	AR will become a tool used by all workers. Before they can adopt it, they should trust it.	All fields in design, construction, maintenance, and operation.	10 years	All enabling technologies need to be involved: hardware, UI, conversations with device, accuracy, reliability, etc.	The technology is too young, and the concept of acceptability is perhaps not sufficiently well understood.	User studies on acceptability for AR technology.	Research on technology acceptability.
*Archiving AR outputs	AR is a live experience. It has the potential of providing lots of insight. Unfortunately, that cannot easily be exported to a format that would enable other users to experience the same situation. A method of recording augmentations and sharing it with other users at a later time would be very useful.	All fields in design, construction, maintenance, and operation.	5 years	Current AR technologies, and a way to record augmentation sessions in a better way than just first-person video.	There is no availability of methods to develop this capability.	A working prototype showing users experiencing a past AR experience, at a later time.	Research on technologies to record, archive and share AR experiences.
*This capability applies for both AR and VR							

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References

Benford, S., Greenhalgh, C., Reynard, G., Brown, C., Koleva, B., 1998. Understanding and constructing shared spaces with mixed-reality boundaries. ACM Trans. Comput. Interact. 5, 185–223. https://doi.org/10.1145/292834.292836

Bray, B., Zeller, M., 2018. What is mixed reality? [WWW Document]. URL https://docs.microsoft.com/en-us/windows/mixed-reality/mixed-reality

Dalton, J., 2018. VR/AR Interactive UK map [WWW Document]. URL https://public.tableau.com/profile/jeremy.dalton#!/vizhome/VRARinteractiveUKmap_0/VRARCompaniesAcrosstheUK_

Mateos-Garcia, J., Stathoulopoulos, K., Thomas, N., 2018. The immersive economy in the UK: The growth of virtual, augmented and mixed reality technologies.

Mckinsey Global Institute, ., 2015. Digital America: A tale of haves and have-mores.

Milgram, P., 1994. A Taxonomy of Mixed Reality Visual Displays. IEICE Trans. Inf. Syst. E77–D.

National Infrastructure Commission, 2017. Data for the Public Good.

Oesterreich, T.D., 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. Comput. Ind. 83, 121–139. https://doi.org/10.1016/J.COMPIND.2016.09.006

PwC, 2018. Growing VR/AR companies in the UK: A business and legal handbook.

Welsh, L., Dalton, K., Doyle, K., Landreil, P., Maza, C., 2018. Construction Technology Report.

Appendix A1: Details of conducted workshops

Table A1-1. List of workshops conducted by the Vision Network

Workshop	Date	Objectives	Location	Represented Organisations*
W1	06 Aug	Identify: • use-cases • limitations • drivers • capabilities Identify: • existing case studies carried out in industry	London	Academia: • Coventry University • Reading University Industry: • BSI • McAvoy Group • Stride Treglown • Willmott Dixon • Mott MacDonald • Xyleminc • Target3D
W2	03 Sept	Identify: • use-cases • limitations • drivers • capabilities Identify: • existing case studies carried out in industry	London	Academia: • Newcastle University • London Southbank Industry: • Galliford Try • Willmott Dixon • WSP • Mott MacDonald • Site Lense • Waldeck Consulting
W3	24 Oct	• Rank and qualify use-cases, stakeholders, and scale of applications	London	Academia: • Middlesex University • Imperial College London • University of Strathclyde Industry: • Galliford Try • Foster + Partners • BuroHappold Engineering • SRM • HSSMI • COMIT • Tony Gee and Partners • Stantec
W4	26 Nov	• Rank and qualify use-cases, stakeholders, and scale of applications	MTC Coventry	Academia: • Coventry University Industry: • MTC • Stantec • Network Rail • KPF • McAvoy Group

* List participants of the workshops excluding the Network Vision core members

Appendix A2: Summary tables with findings from W1 and W2

TABLE 1		
Phase	**Use Cases**	**Rank**
Delivery	Tool finder	
	Design review and design options	3
	Warning system	
	View behind	
	Risk prediction	
	Way finder in new buildings	
	Showing current status of the work	
	Better value judgement	
	Ergonomic Testing	
	Problem solving	
	Feedback loops	
	(AR) it can be used to simulate placing objects in the correct locations	
Operations	Training	2
	H&S	2
	Open source data	
	Planning screening for operation	
	Design focus on disability	
	Ability to view multi - layer for the same object	
	Directions applications	
	Planned maintenance of assets	
	General technical support applications	
	Automatic identifications for objectives	
	Progress monitoring after 4 PM with drones	
Integration	BIM cave	
	Rank=number of times that appeared in a discussion session	

TABLE 2		
Phase	**Capabilities**	**Rank**
Delivery	Increased communication and the understanding with the end user	3
	De-risk Design	
	Increase cost certainty	
	Site safety	2
	As built design and inspection	2

	Read links from real world to 3D models	
	Design review	
	water resistance	
	(VR) Create emotional environment in design development	
	(VR) Non-technical communication tool	
	Staff training (upskilling)	2
	(VR) easy show for Prototyping	
	Accurate tracking and positioning (geolocation)	3
	Quicker variation sign-off	
	Synchronisation between authorities	
Operations	Quicker Maintenance cycle	
	Cyber model visualisation	
	Facility management	
	Better understanding of the building, itself	
	Help in H&S	2
	Remote asset/ supporter	
	Computer vision (object recognition)	
	Object reconstruction	
	Sensing of physical world	
	Future design support	
	Scenario what if analysis	
	Provide integration	
	Recognise different type of materials, Plant elements	
	Room scale experiences	
	Multi-sensory visualisation emergency	
	Object tracking (How many components in the project)	
	Clash detection	
Integration	Consistent data transfer formats (interpretability)	2
	Knowledge Transfer between organizations	
	Link between software	
	Possibility of future linking computer with AI	
	Team meeting	2
	Macro-data Visualisations to show high level impact	
	Shared information collaboration	3
	Rank=number of times that appeared in a discussion session	

TABLE 3			
Type	Limitations	Rank	Examples
Technical	Immature Technology		
	Battery limitation	3	
	Format challenges (data exchange) or interoperability	4	exchange at two levels hardware and software as well.
	Requirement for power, machine and laptops	2	
	Isolation		multi users is not an option
	Un-comfortability (user wellness)	2	User experience using device, motion and sickness
	Integration		
	Connectivity issues		Wi-Fi for mobile connecting
	Processing Power		It will be a challenge as the device move, this could reduce the quality of the Visualisation
	Awkward VR sensors		
	The technology is not mature enough (still half way through)		
	Heavy for heads		
	Low resolution		
	Heavy laptops		
	Low accurate tracking and mapping (AR)		
	Incomplete data, Validation and verification, "false position "		
	No AI		
	Data Server-Centralised data source and Quality of data	2	
	Lack of standards	3	Step (ISO 10303), DWG, DYF
	Low Field of View (FOV)	2	
Economic	Hard to define the ROI		
	High initial investment		
	Expensive hardware		
	Lack of client’s interests		
	Cost of the equipment + training.		
	Who is going to pay?		
	Unclear commercial benefits for owners		
	Cost analysis is not detailed enough to relies the value of the technology		
	Low R&D budget		

	Risky technology		Technology may change in soon future
	It could be a challenge to SMEs		
	Lack of business cases/ Applications	2	No evidence that it will save the cost to the client
	Hard to measure active VAWE		
Social	Limited teleconferencing capabilities.		
	Fragmented industry		
	On site setup may require space.		
	Physiological motion sickness		
	User interface is not suitable		
	Job security		
	Public perception (lack of awareness) it is gaming devices!		
	Lack of privacy		
	Security of data	2	
	H&S for eyes		
	Untrained workforce		which has more priority to adopt of the ARVR in construction/ content making skills (software)/ Technology Making (Hardware)
	Change Mind-set of people	2	People cut things in the middle, Client may see this technology for gaming
	Public perception		lack of awareness
	Space and mobility		
	IP issues, sharing of data and its security.	2	
	Rank=number of times that appeared in a discussion session		

TABLE 4: Capabilities

	Delivery	Operation	Integration
Citizens	– Collaboration between stakeholders. – Better consultation – Multi people can integrate not just technical people. – Client involvement – Design inclusive – Simulation tool for what will be constructed. – Availability of operational information – Level of details (component level) – Public consultation – Capturing feedback	– Software and tools better than the 2d. – Staff Training. – Safety induction. – Visualizing existing asset.	– Multi-user in VR AR. – Collaboration between offices. – Better client communications – Avoid misunderstanding – Better reputation – Increased sales.

	– Helpful for disabled – Design inclusive		
Services	– Training delivery – Health and safety on site – Site management – As built information – Clash detection. – Record of change – Avoid damage. – Virtual walkthrough. – Understanding for the requirements using Visualisations – Building performance. – Hazard identification – Site setup – True information access.	– Management (Defect, Progress As-built) – Accident Planning – Save Material – Improve facility Management – Reduce Cost of Maintenance – Laser scanning – Used for maintenance – Disaster management – Space management – Staff on boarding (familiarization and GSL processing) – Frit safety and strategy	– Collaboration planning – Operations and Installation flow – Health monitor such as (Apple watch and IoT) – Self-drive cars – Collecting data – Facial recognition & Personal Data
Operational Expenditure	– Health and safety – As built information – Reduce Risk – Reduce Time – Reduce Cost – Training in VR – Site progress Visualisation	– Reading the data – Status of the assets – Marketing – Digital Twins – Live Modelling of building – Asset Management – PAS 1192-5 – Security considerations – BIM assisted asset information – Visualisation shelf life – Help in visualize walls for maintenance (Asset management) – Operations (work order definition for workers)	– 5G – Planning and management of integrations of the operations – Translation of (4x) for future design development – GSL – policy improve – O&M delivery – Through AR services – Wearable technology
Capital Expenditure	– Design sign-off – CFD Integration – Site progress Visualisation – Production management	– Asset Management – As-built information – BIM asset Information – Improve Assessing accounting – Construction planning. – Built environment.	– Visualisation data – User integration

Appendix A3: Summary tables with findings from W4 and W5

TABLE 1: Limitations			
Use-case	**Economic**	**Technical**	**Social**
Customer/ Public Engagement	▪ Not everyone can afford team or has access to this technology. ▪ Cost limitations/ Who will pay ▪ Hard to define the ROI. ▪ High initial investment. ▪ Expensive hardware ▪ unclear commercial benefits for owners ▪ Low R&D budget ▪ Risky technology ▪ It could be a challenge to SMEs ▪ Lack of business cases/ applications. ▪ Cost of hardware setup and updating of equipment	▪ Need for hardware support. ▪ Accuracy issues (x2) ▪ Isolation, plus, challenge of engaging multi users ▪ It could cause eye problems ▪ Corporate limitations on software install. ▪ Quality of the image. ▪ People think it is immature technology. ▪ Requirement for power, machine and laptops ▪ Un-comfortability (user wellness) ▪ Low Field of View (FOV) ▪ AR does not look well for large sites, where the model has to be broken down into smaller	▪ Acceptance realism in rendering. ▪ Cyber risk hacking (x3) ▪ perception of generational relevance ▪ Lack of trust ▪ Physiological motions sickness ▪ Public perception and changing mind-set of people (x2) ▪ IP issues, ▪ Hard interactions between industries ▪ Lack of useful applications
Design Review	▪ High spec, expensive technology. ▪ Value/ benefit satisfaction.	▪ Battery life is short ▪ Instant pose estimation in adverse condition ▪ Rich underlying. ▪ Model/ digital twin. ▪ WIFI bandwidth ▪ AR/ VR is not exact depictions of reality ▪ Accessing data beyond objects (meta- data) ▪ Incomplete data, Validation and verification, "false position " ▪ Lack of standards ▪ Low Field of View (FOV) ▪ GPS accuracy issues. ▪ IT polices ▪ Limitations for the use in size ▪ It does not work while wearing gloves. ▪ The user needs a chaperone to be safe when use it	▪ Embedder culture e.g.: drawings ▪ Job security
Construction support	▪ Integration with other systems (facility management systems) such as: CAFM and BMS systems used by O&M. ▪ Time of implementation	▪ Battery life (x2) ▪ WIFI bandwidth ▪ Mismatch between delivery and operation planning. ▪ Difficulty of archiving AR outputs in information management systems ▪ Accuracy and speed of updating information	▪ Lack of risk assessment with VR/AR clauses ▪ Job security

		▪ Low accurate tracking and mapping (AR) ▪ ▪ Incomplete data, Validation and verification, "false position ". ▪ Lack of Standardization/ regulation. ▪ Data exchange (different platforms) ▪ network latency	
Operations and Maintenance Support	▪ No. of devices. ▪ Cost of maintenance	▪ Mismatch between delivery and operation planning. ▪ Accuracy and speed of updating information. ▪ Format challenges (data exchange) or interoperability ▪ Lack of standards ▪ Limited internet access signal ▪ Physical space limitations range ▪ Batter life ▪ Limited FOV (x2). ▪ Overcoming old ways of tested methods. ▪ Need high skilled team to set up	▪ Space and mobility ▪ IP issues
Training	▪ Lack of experts who can produce the content. ▪ Funds for equipment ▪ Cost of training ▪ Need for government commitment for large scale implementation at schools.	▪ Lack of experts who can produce the content. (x3) ▪ Facility shortage. ▪ Need of mastery of multiple platforms. ▪ No GPS signals on site. ▪ Requirement for power, machine and laptops ▪ Lack of common platform/ connectivity	▪ Lack of Untrained workforce ▪ social interaction resilience

TABLE 2: Benefits					
	Designers	**Builders**	**Managers/ Operations**	**Owners**	**End-Users**
Customer/Public Engagement	▪ Timely feedback. ▪ Minimise re-work and waste. ▪ Engagement feedback	▪ Better site planning. ▪ Minimise re-work and waste. ▪ Contextual understanding. ▪ Better understanding for the requirements ▪ Clash detection ▪ Reduce overall cost. ▪ Right 1st time.	▪ Impact assessment	▪ Speed certainty inclusivity. ▪ Reduce risk and less cost. ▪ Better archiving of legacy data. ▪ Improve quality ▪ Simulations give better understanding of the design and built environment. (x2) ▪ Demo of vision/ acceptance of concept. ▪ Visualisation meeting (AR) study up to date of project progress without going to site	▪ Understanding social impact of governmental new construction developments. ▪ Better archiving of legacy data. ▪ Inclusivity. ▪ Improve buyer experience (clarity). ▪ Simulations give better understanding of the design and built environment. ▪ Issues resolved more easily
Design Review	▪ Timely feedback. ▪ Better understanding of cross-discipline interaction (x2) ▪ Efficient design making. ▪ Design complications. ▪ Human factors. ▪ Clash detection. ▪ Clarity ▪ Design for assets	▪ Contextual understanding. ▪ Efficient design making. ▪ Better to plan, temporary works. ▪ Visualisation of CAD. ▪ H&S. ▪ Communication tool with the workers ▪ Rehearsal of construction activities. (x2)	▪ Visualised project planning. ▪ Efficient design making. ▪ Input to design ▪ Cost reduction ▪ More efficient space planning	▪ Efficient design making ▪ Better understanding of the design using VR/ AR. ▪ Efficiency utilizing data ▪ Better space management.	▪ Efficient design making ▪ Understanding functions using data. ▪ Understand the proposal of the project, how it will really look like.
Construction support	▪ Better control over programme by entertaining clashes at the design stage. ▪ Visual quick understanding of a complete programme. ▪ CDM 2015 REGS ▪ Better information ▪ Complains and feedback	▪ Better control over programme by entertaining clashes at the design stage. ▪ Visualised project planning. ▪ Contextual understanding. ▪ Visual quick understanding of a complete programme.	▪ It is a tool for record keeping/ documentation. (x2) ▪ Visual progress	▪ Ability for visual analyses	▪ Social engagement and clarity for government planning. ▪ Avoidance of impatience customers (AR Only) ▪

		▪ CDM compliance for temporary works. ▪ Better cost and time performance. ▪ Interface availability.			
Operations and Maintenance	▪ Better record keeping of existing assets using AR/VR. ▪ Produce knowledge transfer.	▪ Contextual understanding ▪ Minimize travel to and from site (AR only), save in time and reduce CO_2. ▪ Risk reduction. ▪ Re-skilling accuracy	▪ Knowledge reuse. ▪ Aiding the decision-making process for maintenance. ▪ Reducing maintenance time/ Cost. ▪ Clear understandin g for facility needs. ▪ Preventive maintenance	▪ Efficient navigation and evacuation. ▪ Reduce cost on project delivery ▪ Ongoing maintenance.	▪ Social engagement and clarity for government planning. ▪ Enhance user experience. ▪ Asset information interactive / maintenance
Training	▪ Technical Enhancement	▪ Contextual understanding	▪ Informed decision-making support. ▪ Visualisatio n odour (smoke and fumes), environme ntal factors ▪ Training new staff.	▪ Informed decision-making support. ▪ Training operations team consistently ▪ . i.e.: if team members change over the time, the same training can be repeated with cost cheap and same quality ▪ Simulate large scale operations in smaller spaces.	▪ On-Boarding ▪ Safety and risk reduction.

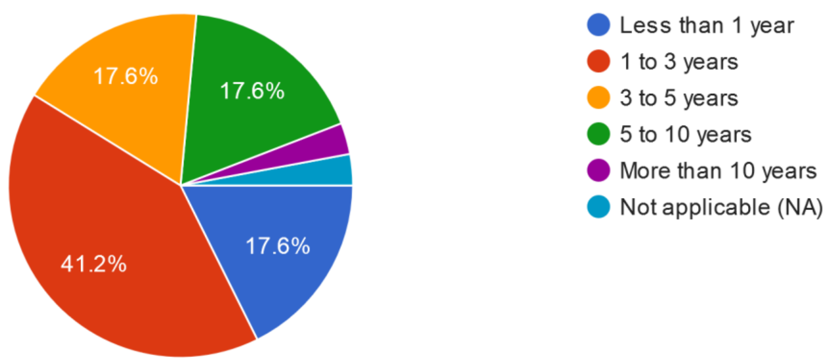
TABLE 3: Use-cases				
	Room	**Building**	**Neighbourhood**	**Region**
Customer/ Public Engagement	▪ Rooms and daylight analysis and shadow position ▪ Clash detection (x2) ▪ Virtual review of new houses ▪ For sale/ improve buyer experience. ▪ View future kitchen ▪ Help in design process ▪ Suggest adjustments. ▪ Design rooms (furniture's, lighting, and space management.	▪ Client involvement in design development ▪ Overview of general layout + arrangement. ▪ assisted navigation for buildings ▪ Architecture on site building Visualisation. ▪ The link with the surrounding buildings. ▪ protect public participation	▪ Smart cities/ Smart infrastructure ▪ Simulation and Visualisation ▪ Public consultation enabling. (x2) ▪ Multi task simulation ▪ Including ARAV presentations during public consultations regarding new developments. ▪ New buildings viewed as actual y public ▪ Project impact on the environment	▪ Planning of new infrastructure with existing one. ▪ Including ARAV presentations during public consultations regarding new developments ▪ For truism explain sites. ▪ Visibility of renewable tech's or new infra. ▪ Public engagement ▪ Air network Visualisation
Design review	▪ Refurb/ renovation new building heritage ▪ Clear sign of operations ▪ Sign off of reviewable design data. ▪ Overlay of services/ finish install (planned vs actual) ▪ Lighting services ▪ Space planning and room layout simulation ▪ Interface of plant with existing structures	▪ H&S ▪ Risk register tagging ▪ Preserved digital twin of listed building that will be demolished. ▪ Use ARVR to cross check between design from various disciplines ▪ Identify clashes ▪ Subject x object assessment ▪ Planning consent ▪ Pre and Post refurbishment ▪ Fire exits simulations ▪ People flow in the building (daily/ emergency) ▪ Identify if people feel safe ▪	▪ Review of conceptual design ▪ Navigation ▪ parking design review	▪ Using gaming engine platforms alongside ARVR for design review. ▪ Environmental considerations + simulation.
Construction support	▪ No need to visit the site (VR only)	▪ Including ARVR check milestones in	▪ Progress reporting 4D timeline (x2)	▪ Applied for smart cities

	▪ Location of materials ▪ Consultancy feedback ▪ Client approvals	the construction programme. ▪ Location of materials ▪ Future expansion	▪ Plan Visualisation for construction activities ▪ Skyline Visualisation ▪ Visual meetings	▪ Statistical data of region ▪ Visualisation growth ▪ New DEV
Operations and maintenance support	▪ Disability engagement and training ▪ H&S ▪ Bentley demos. ▪ Ability to determine what and when a regime need intervention ▪ Knowledge transfer ▪ Asset Handbook ▪ Data distraction	▪ Soft building handover. ▪ Include an ARVR model with the deliverables for maintenance/ support purpose. ▪ Ability to determine what and when a regime need intervention ▪ Localised display of building information ▪ Hidden infrastructure	▪ Tourism and public services/ navigation ▪ Estate- Asset information management. ▪ Estate and healthcare estate. ▪ Identify access to plant for maintenance	▪ re-enactment
Training	▪ Building reality workplace (AR only) ▪ Simulations of building environment for disaster ▪ Simulations for police problems to emergency services. ▪ Demo fire escape routes. ▪ Maintenance training	▪ Simulations of the construction environment factory. ▪ Induction training ▪ Identification Hazards. (x2) ▪ Digital twin though all delivery stages ARVR ▪ Understanding the order prior doing it to reality	▪ Citizen taking on public services ▪ Develop ARVR ambassador to promote the technology in schools ▪ Traffic.	▪ Include ARVR modules in schools. ▪ Surveys.

Appendix B1 Targeted questionnaire results for UK's adoption levels

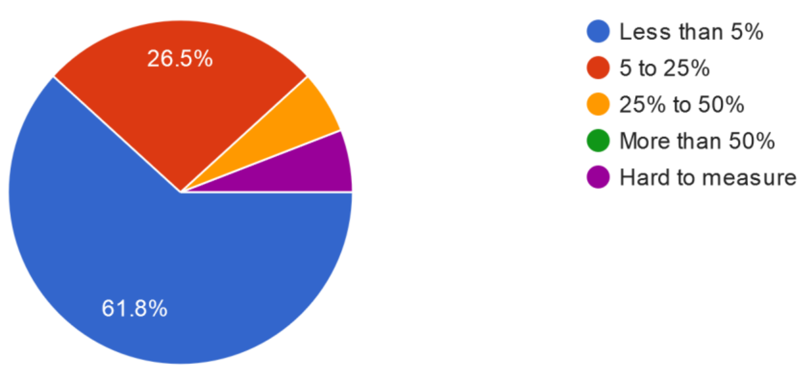
How long have you been using immersive technologies in your organisation?

34 responses

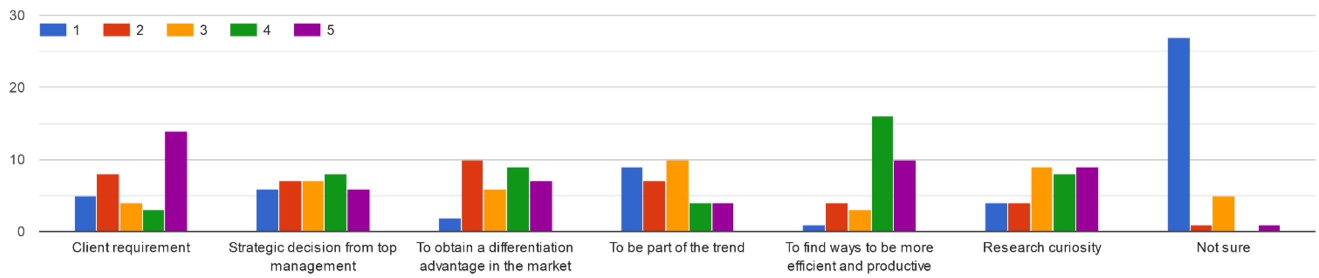


What percentage of projects in your organisation have used an immersive solution?

34 responses

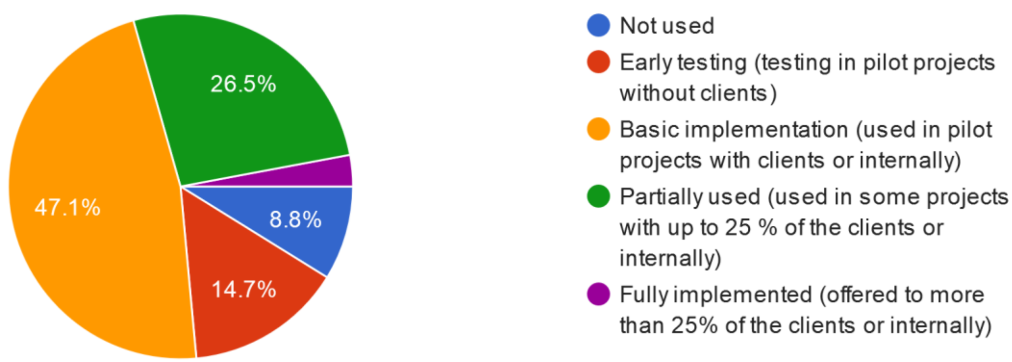


When your organisation first started using immersive technologies, how important were the following factors? Rate from 1 to 5 (1=not important...5=very important)



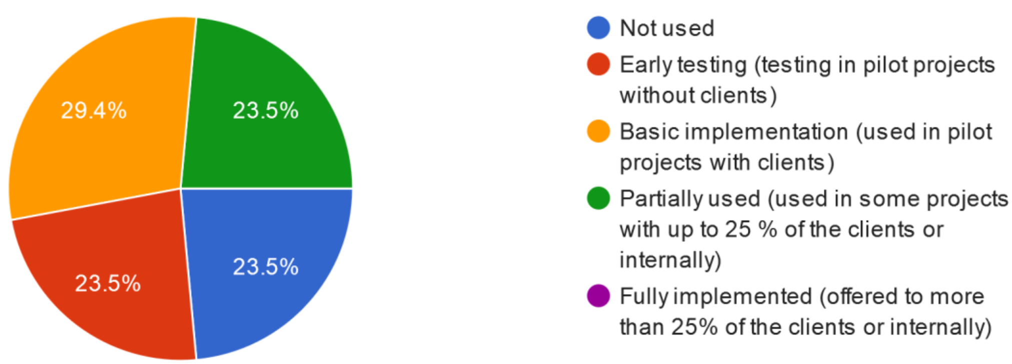
To what extent has your organisation implemented Virtual Reality?

34 responses



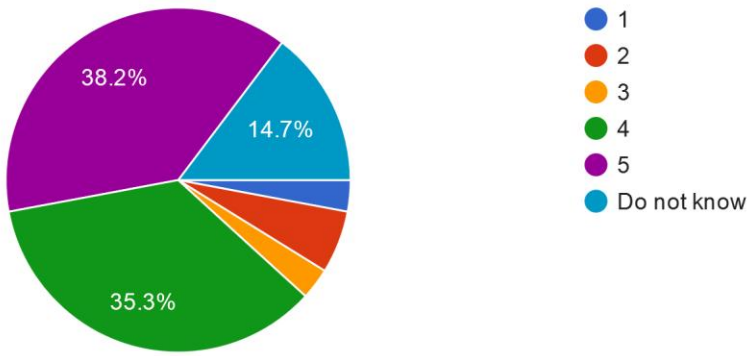
To what extent has your organisation implemented Augmented Reality?

34 responses



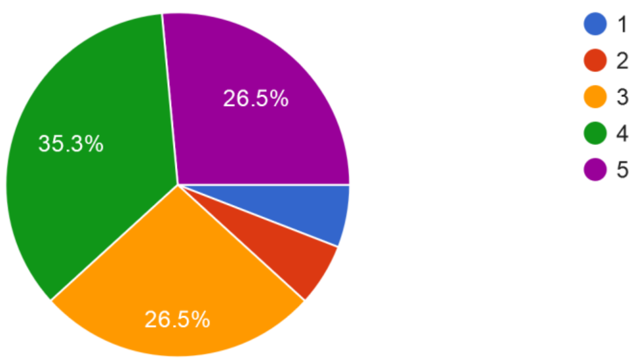
What is the likelihood that your organisation will invest in the adoption of Virtual Reality in the next 3 years? (1=very unlikely...5=very likely)

34 responses



What is the likelihood that your organisation will invest in the adoption of Augmented Reality in the next 3 years? (1=very unlikely...5=very likely)

34 responses



Appendix B2: Research centres and projects

Table B2-1. List of the main academic and research centres.

UK Academic Centres and Labs	
1	Cardiff University • C-HIVE – Cardiff Human Interfaces and Virtual Environments Laboratory http://www.cf.ac.uk/psych/ruddle/C-HIVE/
2	Hull University • Hull Immersive Visualisation Environment (HIVE) http://www.hull.ac.uk/hive/index.htm
3	Loughborough University • AVRRC – Advanced VR Research Centre http://www.avrrc.lboro.ac.uk/JTAP305introd.html
4	University of Nottingham • Collaborative Virtual Environments – COVEN http://www.crg.cs.nott.ac.uk/research/projects/Coven/ • Structured Evaluation of Training in Virtual Environments (STRIVE) http://www.virart.nottingham.ac.uk/Projects_STRIVE.htm
5	Royal Military College of Science at Cranfield University • Flight Deck Officer Training • Parachute Training http://www.rmcs.cranfield.ac.uk/ssel/train.htm
6	Loughborough University Advanced VR Research Centre http://www.lboro.ac.uk/research/avrrc/
7	Glasgow University Centre for the Study of Perceptual Experience The Philosophy of Virtual and Augmented Reality https://www.gla.ac.uk/research/az/cspe/projects/vrar/
8	University of Bristol in Collaboration with University of the West of England Bristol VR Lab https://bristolvrlab.com/ https://www.bristol.ac.uk/news/2018/april/bristol-vr-lab.html
9	Imperial College MSK Lab (Surgical Technology) The MSk Lab is developing novel tools using Augmented Reality (AR) and Virtual Reality (VR) technologies, exploring the optimal use within improvement of surgical care. http://www.imperial.ac.uk/msk-lab/research/surgical-technology/augmented-and-virtual-reality/
10	Manchester Metropolitan University Creative AR & VR Hub https://www2.mmu.ac.uk/creativear/
11	Cambridge University

	Centre for Digital Built Britain, CDBB https://www.cdbb.cam.ac.uk/
12	University of Oxford Digital Education AR and VR Lab https://www.digitaleducation.ox.ac.uk/vr-ar-lab Oxford LibGuides & Radcliffe Science Library The Oxford LibGuides: Virtual Reality gives you information on VR services provided by the Radcliffe Science Library, along with links to helpful VR viewing and capturing resources and tips. https://libguides.bodleian.ox.ac.uk/vr/ VR and AR Oxford Hub To facilitate the use of virtual reality (VR) and augment reality (AR) at the University of Oxford, the VR and AR Oxford Hub has been recently established. One of its goals is to gather researchers from multiple disciplines, and so we are inviting researchers from the University of Oxford to attend our next event Thursday 26th April in Oxford. https://vraroxfordhub.co.uk/
13	De Montford University Interactive and Media Technology, Virtual and Augmented Reality http://www.dmu.ac.uk/research/research-faculties-and-institutes/technology/interactive-media-technologies/research-areas/virtual-and-augmented-reality.aspx
14	Cranfield University The Centre for Competitive Creative Design In partnership with OrangeLV ltd have come together to offer PhD research posts focusing on the development of a novel proof of concept Augmented Reality (AR)/ Virtual Reality (VR) solution.
15	Cardiff University Virtual and Augmented Reality, and Binaural Recording http://www.cardiff.ac.uk/research/explore/research-units/virtual-and-augmented-reality-and-binaural-recording
16	University of Bath, REality and Virtual Environments Augmentation Labs (REVEAL) An interdisciplinary group of researchers from Computer Science, Engineering, Psychology and Health working with VR and AR technology. https://www.bath.ac.uk/research-centres/reality-and-virtual-environments-augmentation-labs-reveal/
17	King's College London Virtual Reality Research Group https://www.kcl.ac.uk/ioppn/depts/psychology/research/researchgroupings/vrrg/virtual-reality-research-group.aspx
18	The University of Sheffield Kroto Research Institute Virtual Reality https://www.sheffield.ac.uk/kroto/research/vr Reflex Studio https://www.sheffield.ac.uk/reflex/about
19	University of Bradford Centre for Visual Computing https://www.bradford.ac.uk/research/rkt-centres/visual-computing/

20	University of Salford Manchester Perception Action Research Lab, Centre for Health Sciences https://www.salford.ac.uk/research/health-sciences/research-groups/virtual-reality
21	NHS, Virtual reality for mental health https://www.nihr.ac.uk/research-and-impact/making-a-difference/virtual-reality-for-mental-health.htm
22	Queens's University Belfast Immersive Interactive Virtual Reality http://www.qub.ac.uk/research-centres/PerceptionActionResearchLab/Publications/ImmersiveInteractiveVirtualReality/
23	UCL C-PLACID & Virtual Reality https://www.ucl.ac.uk/drc/c-placid-study/c-placid-virtual-reality Immersive Virtual Environments Laboratory Com-puter Sci-ence Depart-ment, Uni-ver-sity Col-lege Lon-don https://vr.cs.ucl.ac.uk/
24	Leeds University Leeds Institute for Data Analytics, LIDA https://lida.leeds.ac.uk/research-projects/virtual-reality-leeds/
25	Edge Hill University Data and Complex Systems Research Centre https://www.edgehill.ac.uk/computerscience/research/data-complex-systems-research-centre/ Creative Virtual Reality Lab https://www.edgehill.ac.uk/computerscience/research/creative-virtual-reality-lab/
26	Aston University Centre for Vision and Hearing Research (CVHR) http://www.aston.ac.uk/lhs/research/centres-facilities/cvhr/ ALIVE http://www.aston.ac.uk/lhs/research/centres-facilities/alive/
27	University of Bedfordshire https://www.beds.ac.uk/rimap/projects/augmented_book
28	University of Sheffield AMRC: Advanced Manufacturing Research Centre, Virtual simulation of new Boeing facility based in Sheffield https://amrc.co.uk/ https://amrc.co.uk/case-studies/virtual-simulation-of-new-boeing-facility-based-in-sheffield Urban Studies and Planning https://www.sheffield.ac.uk/usp/news/augmented-reality-technologies-urban-design-teaching-1.667096
29	University of Nottingham Mixed Reality Laboratory The Mixed Reality Laboratory (MRL) was established in 1999, and is an interdisciplinary group exploring the potential of ubiquitous, mobile and interactive technologies to shape everyday life.

	https://www.nottingham.ac.uk/research/groups/mixedrealitylab/
30	Heriot Watt University Immersive Virtual Reality The Immersive and Controlled Environment (ICE) is a research project funded 100% by the construction industry that, among other things, is developing a new kind of immersive virtual reality (VR) technology that the team calls iHR. https://www.hw.ac.uk/research/engage/case-studies/immersive-virtual-reality.htm
31	University of Leicester VR Laboratory https://www2.le.ac.uk/departments/geography/images/facilities/vr-laboratory/view
32	The Manufacturing Technology Centre (MTC) http://www.the-mtc.org/ http://thearea.org/about-us/ http://thearea.org/area-members/manufacturing-technology-centre-mtc/
33	Coventry University The Simulation Centre https://www.coventry.ac.uk/business/facilities/simulation-centre/

Table B2-2. List of the main universities providing immersive technologies courses.

Courses	
1	University of Portsmouth • Virtual and Augmented Reality BSc (Hons) https://www.port.ac.uk/study/courses/bsc-hons-virtual-and-augmented-reality
2	University of Bradford • Virtual and Augmented Reality BSc (Hons) https://www.bradford.ac.uk/courses/ug/virtual-and-augmented-reality-bsc/
3	Staffordshire University • Virtual Reality Design (with a foundation year) BA (Hons) • Virtual Reality Design (with a placement year) BA (Hons) • Virtual Reality Design BA (Hons) https://www.hotcoursesabroad.com/study/provider-result.html?collegeId=3697&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y
4	Glascow School of Art • Virtual Reality Systems Design course • Games and Virtual Reality BSc (Hons) https://www.hotcoursesabroad.com/study/course/uk/games-and-virtual-reality-bsc-hons/56992196/program.html?nationCode=210&nationCntryCode=210
5	University of the Arts London • MA Virtual Reality • Virtual Reality BA (Hons)

	https://www.hotcoursesabroad.com/study/provider-result.html?fromSR=Y&crseCount=2&catDispName=Virtual+Reality+Systems+Design&collegeId=119597&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y
6	University of the West of England • Virtual Reality MA https://www.hotcoursesabroad.com/study/provider-result.html?fromSR=Y&crseCount=1&catDispName=Virtual+Reality+Systems+Design&collegeId=3767&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y
7	University College London, UCL • Virtual Environments, Imaging and Visualisation DEng • Virtual Reality MRes https://www.hotcoursesabroad.com/study/provider-result.html?fromSR=Y&crseCount=2&catDispName=Virtual+Reality+Systems+Design&collegeId=4094&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y
8	Solent University • Virtual and Augmented Reality (Design) BA • Virtual and Augmented Reality (Design) with Digital Arts Foundation Year BA (Hons) • Virtual and Augmented Reality (Design) with Placement and Digital Arts Foundation Year BA (Hons) • Virtual and Augmented Reality (Design) with Placement BA • Virtual and Augmented Reality (Software Development) BSc (Hons) • Virtual and Augmented Reality (Software Development) with Digital Arts Foundation Year BSc (Hons) • Virtual and Augmented Reality (Software Development) with Placement and Digital Arts Foundation Year BSc (Hons) • Virtual and Augmented Reality (Software Development) with Placement BSc (Hons) https://www.hotcoursesabroad.com/study/provider-result.html?fromSR=Y&crseCount=8&catDispName=Virtual+Reality+Systems+Design&collegeId=3858&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y
9	Solihull College and University Centre • Extended Technical Diploma in IT (Virtual Reality and Application Developer) • Games Design and Virtual Reality BSc (Hons) • Games Design and Virtual Reality BSc (Hons) validated by University of Northampton https://www.hotcoursesabroad.com/study/provider-result.html?fromSR=Y&crseCount=3&catDispName=Virtual+Reality+Systems+Design&collegeId=6242&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y
10	Ealing, Hammersmith and West London College • IT (Augmented & Virtual Reality) - Level 3 Diploma https://www.hotcoursesabroad.com/study/provider-result.html?fromSR=Y&crseCount=1&catDispName=Virtual+Reality+Systems+Design&collegeId=866&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y
11	Leeds Trinity University • Digital Media (Visual Effects and Virtual Reality) BA (Hons) http://www.leedstrinity.ac.uk/courses/ug/19/DMVR
12	Falmouth University • Creative Virtual Reality BA (Hons)

	https://www.hotcoursesabroad.com/study/provider-result.html?fromSR=Y&crseCount=1&catDispName=Virtual+Reality+Systems+Design&collegeId=5736&countryId=210&catCode=CB.6631-4&nationCode=210&nationCntryCode=210&studyAbroad=Y

Table B2-3. List of research projects funded by EPSRC.

EPSRC Funded Projects	
1	University of Bristol - VR Virtual Realities - Immersive Documentary Encounters https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P025595/1 01 July 2017, Value (£): 1,051,606
2	UCL - MR Playing the Archive: memory, community and mixed reality play 01 August 2017, Value: 773,695 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P025730/1
3	University of Sussex AURORA: Controlling sound like we do with light 29 June 2018, Value (£): 622,522
4	UCL - VR Virtual Reality Centre for The Built Environment 01 May 1997, Value (£): 952,697 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=GR/L54950/01
5	Imperial College London - VR A Virtual Reality Centre for The Built Environment 01 January 1998, Value (£): 179,408 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=GR/L54943/01
6	UCL - VR Industrial Doctorate Centre: Virtual Environments, Imaging and Visualisation 01 October 2009, Value (£): 5,649,576 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/G037159/1
7	University of Bath - VR 6-DoF VR Video: Towards Immersive 360-degree VR Video with Motion Parallax 25 June 2018, Value (£): 555,408 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S001050/1
8	University of Surrey - VR Functional Models: Building Realistic Models for Virtual Reality and Animation 15 June 1998, Value (£): 197,307 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=GR/L89518/01
9	University of Bristol - VR Virtual Realities - Immersive Documentary Encounters 01 July 2017, Value (£): 1,051,606 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P025595/1

11	University of Cambridge - VR Design the Future 2: CrowdDesignVR 01 January 2018, Value (£): 560,504 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R004471/1
12	Queen Mary University of London - VR MAN^3: human-inspired robotic Manipulation for advanced Manufacturing 01 October 2018, Value (£): 310,597 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S00453X/1
13	Loughborough University, VR/MR 'Thinking Inside the Box': A Mixed Reality Development Platform for co-creating energy efficient retail spaces Loughborough University, Civil and Building Engineering 01 September 2017, Value (£): 197,902 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P033911/1
14	UCL - VR A hub for device personalisation in the treatment of congenital diseases 01 April 2016, Value (£): 1,002,828 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N02124X/1
15	University of Bristol - VR Bioinspired vision processing for autonomous terrestrial locomotion 24 August 2012, Value (£): 548,721 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/J012025/1
16	Heriot-Watt University - VR Disability Inclusive Science Careers 01 September 2018, Value (£): 494,404 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S012117/1
17	University of Reading - VR Testing view-based and 3D models of human navigation and spatial perception 01 February 2013, Value (£): 419,878 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/K011766/1
18	UCL - VR INSTINCTINSTINCT - INtuitive Soft, stiffness-controllable hapTic INterfaCe for soft Tissue palpation during robot-assisted minimally invasive surgery 01 December 2018, Value (£): 357,167 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S014039/1
19	Newcastle University - VR MOTION CAPTURE DATA SERVICES FOR MULTIPLE USER CATEGORIES 01 November 2006, Value (£): 40,506 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/E005624/1
20	Aston University - VR ROSSINI: Reconstructing 3D structure from single images: a perceptual reconstruction approach 01 January 2019, Value (£): 409,881 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S016260/1
21	University of Exeter - VR VSimulators: Human factors simulation for motion and serviceability in the built environment

	01 May 2017, Value (£): 3,246,099 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P020690/1
22	University of East Anglia - VR Dynamically Accurate Avatars 29 June 2018, Value (£): 557,531 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S001816/1
23	University of Leeds - VR Multi-Disciplinary Pedestrian-in-the-Loop Simulator 01 November 2017, Value (£): 653,011 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/R008833/1
24	UCL - VR Industrial Doctorate Centre: Virtual Environments, Imaging and Visualisation 01 October 2009, Value (£): 5,649,576 https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/G037159/1

Table B2-4. Example of research projects.

Example of Research Projects
Loughborough University Advanced VR Research Centre http://www.lboro.ac.uk/research/avrrc/ 1. Virtual Engineering 2. funded by Innovative UK and Airbus 3. Advanced Collaborative Environments for Distributed Systems Engineering Teams 4. Designing for Adaptability and evolution in System of systems Engineering DANSE 5. Sustaining Complex Systems' Reliability 6. Industry 4.0 Related Projects: • The following is only a sample of the projects that will be made available in due course: • ENVISAGE – Enhanced Visual Analytics Insights for Systems and Big Data Engineering • Novel techniques to provide force feedback in a 3D immersive environment • Analysis of the user acceptance of a novel transportation concept through use of a digital twin and its immersive environment • Multi-sensory fusion for autonomous vehicles • Evaluation into the effectiveness of using AR Technologies to aid Service Technicians • Human - machine intervention for future autonomous vehicles • Utility of augmented reality within an engineering context
Glasgow University Centre for the Study of Perceptual Experience The Philosophy of Virtual and Augmented Reality https://www.gla.ac.uk/research/az/cspe/projects/vrar/ • Philosophy of Virtual and Augmented Reality, 2017 - 2022 • Virtual Reality and Teaching, 2017-2021
Manchester Metropolitan University

Creative AR & VR Hub https://www2.mmu.ac.uk/creativear/ Projects: • Virtual Reality & Simulation in Healthcare • VR Health • Actiphons AR • WOW AR • Smart City AR & VR with Shanghai • The Box Project Mixed Reality • Bird Hive Lake District VR • Geevor Tin Mine Museum AR & VR • Manchester Jewish Museum AR • Manchester Smart Tourism AR VR • Manchester Art Gallery Google Glass • MOSI VR • Dublin AR • Moot Court VR
De Montford University Interactive and Media Technology Virtual and Augmented Reality http://www.dmu.ac.uk/research/research-faculties-and-institutes/technology/interactive-media-technologies/research-areas/virtual-and-augmented-reality.aspx • Heritage Augmented Reality Investigation (HARI) • Virtual Romans • Sensory Articulation Speech System (SASSY) • Virtual Reality Interactive Environments for the Blind
King's College London • Using Virtual Reality to improve the understanding of the mechanisms, which play a role in the onset and maintenance of psychosis • VR assisted assessment and VR assisted therapy for psychosis • Using VR to study the effect of Cognitive Bias Modification for Paranoia • VR to explore the efficacy of new medical compounds: Cannabinoid studies • Eating disorders • Neuropsychology
University of Salford Manchester Current: • EU fp7 CROSSDRIVE – Giving scientists, mission planners and engineers the impression of beaming onto the surface of Mars from their respective countries, to plan Rover exploration. • VR Mental Health – Three PhD studentships are sponsored to investigate the use of Virtual Reality in Mental Health. Their respective areas of study are neuroscience of exposure therapy; prosthetic acceptance; and dementia. Previous:

• EPSRC Eye catching – Supporting communicational eye gaze between people in different physical locations who move around together within a simulation. • EU fp AVATARS – Emotional modelling in virtual humans. • EU fp Platform for Network Games – Massive multiplayer gaming • EU i3net Cohabited Mixed Reality Information Spaces – A parrot on your shoulder points out people to intercept or avoid as you walk through a crowd and make appointments for you with people you have yet to meet. • EPSRC HIVE Huge Interactive Virtual Environments – How can audience participation scale up in richness and number?
Queen's Belfast University http://www.qub.ac.uk/research-centres/PerceptionActionResearchLab/Projects/ • TEMPUS_G • Perception/Action in Sport • Movement Based Games • Participate in Our Research
Knowledge Transfer Network KTN & Knowledge Transfer Partnerships funded by Innovate UK https://ktn-uk.co.uk/search?term=virtual+reality http://ktp.innovateuk.org/ Virtual Reality Current KTP Projects: https://info.ktponline.org.uk/action/search/current_res.aspx?srchtype=ext&tech=-1&sic=-1&kbp=-1&progno=-1&keywords=Virtual+Reality&dept=-1&spon=-1&grsize=-1&loc=XX&cobus=+&sector=-1 Virtual Reality Completed KTP Projects: https://info.ktponline.org.uk/action/search/complete_res.aspx?srchtype=ext&tech=-1&sic=-1&kbp=-1&progno=-1&keywords=Virtual+Reality&dept=-1&spon=-1&grsize=-1&loc=XX Augmented Reality current KTP Projects: https://info.ktponline.org.uk/action/search/current_res.aspx?srchtype=ext&tech=-1&sic=-1&kbp=-1&progno=-1&keywords=+Augmented+Reality&dept=-1&spon=-1&grsize=-1&loc=XX&cobus=+&sector=1 Augmented Reality Completed KTP Projects: https://info.ktponline.org.uk/action/search/complete_res.aspx?srchtype=ext&tech=-1&sic=-1&kbp=-1&progno=-1&keywords=+Augmented+Reality&dept=-1&spon=-1&grsize=-1&loc=XX

Table B2-5. List of Immersive Experiences Award Holders.

UK Research and Innovation Immersive Experiences Award Holders, Date: 16/01/2018 https://ahrc.ukri.org/newsevents/news/ahrc-to-fund-32-projects-that-will-lead-the-way-for-future-immersive-experiences/immersive-experiences-award-holders/?previewid=670D536C-CA13-4373-97CED6F5506284FE	
	The Augmented Telegrapher: Multi-player Mixed Reality in a Museum context Falmouth University, Principal Investigator: Tanya Krzywinska http://gtr.rcuk.ac.uk/projects?ref=AH%2FR009406%2F1
	Space, Place, Sound, and Memory: Immersive Experiences of the Past University of Edinburgh, Principal Investigator: James Cook

	http://gtr.rcuk.ac.uk/projects?ref=AH%2FR009228%2F1
	Design Standards for Place-Based Immersive Experiences Glasgow School of Art, Principal Investigator: Steve Love http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010196%2F1
	XR: CIIRKES / Extraordinary Circus: Creative Immersive Interdisciplinary Knowledge Exchanges University of Brighton, Principal Investigator: Helen Kennedy http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010234%2F1
	Metamorphosis: Audiencing Atmospheres: Transforming Perceptions of Place in a Gesture-Driven Ambisonic Environment. Queen Mary University of London, Principal Investigator: Martin Welton http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010390%2F1
	Immersive Pipeline: Production pipelines and translators for the authoring, sharing, and touring of immersive media performance works Goldsmiths College, Principal Investigator: Atau Tanaka http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010145%2F1
	Memoryscapes: re-imagining place through immersive and participatory experiences that re-contextualise memory assets Northumbria University, Principal Investigator: Jon Swords http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010137%2F1
	Within the walls of York Gaol: Memory, Place and the Immersive Museum University of York, Principal Investigator: Gareth Beale http://gtr.rcuk.ac.uk/projects?ref=AH%2FR008701%2F1
	ENSEMBLE Performing Together Apart: Enhancing Immersive Multi-Location Co- Performance in Real Time Edinburgh Napier University, Principal Investigator: Paul Ferguson http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010080%2F1
	User Not Found: Social Media Technologies as Immersive Performance University of Reading, Principal Investigator: Lib Taylor http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010293%2F1
	Augmented Browsing of Books in Historic Libraries University of the Arts London, Principal Investigator: Nicholas Pickwoad Experiencing the Lost and Invisible: AR Visualisation of the Past at Bryn Celli Ddu, Anglesey Manchester Metropolitan, Principal Investigator: Benjamin Edwards Objects of Immersion Lancaster University, Principal Investigator: Paul Coulton http://gtr.rcuk.ac.uk/projects?ref=AH%2FR008728%2F1
	Digital Engagement for Heritage-led Urban Regeneration

	University of Sheffield, Principal Investigator: Dawn Hadley http://gtr.rcuk.ac.uk/projects?ref=AH%2FR009392%2F1
	The Challenge of the Xingu: indigenous cultures in the museum of the future. Queen Mary University of London, Principal Investigator: Paul Heritage http://gtr.rcuk.ac.uk/projects?ref=AH%2FR010366%2F1
	BIM4SME Awards – Best use of Virtual Reality in Construction The McAvoy Group http://www.mcavoygroup.com/mcavoy-wins-major-industry-award-bim/ http://www.mcavoygroup.com/mcavoy-uses-award-winning-bim-technology-complex-offsite-school-building-project-surrey-county-council/ http://www.bim4smeawards.com/

Appendix C1: Summary tables of limitations

Table C1-1. Technical limitations for specific use-cases

Use-case	Technical
Customer/Public Engagement	• Need for hardware support. • Accuracy issues (x2). • Isolation, plus, challenge of engaging multi users at the same time. • It could cause eye problems. • Corporate limitations on software install. • Quality of the image could be low. • People think it is immature technology. • Requirement for power, machine and laptops. • No comfortable devices (user wellness). • Narrow Field of View (FOV). • AR does not look well for large sites, where the model has to be broken down into smaller.
Design Review	• Battery life is short. • Instant pose estimation in adverse condition. • Model/ digital twin. • WIFI bandwidth. • AR/ AR is not exact depictions of reality. • Accessing data beyond objects (meta- data). • Incomplete data, Validation and verification, "false position ". • Lack of standards. • Low Field of View (FOV). • GPS accuracy issues. • IT policies. • Limitations for the use in size. • It does not work while wearing gloves. (in site during cold weather) • The user needs a chaperone to be safe when use it. • The interconnections between different domains • Data limitations -The outcome is only as good as the input • Issues of interoperability
Construction support	• Battery life limitation (x2). • WIFI bandwidth limitations. • Mismatch between delivery and operation planning. • Difficulty of archiving AR outputs in information management systems. • Accuracy and speed of updating information. • Low accurate tracking and mapping (AR). • Incomplete data, Validation and verification, "false position ". • Lack of Standardization/ regulation. • Data exchange difficulties (different platforms). • Network latency.

Operations and Maintenance Support	• Mismatch between delivery and operation planning. • Accuracy and speed of updating information. • Format challenges (data exchange) or interoperability • Lack of standards • Limited internet access • Physical space limitations range • Batter life • Limited FOV (x2). • Overcoming old ways and old testing methods. • Skills and facilities shortage • System integration between CAFM systems and document management systems
Training	• Lack of experts who can produce the content. (x3) • Facility shortage. • Need of mastery of multiple platforms. • No GPS signals on site. • Requirement for power, machine and laptops • Lack of common platform/ connectivity • Technology change-risk of obsolete of technology

Table C1-2. Social limitations for specific use-cases

Use-case	Social
Customer/Public Engagement	• Lack of understanding of the transformative power of those technologies • Acceptance realism in rendering. • Cyber risk hacking (x3). • Perception of generational relevance. • Lack of trust. • Physiological motions sickness. • Public perception and changing mind-set of people (x2). • IP issues. • Hard interactions between industries. • Lack of useful applications.
Design Review	• Embedder culture e.g.: drawings. • Job security.
Construction support	• Lack of risk assessment with VR/AR clauses. • Job security.
Operations and Maintenance Support	• The need for space and mobility • IP issues. • Return on investment-issue of opportunity • Justifying the cost of some aspects of high value of new maintenance activities

Training	• Lack of trained workforce. • Social interaction resilience.

Table C1-3. Economic limitations for specific use-cases

Use-case	Economic
Customers/ Public Engagement	• Not everyone can afford team or has access to this technology. • Cost limitations/ who will pay? • Hard to define the ROI. • High initial investment. • Expensive hardware. • Unclear commercial benefits for owners. • Low R&D budget. • Risky technology • It could be a challenge to SMEs. • Lack of business cases/ applications. • Cost of hardware setup and updating of equipment
Design Review	• High spec, expensive technology. • Value/ benefit satisfaction.
Progress Monitoring	• Integration with other systems (facility management systems) such as: CAFM and BMS systems used by O&M. • Time of implementation.
Operations and Maintenance Support	• No. of devices needed is a challenge (higher cost) • Cost of maintenance.
Training	• Lack of experts who can produce the content. • Need for government commitment for large scale implementation at schools. • Cost of training

Appendix D1: Capabilities to develop

Table D1-1. Technical capabilities to develop

Use-case	Technical
Customer/Public Engagement	• Marketing tool -To win projects/clients-attract new investors • Multi-user experiences with multi viewports can facilitate public engagement • AR can allow visibility of the effect of new construction to the existing built environment • In terms of neighbourhood level- decreasing negativity of new builds, Vision of what will be built, visibility of renewable technology and infrastructure. • Aesthetics uses, benefits of realising the conceptual design, respecting neighbourhood in design • Reducing traffic and conjunction by VR Simulation, crowd control across various layouts • Environmental considerations and simulation. • How a rescue team can access a site when they might not be stationary in the area. Such cases can be dealt with virtually to be fully immersed in various situations/scenarios to help with disaster management. • Application to tourism and public service • Client side of understanding – key focused communication – getting data/information in a context that people can understand. • Opportunities for immersive technologies to be used in public consultations by bringing simulation in design and have VR/AR as part of the deliverables of any project. • Help the end user to understand the social impact of new buildings • Citizens involvement in delivery and public engagement for constructed assets-Informing citizens of changes to existing assets • Applications for design to client to measure their emotional level of satisfaction • Analyse people's judgements • Managing expectations yet achieving customer satisfaction
Design Review	• Ability to view models in VR and review/update/edit them in the authoring tool simultaneously • Accessing different layers of multidisciplinary models at the same time • Validation and verification can be accurate if data was correct and up to date • VR/AR can help to review to validate design buildability and run clash detection before starting on site • CDM Requires designers to design out risk and AR/VR can help to do that in early stages. • It helps to provide subjective and objective assessment of space and how people feel about the design in this space by being present virtually in it. • Design, Development of buildings, clash detection is really usable in today's design and can the design satisfy the requirements/meet the requirements. • Disability/accessibility design measures usually tend to be done according to standards or measurements that might not reflect real life experiences, virtual reality can help designers understand the space from a different accessibility perspective of disabled users and the human factor can be taken into consideration. The ability to manoeuvre is different from a normal person and they might actually have more tolerance that what designers give in a design, simulation of wheelchair users' case studies, visually impaired and blind users as well. Understanding area, space, bends and any other potential obstacles in spaces.

	• Uses in interior design Review where you can place objects into reality using AR and there is the ability to scale furniture and other items and evaluate the space in a better way. • Gaming technology can help get models into a gaming environment. Two-way views between users can allow clash detection and clash prevention. • AR/VR can be incentivized via alternative approaches-can be hosted online with smaller buildings.
Construction support	• VR/AR can help to review the construction sequence • 4D programming can add value to the project, full 4D sequencing showing the phases of project buildability. • Difference between the virtual model that was developed in office and the projection of the model onsite can be detected onsite by checking dimensional errors by utilising AR • Size of site can affect progress monitoring- VR is useful for bigger sites because users can go inside the model and teleport around multiple location whereas in AR users will need a big area to project the model onsite, it might be more useful for smaller spaces and smaller sites • Cost estimation and some level of information can be given through AR/VR • Demonstrating Productivity – demonstrating benefits • Capturing and overlaying digital information in the real world-multi-layered information • Viewing tool for special structures
Operations and Maintenance Support	• Navigation systems -Way finder in a building • Warning system when getting into a dangerous area • Accurate tracking • Object recognition of assets • Operators facial recognition-Colleague finder • Visualising non-visual data- flat data like dashboards, data can be visualised in 3D and different dimensions-benefits can be gained from virtualizing data • AR is more useful in projecting objects i.e. assets for example in MEP boiler room equipment's can be checked virtually • Detecting Services that might be running alongside each other by reviewing virtual MEP models. • Looking at the metrics of models • Identifying parts/ manufacturing components • Site risk factors- AR Requires the user to be physically present on site so for risky or hazardous sites using VR will be the preferred option in Operation and Maintenance applications. • Clients/Owners will keep better records of assets. Using AR/VR will provide a better way of solving maintenance issues • Archived models and new models can be overplayed after few years to detect any changes • AR/VR can help in understanding cross-dispensary interaction. • Reduce a number of claims that result from wrong O&M procedures. Reduce dispute
Training	• Training, using VR, an excellent tool for site induction by putting them in an immersive environment and teaching them before getting to site so it's a big opportunity to educate people. • VR Training is better than traditional way for site induction, people understand visuals and images better than words, and by putting them in an immersive environment that they can scan visually they will be able to remember more of it.

	• Other benefits of VR Training are that it can be recorded, projected and revisited at any time. • Using AR as a tutor and as an assistant. • Adding immersive technologies in education modules at university level and various levels of education. • Situated Simulations.

Table D1-2. Social capabilities to develop

Use-case	Social
Customer/Public Engagement	• Multi-User experiences can allow multiple stakeholder to collaborate in virtual environment to view the project progress • Ability to see projects virtually before they are built on-site • Allowing the public to see the design in context • Ability to project Augmented Reality Virtual models on the real environment to see project upgrades and changes to existing buildings for extensions and refurbishment. • Agile tool sets can be developed to allow changing design while the client is viewing it
Design Review	• AR Models can be a substitute to physical architectural models • VR can allow an immersive experience for clients to review the design themselves
Construction support	• VR Software currently available and can handle project progress monitoring and 4D BIM Sequencing • Building Site Safety
Operations and Maintenance Support	• AR Can allow visibility of hidden and underlying building services via virtual models • A digital twin can be accessed virtually to operate buildings • Virtual assistant can be used in conjunction with AR/VR
Training	• Training in AR/VR is a big opportunity that needs to be explored by training providers as the industry/market needs it • Engaging with education, developing people's skills, public consultations and bringing simulation in design and have VR/AR as part of the deliverables of any project. • Organizations can apply for innovate UK Knowledge transfer partnerships to benefit from training and access to skilled workforce

Appendix E1: List of AR&VR hardware and software

Table D1-1. List of Virtual Reality and Augmented Reality Hardware and Software

Virtual Reality Hardware	**Virtual Reality Software**
Acer WMR headset Alcatel Vision Asus HC102 Deepoon VR E3 Dell Visor Fove 0 Google Cardboard Google Daydream Helmet vision HP WMR headset HTC Vive – Vive Focus- Daydream Lenovo Explore Merge VR/AR goggles Oculus Rift - Oculus Go- Oculus Quest Pico VR Goblin Pimax 4K Razer OSVR-Open source Virtual Reality Samsung Gear VR Samsung Odyssey Sony PlayStation VR Solius VRgineers VRHero 5K Virtual Domes VR CAVE Woxter Neo VR100	Console Daydream Hardware Own Platform Oculus Mobile PC Based devices Steam VR Unity - Gear VR Windows MR **VR Rendering Applications that link with BIM Authoring tools-Some known as Instant renders or One-Click Renders:** Autodesk 360 Panoramas Autodesk Live BRIOVR Enscape EyeCAD VR Fuzor InstaVR IrisVR Kubity Lumion Panoramas Twinmotion Virtalis Visionary Render VR Corona Renderer
Augmented Reality Hardware	**Augmented Reality Software**
Atheer AiR Glasses DAQRI Smart Glasses Installations- AR-Kiosk Meta2 Microsoft Hololens Smartphones and Tablets The Daqri Smart Helmet Trimble Mixed Reality Hololens Data Goggles Google Glass Enterprise Monitorless Snap Spectacles Vuzix M 300	Amazon Sumerian AR Studio ArcBuilder Augmania Augment Augmnetecture AugmentedPro HoloBuilder HP Reveal Infinity AR Layer SDK Trimble Connect for HoloLens Zap works
*This list is not exhaustive but gives an indication of the range of available applications.	