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Exploring the Dynamics of User Uptake of Augmented Reality in Engineering and Construction Projects

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Abstract

With advances in digital technology, augmented reality (AR) can play a substantial role in project development and sustainable growth in engineering and construction. Utilising AR technology with digital overlays offers a three-dimensional (3D) setting that combines real and virtual environments in real time. This immersive capability enables an improved spatial understanding and real-time data benefits for construction and engineering projects. Researchers have conducted extensive research on user acceptance of technology. There is, however, a lack of qualitative research that provides a more comprehensive view of the factors driving user acceptance of AR technology in engineering and construction projects. This research provides insight into the dynamics of user acceptance in engineering and construction projects through grounded theory in a real-world context. This research collected data through open-ended survey questionnaires and interviews. The obtained data were analysed using an iterative approach based on grounded theory principles in this study. A total of 248 open codes, 49 axial codes and 18 selective codes were generated. This process provided a causal loop diagram identifying the relationships of the user acceptance of AR technology adoption in engineering and construction.

Keywords: augmented reality; project management; engineering; construction; causal loop; relationships; grounded theory

1. Introduction

The engineering and construction industry is experiencing a clear shift towards digital transformation, and it is evident that augmented reality (AR) is becoming a favoured technology for success [1]. It is recognised that digital transformation makes precise information readily available to managers and all stakeholders in real time [2]. The engineering and construction industry is increasingly adopting digital interfaces, which are proving beneficial. It is evident that AR technology is underutilised due to several factors, but with the right approach, it has the potential to revolutionise various industries [1,3–6].

The aim of this research is to explore the research question and examine user dynamics in the acceptance of AR technology within the engineering and construction sector. The aim is to develop a theory and a theoretical framework on the user acceptance of AR technology. To ensure a comprehensive framework, this research utilises grounded theory, along with the DeLone and McLean information system (IS) model approach [7,8]. This research uses a qualitative approach to identify the factors of user acceptance and integrates them into

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a framework. This research can enhance academic knowledge and offer practitioners an insightful understanding of digital transformation and how to integrate this transformation into current workflows.

Therefore, in addressing the research question: What are the dynamics of user acceptance of AR technology in construction and engineering projects? By exploring the dynamics of user acceptance in engineering and construction projects, the research utilises a qualitative approach that has not yet been recognised in these fields. Unlike previous research on user acceptance of AR technology, which has mainly examined AR use in controlled study environments, more research is needed in real-world working environments. Thus, identifying factors and understanding the dynamics of user acceptance in engineering and construction projects will ultimately benefit all project practitioners and companies in achieving positive project outcomes.

Although previous research has explored user acceptance of AR technology, it has mainly relied on technology acceptance models in controlled environments. While this offers valuable insights, it provides a limited understanding of the individual factors that influence AR technology acceptance in complex real-world environments. This study provides an interconnected technological perspective on engineering and construction projects and highlights organisational, process, and stakeholder impacts that are not represented in previous studies. This study identifies this gap using a qualitative grounded theory approach, focusing on factors influencing AR technology acceptance and exploring the interconnected relationships by extracting real-world experiences from professionals in construction, engineering, and software technology. Therefore, this study has evolved from simply identifying AR user acceptance in isolated, controlled environments to establishing a comprehensive, interconnected, relationship-driven study in real-world scenarios, highlighting how relational factors shape users' acceptance of AR technology use.

Based on this research in the engineering and construction field, practitioners can utilise technological resources to support a project and achieve positive results. Alizadehsalehi and Yitmen [9] state that technological advances are not sufficiently utilised in companies and that they have a positive impact on real-time automated processes. In addition, incorporating AR into new product development leads to sustainable growth in business [10]. Therefore, the findings suggest that there is a gap in the research. This includes a lack of knowledge gained from real-world environments, not just in a classroom setting [11,12]. Additionally, AR technology has advanced significantly and provides many benefits in the construction industry [13]; however, it must be recognised that technology maturity and organisational integration need to be differentiated from each other. It can be noted that a clear framework and a complete system to fully integrate AR remain underdeveloped, and further research on integrating AR technology effectively is required [11,14,15]. This highlights the limited number of studies that outline how organisations can effectively use AR technology, including a clear outlook on benefits and limitations [15].

There are common misconceptions about the terminology associated with AR technology, and individuals often confuse AR with other forms of technology, such as Virtual Reality (VR) and Mixed Reality (MR) [16]. Understanding the distinctions between these technologies is crucial for differentiating them. In this study, AR technology remains the primary focus for integrating digital technology. Participants frequently referred to this technology interchangeably with terms such as AR, VR, and MR. In addition, participants also described their experiences using terminology such as immersive technology and virtual environments. Milgram and Kishino's reality–virtuality (RV) continuum describes a spectrum in which the real environment lies at one end and the virtual environment lies at the opposite end, with augmented reality (AR) and augmented virtuality (AV) positioned between them and moving towards each other within the mixed-reality region. Blending

these environments is described as MR [17]. Therefore, this research can advance academic knowledge and offer practical benefits by identifying user acceptance of AR technology in the engineering and construction field.

This research highlights a gap in existing knowledge concerning AR technology in the engineering and construction sectors. This research suggests that engineering and construction projects are reliant on the acceptance of technology [10]. In addition, AR environments improve and support performance in project management, and there are difficulties associated with technology acceptance [18]. There are also limited advancements in the engineering and construction sector due to the inability to embrace digitalisation [19]. Therefore, further research can benefit these types of projects through AR technology acceptance in these fields.

The potential benefits of investigating the dynamics of user acceptance in engineering projects include improving project performance and supporting practitioners in achieving desired, constructive outcomes. Ultimately, this helps practitioners adopt new technologies and develop their project management skills, enabling organisations to deliver projects satisfactorily. This will benefit not only the engineering and construction fields but also ultimately all project types through the adoption of new technology.

In addition, this work could make more engineering projects feasible to complete in Australia, as the main concern is that most design and engineering projects are outsourced overseas due to cost. For instance, manufacturing has predominantly been outsourced from Australia. By utilising AR technology and designing engineering prototypes in Australia, followed by outsourcing manufacturing overseas, this would enable economic growth. By utilising AR technology, the project design phase can be facilitated and executed within Australia.

2. Related Works

Exploring the user acceptance and adoption of AR technology in engineering and construction projects is vital for digital transformation. AR technology is increasingly used to support immersive digital transformation, providing real-time data to all stakeholders and managers and thereby promoting a digital shift that enhances project efficiency and drives digital innovation within the workforce [2]. In addition, this can revolutionise digital communication and stakeholder collaboration [20]. Therefore, exploring digital transformation and the use of AR technology in the engineering and construction sectors is becoming increasingly common, guiding us into a new era in which AR technology evolves and helps drive success [1].

The rapid adoption of AR technology is becoming vital for the engineering and construction sectors, and with the right approach, it can be beneficial; however, it remains underutilised [1,3–6].

Upon reviewing the literature and identifying the gap, it has been found that there is a lack of real-world validation of AR technology. There are also technical limitations and immaturity in the development of a standardised system for AR integration. Additionally, there are training and skill gaps and a lack of a comprehensive framework for integrating AR technology, highlighting the need for further research.

It is noted that there is limited research on AR systems tested in real-world projects, and a lack of knowledge and understanding of AR technology in these projects [12]. It is further noted that an established methodology for AR technology has not yet been integrated into large real-world environments [11]. Additionally, AR technology in the construction sector has not been fully embraced [19]. Furthermore, research on real-world scenarios is required to refine practical and environmental factors [21].

The literature review on the use of AR technology in engineering and construction projects included 56 studies, as outlined in Table 1. The literature review included studies

on AR technology adoption and the implementation of digital innovation in engineering and construction projects. The literature review focused on the benefits and challenges of integrating immersive technology in these sectors. The literature review covered the engineering, construction, and AEC sectors.

Table 1. Literature review.

#	Reference	Year	Sector	Factors Driving AR Use	Outcome
1	[10]	2019	Engineering	Technology interventions within new product identification	System use and user acceptance
2	[22]	2007	Engineering	Interaction and processes	System use
3	[23]	2011	Engineering	Perceived usefulness and ease of use	System use
4	[24]	2020	Engineering	User interaction and robot motion	User acceptance
5	[25]	2017	Engineering	Perspective technique and user effort	User acceptance
6	[26]	2025	Engineering	Digital transformation and improved operational processing and safety	User acceptance and efficiency
7	[27]	2025	Engineering	AR use and real-time data to reduce errors	User acceptance and satisfaction
8	[28]	2025	Engineering	Smart manufacturing	System use in manufacturing
9	[29]	2025	Engineering	Immersive environment and visual communication	Immersive AR use and learning
10	[30]	2025	Engineering	User friendly AR technology system and real time feedback loop	Improved performance and usability
11	[31]	2021	Engineering	Real time solutions and digital technology growth	Immersive experience
12	[32]	2024	Engineering	Immersive learning environment	AR Technology use in learning environment
13	[33]	2022	Engineering	AR technology and AI use with real-time data	AR integration
14	[34]	2011	Engineering	Real-time data in maintenance and complex systems	AR integration
15	[35]	2018	Engineering	Real-time data and improved decision making	AR integration
16	[36]	2020	Engineering	Real-time data with enhanced accuracy and efficiency	System use
17	[37]	2018	Engineering	Immersive and engaging environment	Improved learning and engagement
18	[38]	2019	Engineering	Real-time data and reduced errors	System use
19	[39]	2017	Engineering	Real-time data with collaboration and problem solving	System use
20	[40]	2018	Engineering	Real-time data and efficient training	System use and AR user satisfaction
21	[16]	2024	AEC	Rapid growth in AR technology and a lack of framework	User acceptance
22	[13]	2025	AEC	Real-time data and visual communication. Complexity in construction projects	User acceptance and ease of use

Table 1. *Cont.*

#	Reference	Year	Sector	Factors Driving AR Use	Outcome
23	[15]	2020	AEC	Enhanced collaboration and communication	User acceptance
24	[41]	2020	AEC	Real-time data and visual communication	System use with improved accuracy and communication
25	[42]	2020	AEC	Real-time collaboration and need for immersive environment	System use
26	[43]	2022	AEC	Real-time data and decision making.	AR integration
27	[44]	2019	AEC	Real-time data	AR integration
28	[45]	2018	AEC	Complexity in construction projects and limitations in two-dimensional (2D) drawings	AR integration
29	[46]	2018	AEC	Real-time data with accuracy and efficiency	AR integration with improved accuracy, visualisation and reduced time
30	[47]	2019	AEC	Immersive communication with time and cost variables	Device limitations with weight and time. Lack of AR training
31	[48]	2018	AEC	Real-time data with sustainable practices	AR integration
32	[49]	2018	AEC	Real-time data and communications. Two-dimensional drawing ambiguity	AR integration
33	[50]	2019	AEC	Digital technology advancements, sustainability and communication	AR integration with real-time data and improved decision making
34	[51]	2019	AEC	AR learning ability and skill base	User acceptance
35	[52]	2025	AEC	AR integration and cost management	AR integration with improved decision making
36	[53]	2019	AEC	Challenges in 2D drawings and real-time data	AR integration and improved performance and accuracy
37	[12]	2019	Construction	Enhanced design making and defect inspection. Inadequate training for future professionals	Limited research involving industries
38	[9]	2019	Construction	Perceived usefulness and ease of use	System use
39	[18]	2018	Construction	Digital technology integration with perceived usefulness and ease of use	User acceptance
40	[54]	2025	Construction	Real-time data solutions, and defect reduction	User acceptance and performance improvements
41	[55]	2025	Construction	Inefficiencies with manual use of inspections and automation in real time. AI integration	User acceptance and improved efficiencies

Table 1. *Cont.*

#	Reference	Year	Sector	Factors Driving AR Use	Outcome
42	[56]	2025	Construction	Real-time data integration and efficiencies in construction	AR integration and improved communication and decision making
43	[57]	2025	Construction	Visual communication and cost management	AR integration with improved knowledge and cost reduction
44	[58]	2018	Construction	High-risk injury in the construction sector with safety training limitations and real-time monitoring	AR integration and hazard awareness
45	[11]	2020	Construction	Real-time data, design evaluation and sustainability	AR integration and decision making and real-time data
46	[19]	2023	Construction	Digital transformation and complexity in the construction industry	AR integration and real-time data accuracy
47	[14]	2022	Construction	Real-time data and complexity with interpreting 2D drawings	AR integration with immersive communication and improved accuracy
48	[15]	2020	Construction	Need for real-time data and communication	AR integration and improved communication
49	[21]	2021	Construction	Digital transformation, real-time data and complexity with interpreting 2D drawings	AR integration with improved designs and communication
50	[59]	2022	Construction	Increase cyber attacks and digital awareness	Cybersecurity importance and urgent need for standards
51	[60]	2011	Construction	Real-time data and communication with safety awareness	AR integration with improved safety and real-time data
52	[61]	2018	Construction	Real-time data, communication, safety and collaboration with digital technology	AR integration with improved communication, real-time data and decision making
53	[62]	2019	Construction	Real-time data, reduce incidents, safety training and ergonomics	AR integration for safety training, prototyping and hazard awareness
54	[63]	2025	Construction	Safety with reducing workplace incidents with AR technology training	AR integration with hazard awareness
55	[20]	2022	Construction	Immersive training and education	AR integration
56	[64]	2021	Construction	Digital transformation and innovation, real-time data and collaboration	AR integration

It can be noted that the main factors driving AR technology in the construction industry include improved efficiency and safety, followed by project challenges and real-time data, both of which have a significant influence. In addition, factors driving AR technology

in the engineering industry include improved efficiency and safety, followed by AR technology acceptance and AR technology capabilities, which also have a significant influence. Furthermore, factors driving AR technology in the AEC industry include improved efficiency and safety. Additionally, project challenges, communication, and collaboration are also significant influences.

Therefore, the engineering, construction and AEC sectors have all been analysed and compared across all technology and project types, including a comparison of AR and engineering projects. However, it can be noted that there is a lack of qualitative research that provides a comprehensive analysis of the drivers of user acceptance and their dynamics in engineering and construction projects.

The search strategy implemented for this literature review involved the use of Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) to guide the systematic selection of literature related to AR technology in engineering and construction. The PRISMA process began with a comprehensive search across online academic platforms, including Scopus and the Victoria University A–Z databases. When utilising these platforms, predefined keywords such as 'AR technology' combined with one of the following—'construction', 'engineering', 'project management', 'communication', or 'implementation'—were employed to find relevant literature aligned with the research question. During this process, duplicate records were removed, followed by title screening and further review of abstracts to ensure relevance. After screening abstracts, the full texts were examined for eligibility based on the inclusion and exclusion criteria. The included studies were those directly related to AR technology within the architecture, engineering, and construction (AEC), construction, and engineering sectors, published within the last 10 years. Excluded papers included papers irrelevant to AR, MR, and VR technology, papers outside the construction and engineering industries, or papers published outside the 10-year timeframe, unless they were historical or highly informative.

Upon reviewing the literature and research to identify the gap, it has been found that there is:

- A lack of real-world validations for AR technology in the literature;
- Technical limitations and immaturity in the development of a standardised system for AR integration;
- Training and skill gaps;
- A lack of a comprehensive framework for integrating AR technology;
- Perception of AR technology with maturity and cost;
- Inconsistent terminology of AR Technology;
- Limited research on AR systems tested on real-world projects;
- A lack of knowledge and understanding of AR technology in projects [12];
- An established methodology for AR technology has not yet been integrated into large real-world environments [11];
- AR technology in the construction sector has not been fully embraced [19].

The literature indicates that AR technology, along with other immersive technologies, can benefit engineering and construction projects by enhancing communication, efficiency, design, prototyping and 3D modelling. AR technology is commonly used for 3D modelling, real-time data visualisation, visual communication, immersive experiences and interactive workflows.

However, along with these benefits, there are some challenges. The literature outlined that many organisations lacked AR training and processes for implementing new technologies. It is also noted that organisations that incorporate new immersive technologies are more likely to adopt AR when there is a clear benefit. There is also a lack of commercial standardisation for AR technology, as well as concerns about cybersecurity. The literature review outlines that there is a gap when it comes to successfully incorporating AR technology.

3. Methodology

The methods utilised for this research are outlined in Table 2. The data collected for this research consist of primary data obtained through questionnaires, interviews and focus groups. The research method for this study includes an interpretivist, qualitative approach and the incorporation of grounded theory. Table 2 presents the methodological framework used in the study to investigate AR user acceptance.

Table 2. Research method.

Research Method	Type	Analytical Procedure
Research paradigm	Interpretivism	To understand the action, experience and interpretation of the participant [65] with AR technology
Research approach	Qualitative	Used to interpret and analyse the data, therefore identifying any themes that develop [65] from participants' experience through AR technology
Research method	Grounded theory	Grounded theory outlines and proposes the outcome. It also generates a conceptual framework [66] and involves a phenomenon being observed [67].
Data collection	Primary data	Data collected directly from construction, engineering and software professionals who have experience or work with AR technology
Data analysis	Grounded theory	Data was analysed through open, axial and selective coding to form relationships [68,69] from AR technology acceptance

In this research, interviews, focus groups, and questionnaires were used as part of a qualitative approach, supported by a constructionist approach, to answer the research question. Many researchers have explored factors related to the user acceptance of AR technology [70–74]. However, the literature has identified a lack of qualitative research that provides a comprehensive understanding of the drivers of user acceptance of AR technology in engineering and construction projects, as well as their dynamics.

Therefore, the primary objective of this research is to identify the drivers of the user acceptance of technology and the factors that contribute to it. Previous research has failed to incorporate the value of AR technology and the surrounding environment into the project scope to effectively foster technology acceptance. By utilising grounded theory, a theoretical approach to the methodology is used in addition to a systematic methodology involving a combination of theories and data analysis [65,75]. The grounded theory method, through a series of events, can identify a theory based on the analysed data [75].

The theoretical perspective, also known as the research paradigm, is an interpretivist approach to this research. Levers [65] identifies interpretivism as an approach that involves the interpretation and analysis of data. This theoretical perspective identifies the action, experience and interpretation of the participant; therefore, it is defined by understanding the phenomenon by defining the research interpretations and observations in terms of value and theory [65]. With the incorporation of interpretivism, the next question is: Which research approach is best suited to answer the research question?

The purpose of using the interpretivism paradigm is to gather data to provide an interpretive clarification of the theory, thereby revealing social reality from another person's perspective by revealing their interpretation, significance and principles [75]. Therefore, regarding technology and user acceptance, Didehvar et al. [18] identify that project failure due to poor project management and performance can be reduced by encouraging management to adopt technology, thereby increasing project success. Thus, it can be seen that the interpretivist approach can be used for this research in the technology field, as it can

identify different perspectives and the environment in which technology is used, where the influence of management can be observed.

The primary data used for this research and data collection incorporate interviews, focus groups and open-ended survey questionnaires. The data collected includes data from software developers, engineers in leading and management roles, and construction managers and leads. Interviews were one type of qualitative data used in this research, and the interview process followed a semi-structured approach, in which a set number of open-ended questions were asked; however, these questions led to the identification of additional topics. Questionnaires were another type of qualitative method used in this research. This method was utilised because it allowed participants to answer questions via Qualtrics without needing to speak with them. This structured format is quick and easy for participants to use at their convenience.

The interview and questionnaire contained a total of 10 questions for each area of study in engineering and construction. There was a total of 11 questions for software developers. This was set up through Qualtrics, in affiliation with Victoria University. The set of questions has been developed by identifying gaps in the literature review. Using Qualtrics allows participants to complete the questionnaire in their own time. This setup included the consent form and the participant information form, which were provided prior to the questions. These forms were dated and signed by the volunteers, indicating their consent and confirmation of participation in the study, before any data were collected, in accordance with the ethics process.

The design process for the open-ended questionnaires began with completing a draft of the literature review, which was crucial in identifying the current gap in AR technology within the engineering and construction sectors. The literature review identified the following gap: real-world scenarios were predominantly limited to experienced personnel, and most studies were conducted within educational settings or controlled experimental environments. Recognising this gap highlighted the need for qualitative data and led to the development of open-ended questionnaires designed for digital technology users or developers.

Following the initial drafting of the open-ended questionnaires, development continued until the questionnaires were open and aligned with the grounded theory methodology. The open-ended questionnaire was arranged in a logical sequence, starting with participants' definitions of AR technology, followed by topics related to benefits, challenges, and user acceptance. This structure of the open-ended questionnaires ensured participants gradually settled into the interviews, focus groups, and survey questionnaires, ensuring that the data collected would be suitable for the grounded theory methodology with coding and theory development.

The construction and engineering questions from the research are detailed below:

1. What is your understanding of AR?
2. What are the facilitators and barriers for you to accept and use this technology?
3. I'm primarily interested in finding out what factors drive users to accept and use this technology. What are your thoughts on that?
4. What are the barriers and the possible reasons for your resistance to using this technology, and why?
5. What do you think are the factors that impact your decision to purchase AR technology?
6. Have you noticed that there are different levels of acceptance with AR technology by different users?
7. How have you been trained and educated about the AR system?
8. How do you come up with and communicate your requirements to the technology developer company?
9. How do you evaluate the success and performance of a specific AR product you have used?

10. What are your thoughts on the future of AR in projects?

During the data collection process, the COVID-19 pandemic occurred, which posed significant challenges. During the initial data collection phase, the data collection process was designed for face-to-face interactions that involved the physical use of digital technology. During the pandemic, many participants who initially agreed to be interviewed declined the invitation due to the uncertainty at the time. Because of this, the data collection scope transitioned entirely to online and required a new method for inviting participants, resulting in all interviews being carried out via digital means, as the COVID-19 pandemic highlighted the need for this approach. Using digital means to gather data through interviews is perceived as face-to-face, as one can still interpret body language and verbal cues in participants' responses. All interviews were recorded with the participants' approval, even though the data were anonymous. After all the interviews, notes were also taken and continuously analysed to interpret the interviews.

The study involved a diverse group of participants, including engineering leads, managers, and directors, who were interviewed to gather insights into AR technology in their respective fields. Of the 23 interviews conducted, 5 were with large organisations employing over 1000 individuals, all of which operated in the engineering sector. Furthermore, an additional five participants were associated with the construction industry, representing companies that had more than 500 employees. The study also highlighted that all nine software developers were working at smaller firms, with fewer than 100 employees. In addition to individual interviews, the research included perspectives from two focus groups. This is detailed in Table 3.

Table 3. Organisational data.

#	Title	Reports to	Industry	No. of Employees	Communication
E1	Manager	Manager	Engineering	<1000	Down/Up
E2	Manager	Manager	Engineering	>1000	Down/Up
E3	Engineer lead	Manager	Engineering	>1000	Down/Up
E4	Manager	Manager	Engineering	>1000	Down/Up
E5	Engineer lead	Manager	Engineering	<1000	Down/Up
C6	Manager	Manager	Construction	<100	Down/Up
C7	Director	Director	Construction	<100	Down
C8	Manager	Manager	Construction	<100	Down/Up
C9	Director	Director	Construction	<100	Down
E10	Manager	Manager	Engineering	>1000	Down/Up
E11	Engineer	Manager	Engineering	>1000	Down/Up
S12	Director	Director	Software	<100	Down
S13	Director	Director	Software	<100	Down
S14	Director	Director	Software	<100	Down
C15	Manager	Manager	Construction	>1000	Down/Up
C16	Manager	Manager	Construction	>1000	Down/Up
C17	Manager	Manager	Construction	>1000	Down/Up
S18	Director	Director	Software	<100	Down
S19	Director	Director	Software	<100	Down
S20	Manager	Manager	Software	<100	Down/Up
S21	Director	Director	Software	<100	Down
S22	Director	Director	Software	<100	Down
S23	Director	Director	Software	<100	Down

The collected data indicated that among the 23 participants interviewed, 5 were female and 18 were male. This suggests that the majority of participants are male, highlighting a gender trend in the software, engineering and construction fields. Additionally, the age

distribution includes one participant aged 20–29, while another two were in the 40–49 age group. This shows that participants are aged between 20 and 50 years, with a 30-year age range. Among the participants in the interviews, 20 were in the 30–39 age range, suggesting that this age group constitutes a significant portion of the data. Having a large dataset for this age group implies that individuals aged 30 to 39 are not just participants; they are the driving force behind advancements in software, engineering, and construction. This is detailed in Table 4.

Table 4. Background data.

Total	Age	Male	Female
1	20–29—4%	100%	0%
20	30–39—87%	75%	25%
2	40–50—9%	100%	0%

Utilising grounded theory in this qualitative data collection process enables the theory to develop. Thus, the objective of this research is to outline the user dynamics of technology in engineering and construction projects, with a focus on enhancing project success. To develop sufficient data to support the theory, the original data analysis had to be broadened to include engineering and construction projects, and data needed to be gathered from individuals in various roles across different leadership dynamics, not just project managers.

Given the evolving and complex nature of AR technology in construction and engineering, this study incorporated a qualitative grounded theory approach to enable relationships to emerge from real-world data rather than from controlled settings. This method identified factors affecting AR acceptance and highlighted valuable relationships. Using grounded theory to explore AR user acceptance enables the capture of previously unknown interconnected relationships among technology, stakeholders, and organisational processes.

The grounded theory research process is not always linear; it allows the researcher to stop and start whenever an idea is generated. More often than not, the methodology gives the user more than one direction; Figure 1 depicts the grounded theory methodology approach [65].

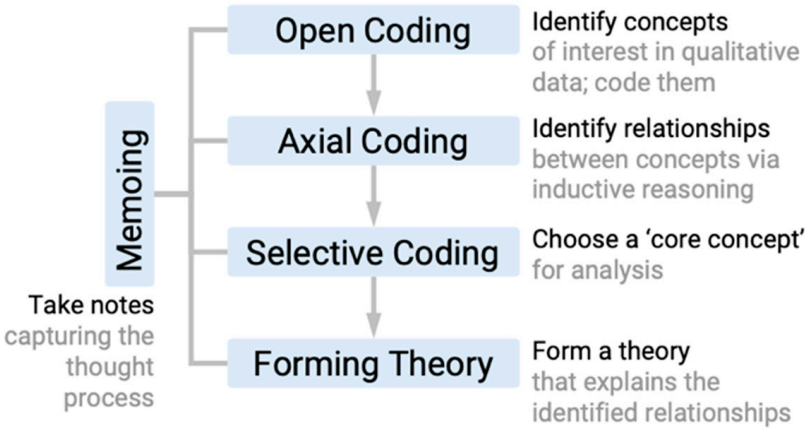


Figure 1. Grounded theory framework [68,69].

The grounded theory process involves several key steps, which are detailed below and outlined in Figure 1:

1. Formulate the research question.
2. Collect data through theoretical sampling.
3. Identify initial codes (open coding).
4. Identify concept codes (open coding).

5. Identify relationships (axial coding).
6. Analyse and compare the identified codes with existing codes.
7. Repeat steps 2–6 (theoretical saturation).
8. Define the core concept (selective coding).
9. Write the theory (forming a theory).

Utilising the grounded theory framework, open coding serves as the initial step in the analysis. In this study, open coding was performed by reviewing the data in NVivo 15 and identifying codes derived from selected keywords and sentence-level understanding. Once this was achieved, the selected words were categorised accordingly. Additionally, memoing was conducted; this was facilitated through Microsoft Excel.

Axial coding occurs during the review of open codes. This process involves forming groups based on common themes, which helps establish relationships. In this study, NVivo software was utilised; however, much of the relationship formation through memoing was conducted using Microsoft Excel. This platform enabled the use of multiple tabs, facilitating the organisation and presentation of all relevant information and allowing for viewing of previous changes and corrections.

While utilising the grounded theory framework, selective coding occurred during the analysis of the relationships. In this study, NVivo software was used to capture coding; however, Microsoft Excel was utilised for memoing to sort through relationships and group them into further core concepts. After every interview and focus group, and after the last survey was conducted, the codes were reevaluated to ensure that the categories and relationships were accurately grouped.

Overall, the coding process involved open, axial, and selective coding. This study was lengthy and meticulous. It required constant data review, with ongoing feedback from the researchers to ensure the correct data was reviewed and accurately interpreted. The data was regularly consolidated to eliminate duplication and to ensure that the original intent and meaning were being expressed. Throughout this process, the codes and categories were consistently reviewed to ensure the findings were grounded in the primary data and that consensus was reached on the codes and relationships established. Any discrepancies in the codes required a re-examination of the entire data set in that area to maintain consistency and ensure accurate representation of the data.

The identified codes formed the relationships, and with the incorporation of grounded theory, the theory that aligned with the data was developed [76]. This approach allowed the theory to grow directly from the data, creating a strong connection between the two [76]. During this research, data were reviewed continuously; this occurred not only after each interview but also periodically to ensure that the codes and relationships were correctly grouped. This research method first developed a taxonomy of relationships, then compiled it into a framework, which allowed the theory to emerge from the analysed data.

4. Analysis and Results

The research consisted of collecting data from 27 open-ended survey responses and conducting 23 interviews, in addition to two focus-group sessions with two participants per session. During the interviews, both structured and semi-structured formats were employed to gather data, resulting in over 200 pages of information. The interviews were conducted over the period from July 2021 to November 2024. This period of data collection encompassed various developments, including the COVID-19 pandemic and the introduction of online platforms, between 2021 and 2022. All interviews were conducted using Zoom, Microsoft Teams and Google Meet.

A total of 65 individuals gave consent to participate in this study, which focused on the engineering and construction group of participants. Of these, 10 agreed to take part in the

software development open-ended survey questionnaire, while 55 agreed to respond to the construction and engineering open-ended survey questionnaire. Within the engineering and construction group, we collected a total of 24 responses to the open-ended survey questionnaire, resulting in 21 pages of data. This dataset offers insights into the engineering and construction field, outlining organisational needs and challenges. The open-ended survey questionnaire administered to software developers yielded 3 responses, totalling 14 pages of data. This is outlined in Table 5.

Table 5. Open-ended survey questionnaire data.

Data Type	Engineering	Software Developers
Consent	55	10
Open-ended survey questionnaire response	24	3
Pages	21	14
Word count	5478	1058

In this study, a total of 23 interviews were conducted, along with two focus groups. This resulted in 237 pages of interview data, accumulating over 75,000 words. The duration of the interviews varied, from 30 min to greater than an hour for one focus group. It is noted that seven interviews were conducted with construction managers, providing perspectives in the construction industry, and seven interviews were held with engineering managers, providing perspectives in the engineering sector. The remaining nine interviews were conducted with software professionals, who shared their experiences and viewpoints as they relate to technology in engineering and construction projects. This diverse range of interviews provided a comprehensive understanding of technological advances and AR in the engineering and construction industry. This is outlined in Table 6.

Table 6. Interview data.

#	Interviewee's Code	Industry	Duration	Pages	Words	Codes
1	E1	Engineering	<1 h	3	826	26
2	E2	Engineering	<1 h	5	1672	26
3	E3	Engineering	<1 h	7	3041	40
4	E4	Engineering	<1 h	4	1391	25
5	E5	Engineering	<1 h	3	737	23
6	C6	Construction	<1 h	6	1153	20
7	C7	Construction	>1 h	7	1657	32
8	C8	Construction	>1 h	7	1657	32
9	C9	Construction	<1 h	5	943	18
10	E10	Engineering	<1 h	9	3319	61
11	E11	Engineering	<1 h	8	3358	30
12	S12	Software	<1 h	11	3569	41
13	S13	Software	<1 h	12	4166	26
14	S14	Software	<1 h	15	5600	46
15	C15	Construction	<1 h	11	5099	64
16	C16	Construction	<1 h	18	4171	49
17	C17	Construction	<1 h	16	5723	61
18	S18	Software	<1 h	10	3551	31
19	S19	Software	>1 h	23	9777	101
20	S20	Software	>1 h	23	9777	101
21	S21	Software	<1 h	6	2586	39
22	S22	Software	<1 h	6	1727	16
23	S23	Software	<1 h	17	5172	48

The analysed data were derived from a grounded theory approach and were gathered from 27 open-ended survey respondents and 23 interview candidates. Data collection was conducted through theoretical sampling, ensuring that the selected participants were relevant to the research question. Initially, these data were broken down into a set of initial codes to identify key concepts and themes within the responses. These initial codes underwent revision and were systematically organised into relevant open codes, facilitating a clearer understanding of the data. Please note that C7 and C8 are from a focus group, as are S19 and S20. When calculating the total data, only one value was used for each focus group.

Once the open codes are established, axial codes are then formed. This phase involved a detailed analysis of the relationships between the identified open codes to identify any connections and patterns within the data. Once axial codes are developed, the process of selective coding is introduced. During selective coding, core concepts are derived from the relationships found among the axial codes. This step led to the development of the theory and framework.

4.1. Open Coding

The open codes derived from the qualitative data analysis totalled 248 codes; please refer to Appendix A. The open coding process employs a thorough, line-by-line analysis to systematically formulate these open codes. Line-by-line analysis not only facilitates the creation but also captures subtle nuances in the study [66].

The methodical open coding process was derived directly from the raw qualitative data. The participants' responses were reviewed line by line and coded according to the expressed meaning. For example, participant E10′s interview response related to cost management: '*And I guess that's a common issue with projects, really your phases of your project. And there's always that scheduling factor, right. And the cost as well, like, you know, implementing a new technology when this one might not cost a lot, it's still a cost that wasn't factored in to begin with.*' This involved extracting raw data, outlining a code, and identifying that multiple codes could be assigned, such as project scheduling in this case. As the open coding progressed, a constant comparison was utilised throughout the study to compare the identified codes with the new raw data. By repeatedly recognising recurring codes and concepts and considering open codes as needed, the process yielded 248 open codes. To provide a clear audit trail of the obtained raw data, NVivo 15 was used to save the data and categorise the open codes; this data was reassessed throughout the study.

Among the collected references, cost management emerged as the most frequently cited code, with 133 references from both interviews and open-ended survey questionnaires conducted during the study. Table 7 outlines the top 50 open codes, illustrating the key themes and patterns identified in the data.

Table 7. Open codes.

#	Name	References in Interviews and Open-Ended Survey Questionnaires	References of Codes
1	Cost management	19	133
2	Training	18	65
3	AR equipment	14	56
4	Productivity (efficiency)	11	55
5	Capabilities	14	49
6	Ease of use	11	47
7	3D virtual environment	11	43
8	AR limitations	14	43
9	Visual display	16	31

Table 7. *Cont.*

#	Name	References in Interviews and Open-Ended Survey Questionnaires	References of Codes
10	Understanding of AR	18	30
11	Augmented graphics	8	29
12	Positive impact	15	29
13	Marketing	5	25
14	AR user case	10	24
15	Time management	8	24
16	User acceptance	10	24
17	Collaboration	12	22
18	Design aspect	7	22
19	Headsets used	9	22
20	Real time	9	21
21	General overview of AR future	16	20
22	Data privacy	6	19
23	New technology-exposure	11	19
24	Interaction	9	17
25	Accuracy	8	16
26	AR benefits	9	16
27	Education	10	16
28	Problem-solving	9	16
29	Software integration	8	16
30	Applications on devices	8	15
31	Modelling	9	15
32	Project needs	5	15
33	Software applications	8	15
34	Stakeholder communication	4	15
35	AR technology advancements	9	14
36	Learning	4	13
37	Project feedback	8	13
38	Project visualisation	9	13
39	Customisation	5	12
40	Prototyping	8	12
41	Construction	5	11
42	Data overlay	7	11
43	Scope management	6	11
44	User expectation	7	11
45	Visual communication	4	11
46	Workflow	3	11
47	Written communication	5	11
48	Artificial intelligence (AI)	6	10
49	Functionality	6	10
50	Health and safety	4	10

4.2. Axial Coding

Through data analysis, the 248 open codes were grouped into 49 axial codes. The grouping of the codes is an essential part of the axial coding process, which incorporates a strategic approach to categorise the initial open codes into subcategories of axial codes [77,78].

The axial codes were developed by grouping the open codes into relationships, which then formed the axial codes. For example, all open codes related to communication were grouped under the category of 'communication management'. This is further detailed in Table 8.

The purpose of axial coding is to itemise and sort large amounts of qualitative data, grouping them into subcategories after open coding [66]. Therefore, axial coding plays

an essential role in integrating the data to determine relationships among categories [77]. Furthermore, a comprehensive outline of the axial codes can be found in Table 9, which provides the 49 axial codes, the number of assigned open codes and the number allocated to the grouped open codes.

Table 8. Axial code grouping—communication management example.

Selective Code	Communication Management	Axial Code Reference
Axial code	Verbal communication	236
	Written communication	246
	Project feedback	156
	Questions and answers (Q&A)	173
	Visual aids-handover	239
	Visual communication	240
	Visual instructions	242
	Stakeholder communication	200
	Stakeholder engagement	201
	Communicating project needs	47

Table 9. Axial codes.

#	Axial Codes	# Grouped Open Codes	Underlying Open Code References
1	Project deliverables	5	185, 186, 150, 224, 31
2	Organisational deliverables	5	144, 244, 141, 159, 182
3	Financial aspects	4	60, 184, 172, 157
4	Legal and contractual	3	58, 133, 179
5	Licensing and subscriptions	6	238, 247, 225, 190, 84, 42
6	Regulatory aspects	6	40, 46, 175, 178, 79, 137
7	Cognitive ergonomics	1	103
8	Safety	5	89, 135, 136, 102, 90
9	Early technology adoption	8	77, 151, 155, 160, 152, 93, 163, 128
10	Project strategic management	5	139, 209, 217, 109, 167
11	Project design	4	68, 69, 70, 71
12	Project development	15	165, 166, 62, 20, 94, 95, 131, 56, 241, 15, 50, 55, 14, 180, 76
13	Project deliverables	5	158, 67, 75, 153, 162
14	Schedule deliverables	4	220, 221, 174, 183
15	AR sectors	10	32, 82, 53, 54, 85, 119, 83, 222, 145, 107
16	Advertising	3	206, 120, 23
17	Environmental and sustainability	3	88, 87, 177
18	Generational factors	2	129, 248
19	Expert skills	5	207, 92, 204, 219, 189
20	AR applications and platforms	9	86, 121, 192, 10, 11, 38, 191, 127, 39
21	AR capabilities	5	194, 196, 197, 41, 112
22	Software analysis	1	27
23	Device compatibility	6	73, 125, 126, 49, 243, 203
24	Integration	4	21, 24, 195, 61
25	Hardware and equipment	10	37, 100, 101, 99, 106, 130, 132, 169, 18, 25
26	Technology user connection	3	212, 214, 215
27	Machine learning integration	3	98, 9, 33
28	Computer-based modelling	5	51, 237, 34, 124, 205
29	Technology automation	2	36, 74
30	3D virtual environments	8	1, 2, 3, 4, 198, 35, 96, 104,
31	Data analytics	3	63, 64, 65
32	Data management	2	66, 115

Table 9. *Cont.*

#	Axial Codes	# Grouped Open Codes	Underlying Open Code References
33	User acceptability	13	6, 134, 228, 230, 231, 232, 233, 78, 245, 81, 154, 105, 193
34	Adaptability of new technology	2	8, 234
35	Augmented reality advantages	5	12, 13, 19, 17, 29
36	Project challenges	4	142, 123, 44, 108
37	Technology challenges	11	216, 218, 118, 211, 210, 16, 22, 26, 229, 227, 5
38	Efficiency	3	168, 176, 146,
39	Project evaluation	4	148, 117, 161, 208
40	Quality control	5	170, 171, 235, 110, 91,
41	Practical solutions	6	138, 140, 59, 213, 164, 143
42	Quality improvement	5	147, 57, 72, 43, 30
43	Performance criteria	2	122, 113
44	Project collaboration	4	48, 181, 52, 45
45	Training environment	6	7, 187, 188, 223, 149, 28
46	Learning environment	4	80, 226, 111, 97
47	Education environment	2	114, 116
48	Communication management	10	236, 246, 156, 173, 239, 240, 242, 200, 201, 47
49	Stakeholder management	2	199, 202

During the axial coding process, the 248 open codes were assigned to 49 axial codes. When one open code could be placed within another axial code, we reviewed the participant's response to determine the applicable axial code based on the context of the participant's primary data. This method was adopted to represent the accurate and dominant meaning while still allowing interrelationships between categories to emerge later in the data analysis.

4.3. Selective Coding

The analysis identified 18 themes derived from a total of 49 axial codes. The identified themes illustrate the findings that contribute to the research question, thereby providing a conceptual framework. Further details are provided later in this chapter.

The selective codes were developed by further analysing the axial codes. The axial codes were grouped into core concepts for the analysis. For example, all axial codes related to 'performance and quality assurance' are grouped together, forming a selective code. This example is detailed in Table 10.

Table 10. Selective coding—performance and quality assurance example.

Selective Code	Performance and Quality Assurance	Axial Code Reference
Axial code	Efficiency	3
	Project evaluation	4
	Quality control	5
	Practical solutions	6
	Quality improvement	5
	Performance criteria	2
	Project collaboration	4

Selective coding, as part of the grounded theory methodology, allows data to be integrated and brought together [77]. With the initial phase of open coding, the data are analysed, and codes are formed. Once the open codes have been correctly categorised and axial coding subcategorised, central themes can be outlined in the selective coding process [66]. Selective coding is examined in the final stage of the analysis, during which

central themes emerge. This enables the refinement of findings to accurately reflect the concepts presented in the data. The selective codes are outlined in Table 11.

Table 11. Selective coding.

#	Selective Coding	# Axial Codes	Underlying Axial Code References
1	Organisational deliverables and project scope	2	1, 2
2	Financial aspects	1	3
3	Legal and regulatory deliverables	3	4, 5, 6
4	Safety deliverables	2	7, 8
5	Early adopters	2	9, 10
6	Project management	4	11, 12, 13, 14
7	Specific use cases	3	15, 16, 17
8	Expert skills and development	2	18, 19
9	Software and hardware integration	7	20, 21, 22, 23, 24, 25, 26
10	Artificial intelligence (AI) integration	1	27
11	Automation and 3D environments	3	28, 29, 30
12	Data privacy and management	2	31, 32
13	User experience and AR use	2	33, 34
14	Technology advancements	1	35
15	Technology and project challenges	2	36, 37
16	Performance and quality assurance	7	38, 39, 40, 41, 42, 43, 44
17	Knowledge and lessons learnt	3	45, 46, 47
18	Communication	2	48, 49

The main findings from the data analysis used qualitative data derived from grounded theory and principles from DeLone and McLean's Information System (IS) success model. Utilising the grounded theory approach of coding, categorising, and identifying relationships, the study formed relationship chains and feedback loops that outline the complex dynamics of user acceptance of AR technology in the engineering and construction sectors. Each relationship chain has interconnected pathways that collectively illustrate the successful integration of AR. Using the causal loop diagram to outline the chains of causality and feedback loops, this analysis identifies that user acceptance of AR technology is not a single item but the interconnections among technology, organisational processes, and internal and external stakeholders. A detailed review of the relationship chains and feedback loops is provided below, supported by the literature, primary data collected through the grounded theory approach and principles from DeLone and McLean's IS success model.

Figure 2 provides a visual representation of the open, axial and selective coding process, using organisational deliverables and the project scope as an example.



Figure 2. Relationship for organisational deliverables and project scope.

Organisational deliverables and the project scope outline the requirements for using this technology and integrating AR to meet business needs and objectives. Client requirements illustrate this, ensuring that project needs are adequately addressed. Additionally, user requirements are considered to support organisational outputs, confirming that the

appropriate applications and software are being used. Figure 2 depicts organisational deliverables and the project scope.

Organisational deliverables and the project scope are crucial components of any project. They are interconnected with the financial, legal and safety deliverables. Understanding these relationships and their meanings is essential to interpreting the dynamics of AR technology in the project and its relationships in the framework. An example of project deliverables and scope management is detailed below:

The relationship between project deliverables and scope management can be seen as a means of ensuring that the implementation of AR aligns closely with the specific needs and objectives outlined by the client or organisation. Clarifying the client's requirements impacts scope management, and this is detailed in the quote below:

> '*Yeah. So we have like, when we're scoping out a project, we scope it out in regards to what we need to do on a technical perspective. And we also really get clarity from the client as to the nuts and bolts of what they need us to develop. And then we work very closely with them because we're creating something bespoke for their use case. So it's really not so much about us just presenting them with the solution as sort of us finding out what they need, and then guiding them like oftentimes clients will have a wrong idea of strengths and weaknesses of their technology and what can . . . be done and what's easy and what's hard so we tend to guide them*'. (S21)

4.4. Causal Loop

The causal loop diagram is represented in Figure 3, outlining the 11 relationship chains and the two feedback loops. The data analysis indicates how grounded theory was used to apply open, axial, and selective coding to the primary data sets. This comprehensive data analysis outlines the user adoption of AR technology in engineering and construction projects. The data originated from raw primary data collected through interviews, focus groups, and open-ended questionnaire surveys. Grounded theory was used throughout the data analysis, leading to the development of a causal loop diagram that visually maps the relationships involved in AR technology integration.

Relationships were developed through the processes of open, axial, and selective coding. These relationships were derived from the data analysis to identify common themes and were organised into 11 relationship chains and 2 feedback loops. Each of the relationship chains was analysed to identify connections and feedback loops. During the data analysis, the primary data sets were revisited to ensure that the proposed relationships and feedback loops remained grounded and represented the participants' experiences. The process for the causal loop incorporated open, axial, and selective coding, with higher-level analysis following selective coding to identify potential relationships. Primary raw data were analysed to establish links and interactions, such as how knowledge improves understanding of AR technology, thereby providing the relationship between knowledge and user acceptance. The primary data were then cross-referenced with the interview and questionnaire data, allowing relationships to be grouped to identify patterns. The identified relationships were traced back to the coding to ensure they were accurately represented per the interpreted data analysis.

The development of the causal loop diagram incorporated the allocation of positive and negative polarities to the variables and the interpretation of the participants' statements. The participants' statements were assigned as per their experience. Therefore, a positive statement reflected benefits, and a negative statement reflected barriers to AR technology adoption. Therefore, through the grounded theory approach, the participants' statements were identified and represented according to the nature of the statement.

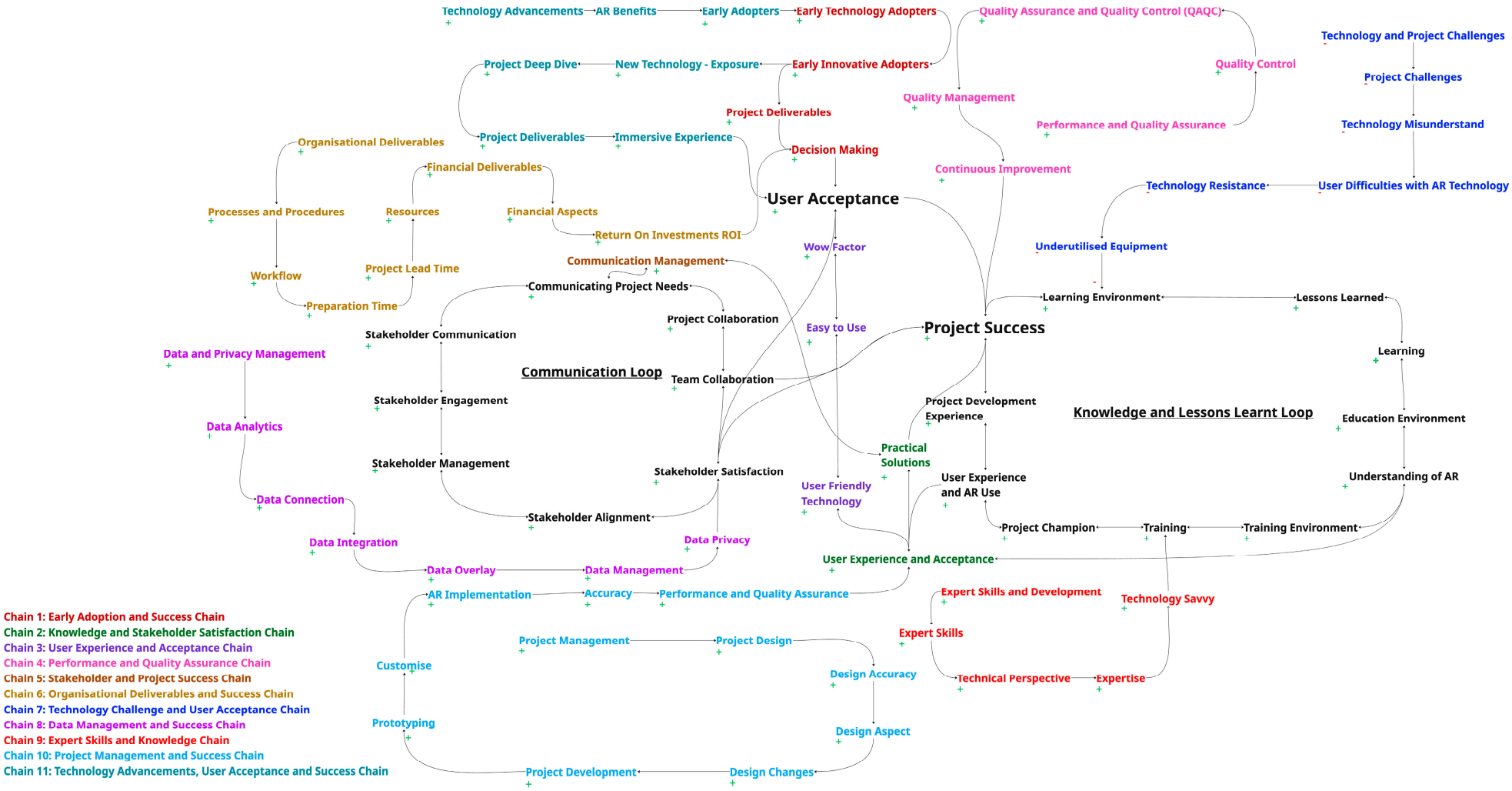


Figure 3. Causal loop.

Once the relationships were identified using grounded theory, each category was clearly defined and incorporated into a causal loop diagram that could increase or decrease. Within this study, each increase or decrease represents a qualitative change in the frequency or quality, as per the participants' data. For example, an increase in training would mean that training is becoming more efficient, while a decrease would mean it is becoming less efficient.

The causal loop polarity for each relationship was examined based on how one variable would affect the connecting variable. This incorporated an additional step in the process. Therefore, a positive polarity was assigned to variables that changed in the same direction. For example, user experience and acceptance, connected to practical solutions, were linked to project success. A negative polarity was assigned to variables that changed in opposite directions. For example, user difficulties with AR technology were linked to technology resistance.

Not all negative statements produce a negative polarity. For example, the statement outlining that poor training reduces AR technology use is a negative term. However, understanding of AR and the training environment has a positive polarity. This process enables the analysis to utilise the grounded theory approach while establishing the causal loop diagram identified from the qualitative data. The causal loop diagram data were developed by progressing from participants' input through the grounded theory approach to identify relationships, causal variables, relationship chains, and feedback loops.

Once the 11 relationship chains and 2 feedback loops were identified, these were compared and examined holistically, therefore identifying interconnections and pathways. The 2 feedback loops identified include communication, knowledge and lessons learnt. The feedback loops emerged when the direction of the relationship formed a consistent, closed structure, and many of the relationship's chains formed part of the feedback loop, highlighting the importance of both communication and knowledge and lessons learnt. Therefore, these feedback loops overlap with the relationship chains and highlight that the feedback loops extend beyond the linear chains and can integrate into the representing relationships. Thus, highlighting the interactions that influence user acceptance. For example, relationship chain 1, early adoption and success, outlines that stakeholder satisfaction influences user acceptance and that it is represented within the communication feedback loop, while user acceptance is represented in chain 1.

The causal loop diagram is a visual display of the relationships and interdependencies outlined in the data analysis. The relationships and feedback loops illustrate how AR technology integration emerges from the technology, people, processes, procedures, and organisational learning.

4.5. Relationship Chains

Overall, 11 relationship chains are identified in the study. These chains were built by analysing the taxonomy relationships and data gathered during the research, and they include the following:

1. Early adoption and success chain;
2. Knowledge and stakeholder satisfaction chain;
3. User experience and acceptance chain;
4. Performance and quality assurance chain;
5. Stakeholder and project success chain;
6. Organisational deliverables and success chain;
7. Technology challenge and user acceptance chain;
8. Data management and success chain;
9. Expert skills and knowledge chain;

10. Project management and success chain;
11. Technology advancements and the user acceptance chain.

Each relationship chain represents interconnected relationships that transpired. For example, for the first relationship chain, the 'early adoption and success chain', this study outlines each connecting relationship. These relationships include the following:

- Early Technology Adoption → Early Innovative Adopters: This focuses on the early adopters for the use of AR technology and integrating it into projects.
- Early Innovative Adopters → Project Deliverables: This identifies the deliverables and drivers for AR integration.
- Project Deliverables → Decision-making: This involves deciding on whether to use AR technology.
- Decision-making → User Acceptance: This refers to the process of adopting AR technology.
- User Acceptance → Stakeholder Satisfaction: Stakeholders recognise and appreciate the benefits of AR.
- Stakeholder Satisfaction → Stakeholder Alignment: This refers to ensuring that all stakeholders are satisfied with the use of AR.
- Stakeholder Alignment → Stakeholder Management: This refers to ensuring that all stakeholders are aligned.
- Stakeholder Management → Stakeholder Engagement: This refers to ensuring that all stakeholders are engaged.
- Stakeholder Engagement → Stakeholder Communication: When AR is aligned, communication is improved through AR technology.
- Stakeholder Communication → Communicating Project Needs: This refers to the clear communication of project needs and understanding among stakeholders.
- Communicating Project Needs → Project Collaboration: This refers to sharing project needs and progressing towards common goals.
- Project Collaboration → Team Collaboration: The project and team work together to implement AR technology.
- Team Collaboration → Project Success: This refers to a successful implementation of AR that meets the project needs.

Early Adoption and Success Chain

The relationship chain for early adoption and success is illustrated in Figure 4.

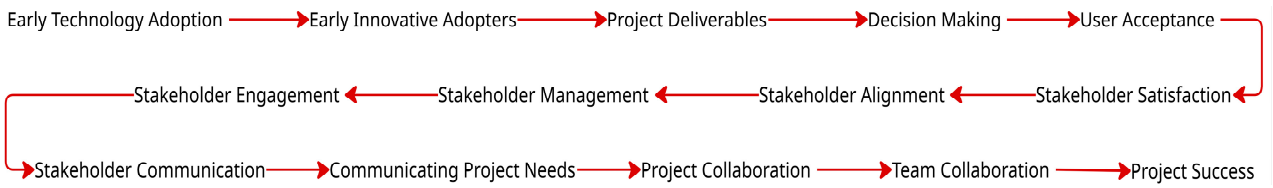


Figure 4. Relationship chain 1: Early adoption and success.

The early adoption and success relationship chain for the construction and engineering sectors illustrates that the main areas of this chain include early adoption, project management and deliverables, stakeholders, and communication and collaboration. This relationship chain acts as a catalyst for the successful integration of AR technology. It is highlighted that *'there is no set way that they do things that this sort of technology can kind of stand up. And it won't be until that's more common place that more people get on board. So finding those early adopters is going to be a sort of real key'* (E10). This data extract highlights the need to find early adopters and set a standard for new technology integration. It is also

noted that organisations that effectively encourage early innovative adopters set a positive precedent for the acceptance of AR technology and increase expert skills.

The early adopters and success relationship chain is derived from this research in relation to the engineering and construction sectors, suggesting that the early adoption of AR technology has many benefits. This is consistent with the literature, as Han and Clevenger [13] highlight that AR technology is mature enough to bring benefits to construction projects. According to Rohil and Ashok [6] and Yunus et al. [57], it is vital for organisations and stakeholders to embrace innovation through the adoption of new technologies and trends. Furthermore, Arowoiya et al. [79] highlight that there are crucial success factors for AR technology use, and one of the factors includes the need for innovativeness in project execution. DeLone and McLean's IS success model [8] aligns with these findings, as it details how users and systems correlate with net benefits.

The relationship chain identifies an early adoption approach to user acceptance of AR technology. This chain begins with early technology adoption and outlines the need for an organisational approach to digital transformation in real-world projects. However, there is often apprehension and resistance to change [14]. The successful integration of AR technology relies on organisations being open to innovation and identifying early adopters [79]. Therefore, the findings indicate that early adopters play a crucial role in supporting and accelerating digital transformation within construction and engineering organisations. These findings suggest there is a connection between early adoption and digital transformation, with participants' experiences and lessons facilitating the early acceptance of ER technology.

4.6. Communication Feedback Loop

In total, two feedback loops were identified within the study. These loops were established by analysing the relationships detailed in the taxonomy and the data collected during the research; they are listed as follows:

1. Communication feedback loop;
2. Knowledge and lessons learned feedback loop.

Each feedback loop represents an interconnected relationship chain that occurred and formed a loop. For example, for the first feedback loop, the 'communication feedback loop', each of the connecting stages is outlined as follows:

- Stakeholder Communication → Communicating Project Needs: The stakeholder has been told about and understands the AR technology integration.
- Communicating Project Needs → Project Collaboration: The project needs have been communicated.
- Project Collaboration → Team Collaboration: The project needs are communicated, and teamwork is involved in the integration of AR technology.
- Team Collaboration → Stakeholder Satisfaction: The stakeholder is satisfied with the AR technology.
- Stakeholder Satisfaction → Stakeholder Alignment: With stakeholder satisfaction, the stakeholders all need to align their expectations.
- Stakeholder Alignment → Stakeholder Management: The stakeholders have aligned their expectations.
- Stakeholder Management → Stakeholder Engagement: All stakeholders are engaged with the expectations of AR technology integration.
- Stakeholder Engagement → Stakeholder Communication: The stakeholders are communicated with, and the feedback loop begins again to ensure that there is communication across the whole project phase.

The feedback loop for communication is illustrated in Figure 5.

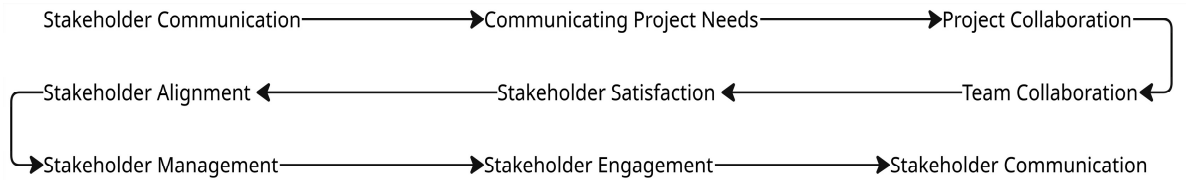


Figure 5. Communication feedback loop.

The communication feedback loop for the construction and engineering sectors emphasises that the main focus areas include communication and stakeholder management. Quality communication with all stakeholders is essential for successful AR technology integration, effective stakeholder collaboration and overall satisfaction and alignment.

Effective communication is essential when implementing AR technology, particularly when numerous stakeholders are involved. Therefore, effective communication through AR technology adds value by providing real-time, transparent visual data displays. This is further explained by participant S19, who outlined that communication can be enhanced with a visual component: '*So two things on which work together, which is one being the communication tool. And for people to understand what they can expect to see in their local landscape, or, you know, like, in the story of, you know, taking it to community consultations, and letting stakeholders see, you know, what, for especially large infrastructure projects, how, yeah, you know, adding an element of transparency, but also, you know, enhancing the level of communication between private or public companies, with interested stakeholders, compared to having to do lengthy processes, often in photogrammetry, which is your traditional way of doing Photoshop on a strict viewpoint, you know, using augmented reality really takes that level of communication, transparency.*'

Delgado et al. (2020) emphasise that effective communication and collaboration foster a higher level of stakeholder understanding and productivity. It is also recognised that AR technology effectively communicates context to personnel who work on- or off-site and at different locations by aiding in reducing any misunderstandings [21]. This is further elaborated by participant E10, who emphasised the importance of communication with AR integration: '*So project management is all about communication, like very heavily communication, like 90%. So having another communication tool, whether it be for stakeholders, or subcontractors, or end users is really quite valuable.*'

Integrating AR technology offers many benefits, primarily driven by the need for improved communication. Some advantages of AR technology communication include improved stakeholder collaboration and on-site visualisation [55,56,79]. As found using the grounded theory approach during the collection of primary data, participant E10 stated that AR technology is a communication tool, and utilising AR technology stems from a need: '*We'll I think that the drive for people to use the technology, it drives it comes from a need right? So usually that need is a communication tool. So it needs to be a scenario where you're trying to show somebody what something could look like or invest in the identification of like conveyancing say you're doing maintenance on aircraft or something in your had a setup is familiar with inside the landing gear augmented reality could point a maintenance person to a particular line to say that's what you need to do, and bring up information that actually shows what they need to do step by step.*'

AR technology is supported by communication, enabling the real-time delivery of digital information. This technology creates a visual reference for the user and provides stakeholder collaboration. AR also aligns with the VR, MR, and extended reality (XR) domains, where digital technology serves as an interface between the user and the environment and functions as a communication tool.

According to DeLone and McLean's IS success model, the system quality, information quality and user success [8], highlight information systems that reflect a communication

feedback loop, which was collected through grounded theory. Leveraging DeLone and McLean's IS success model, the communication feedback loop is evident.

It is evident that communication is essential for integrating AR technology. Both grounded theory, based on primary data, and the literature review, which includes DeLone and McLean's IS success model, support this.

5. Discussion and Conclusions

There have been many studies on AR technology, and among them, one sector or application receives focused attention. This is evidenced by Hajirasouli et al. [12], who identify benefits within the construction sector, highlighting that digital technologies can reduce project costs; however, there was limited research involving real-world scenarios in the construction sector, as the study focused on experiments, simulations, and laboratory environments. In addition, Rohil and Ashok [6] researched urban planning in construction, finding that AR technology enables full-scale design walkthroughs to be showcased; however, this research is still in its initial phase.

Delgado et al. [15] investigate the AEC sector and outline that the main factor limiting AR use in the construction sector is its technical limitations. Liao and Luo [54] researched green construction and highlighted that AR technology combined with building information modelling (BIM) in the construction sector provides real-time defect detection and monitoring, thereby offering innovation and practical solutions; however, they also state that in the construction sector, there is an absence of an integrated solution that provides both AR and BIM technologies.

The literature has highlighted many contradictions. While numerous researchers have explored AR technology, there is no single framework that describes real-world scenarios for both the engineering and construction sectors, with skilled software developers providing their perspectives.

This study has contributed to the literature by providing comprehensive insight into AR technology based on current practical outcomes in the engineering and construction sectors and by outlining the factors influencing user acceptance of AR technology using a causal loop diagram. This research includes rich data from real-world scenarios collected from participants who either work directly with AR technology or work for an organisation that uses it.

This research provides sector-specific insights into the successful use of AR technology, outlining its impacts across sectors and the enablers. This also highlights the need for further research in areas such as the standardisation of digital technology integration, long-term use, and cross-platform use in BIM.

This research serves as the groundwork for subsequent research that supports digital transformation in the construction and engineering environment by developing frameworks and relationships to facilitate user acceptance of AR technology. This is achieved by theory building based on DeLone and McLean's IS success model [8] and identifying the lack of existing theoretical models of the user acceptance of digital technologies. Furthermore, integrating ISs with the grounded theory approach indicates that IS success models can be utilised to validate new methodologies.

Additionally, the study details key relationships and identifies relationship chains and feedback loops within a causal loop diagram. The findings indicate that AR acceptance requires careful consideration and suggest that the developed causal loop provides a foundation for understanding the relationships influencing AR technology adoption. This visual method emphasises the interactions influencing AR user acceptance and the dynamics of digital technology.

Therefore, the research contributions include advancing academic knowledge by integrating AR use into holistic models. Additionally, the research presents a causal loop diagram that outlines relationships and feedback loops not previously captured in the literature, and, lastly, it provides a foundation for future studies using a qualitative and mixed-methods approach.

Therefore, this study provides evidence-based research that can contribute to both research and practical recommendations for digital technology implementation and user acceptance, including how organisational, technological, and managerial inputs can lead to positive outcomes for technology integration and to AR technology success [6,54].

As the use of digital technology rapidly increases, AR is reshaping how projects are managed; however, a review of the literature shows that it is poorly understood and not widely accepted.

The data were analysed using the grounded theory approach, which involved identifying themes and relationships through open, axial, and selective coding of transcribed interviews and responses to open-ended survey questions. The developed models were derived from these themes and relationships. An understanding of the relationships that influence user acceptance of AR technology informed the models, and from these data, further contributions, implications, limitations, and directions for future research have been outlined. Therefore, future research could focus on other sectors where this proposed causal loop could be applicable. The relationships defined in this study could be further explored across different project types to examine whether these relationships and feedback loops can change the organisation's experience when incorporating AR technology. Exploring other sectors and project types can refine these relationships and deepen understanding of AR technology.

Therefore, the findings in this research indicate an increase towards digital transformation across the engineering and construction sectors. The findings highlight growing exposure to digital technology and the need for organisations to consider integrating technologies such as AR. There is also organisational readiness to integrate new technologies. AR technology is increasingly promising for real-time decision-making, communication, and collaboration. Additionally, AR technology, through immersive real-world environments, addresses many limitations of traditional practices, such as interpreting 2D drawings and inefficient workflows and communication in projects. This research highlights that AR technology may provide benefits, including improved accuracy and visualisation through the interpretation of real-time project data, leading to better decision-making and more collaborative communication among all stakeholders. Consequently, this supports user acceptance in integrating AR technology.

By developing these data into relationship chains and causal loop diagrams, this research contributes to a holistic view of user acceptance of AR technology, highlighting its benefits, limitations, and implications. This research addresses the research question and provides answers by presenting detailed findings and a causal loop diagram of relationships for user acceptance of AR technology. This was then further analysed to create a framework for project integration and reanalysed to develop relationship chains and a causal loop diagram.

The contribution of this study, therefore, identifies not only AR technology user acceptance but also the participants' perceived factors related to AR technology and the influence these have in real-world scenarios. By providing a causal loop diagram to understand the dynamics of AR user acceptance in construction and engineering projects, this study identifies how these factors interact in these sectors. This study also suggests that these relationships influence one another as AR integration progresses across projects. Therefore, this research not only identifies individual technology acceptance but also

examines how these factors interact within the relationship chains and feedback loops that influence user acceptance of AR technology.

In summary, this research, based on a qualitative grounded theory study, investigated user acceptance of AR technology in the engineering and construction sectors. This research provides a causal loop diagram representing interconnected relationships. This research contributed to both research and practice by identifying crucial elements of the user acceptance of AR technology.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets presented in this article are not readily available due to ethical restrictions.

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Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-dimensional
AEC	Architecture, engineering and construction
AI	Artificial intelligence
AR	Augmented reality
BIM	Building information modelling
IS	Information Systems
MR	Mixed reality
Q&A	Question and answers
VR	Virtual reality
XR	Extended Realityreality

Appendix A

#	Name	Files	References
1	360 Laser Scanning	2	2
2	3D Mapping	2	4
3	3d Storyboards	1	3
4	3D Virtual Environment	11	43
5	Accessibility	3	3

#	Name	Files	References
6	Accuracy	8	16
7	Ad-Hoc Training	3	3
8	Adaptability	3	3
9	AI Imagery	1	1
10	Application Programming Interface (API) AR	1	1
11	Applications on Devices	8	15
12	AR Availability	5	7
13	AR Benefits	9	16
14	AR Demonstration	5	6
15	AR Development	4	5
16	AR Elements-Limitation	1	1
17	AR Enhanced Experience	3	6
18	AR Equipment	14	56
19	AR First Impression	1	1
20	AR Implementation	4	5
21	AR Integration	8	9
22	AR Limitations	14	43
23	AR Packages	1	1
24	AR Programming	3	4
25	AR Projector	1	1
26	AR Side Effects	2	2
27	AR Software Comparison	1	1
28	AR Support Representative	2	2
29	AR Technology Advancements	9	14
30	AR Testing	2	2
31	AR User Case	10	24
32	Architectural, Engineering and Construction (AEC)	2	2
33	Artificial Intelligence (AI)	6	10
34	As Built Verification	2	2
35	Augmented Graphics	8	29
36	Automation	1	1
37	Battery Life	2	3
38	Bespoke Applications	2	3
39	Building Information Modelling Software (BIM)	2	2
40	Business as Usual (BAU) Aspect	3	6
41	Capabilities	14	49
42	Catia	1	1
43	Change Management	3	6
44	Cheaply	1	1
45	Collaborative	12	22
46	Commercial Application	2	5
47	Communicating Projects Needs	4	8
48	Community	1	4
49	Compatibility	4	8
50	Comprehensive Investigation	1	1
51	Computer Simulation	1	2
52	Consolidative Process	1	1
53	Construction	5	11

#	Name	Files	References
54	Construction Manager	1	1
55	Consultation	1	2
56	Content Gathering	1	1
57	Continuous Improvement	1	1
58	Contractual Requirements	1	1
59	Convenience	2	9
60	Cost Management	19	133
61	Cross Platform Integration	3	3
62	Customise	5	12
63	Data Connection	2	2
64	Data Integration	4	8
65	Data Overlay	7	11
66	Data Privacy	6	19
67	Decision Making	5	9
68	Design Accuracy	2	2
69	Design Aspect	7	22
70	Design Changes	1	2
71	Design Script	1	1
72	Design Troubleshooting	1	1
73	Device and Browser Authentication	1	1
74	Digitalisation	4	4
75	Documentation Management	1	2
76	Due Diligence	1	1
77	Early Adopters	4	7
78	Easy to Use	11	47
79	Economics	1	5
80	Education	10	16
81	Embracing Technology	4	5
82	Engineer	1	1
83	Engineering	2	4
84	Enterprise Licence	1	1
85	Enterprise Sectors	2	4
86	Entertainment Applications	2	5
87	Environment Interaction	3	3
88	Environmental Projects	1	1
89	Equipment Safety	1	1
90	Ethics-Technology	1	1
91	Evaluation Period	1	1
92	Expertise	4	7
93	Feasibility	2	2
94	Functionality	6	10
95	Future Concept	1	1
96	Game Engine AR	1	1
97	General Overview of AR Future	16	20
98	Generative AI	4	5
99	Hardware Availability	1	2
100	Headset Size	2	3
101	Headsets Used	9	22
102	Health and Safety	4	10

#	Name	Files	References
103	Human Factors	2	4
104	Imagery	1	1
105	Immersive Experience	3	3
106	Implementation of Hardware	2	2
107	Infrastructure	1	6
108	Initial Problems	1	1
109	Innovation	4	5
110	Inspections	1	1
111	Instruction Sheet	1	1
112	Interaction	9	17
113	KPIs	1	1
114	Learning	4	13
115	Legacy Systems	2	7
116	Lessons Learned	1	1
117	Level of Development (LOD)	1	2
118	Longevity of Technology	3	4
119	Manufacturing	4	5
120	Marketing	5	25
121	Medical Applications	1	1
122	Metrics	2	3
123	Misaligned Expectations	1	2
124	Modelling	9	15
125	Multiple Programs	1	1
126	Multiple Users	3	3
127	Native Applications	1	2
128	New Technology-Exposure	11	19
129	Older Generation	6	6
130	On Site Functionality	1	1
131	Onboarding Project	1	1
132	Other Devices	2	4
133	Permission Issues	1	1
134	Personal Reality	3	3
135	Physical Limitations	1	1
136	Physical Safety	1	1
137	Politics	1	1
138	Positive Impact	15	29
139	Potential Strategy	5	6
140	Practical	3	3
141	Preparation Time	2	2
142	Pressure	1	2
143	Problem Solving	9	16
144	Processes and Procedures	6	10
145	Procurement	1	1
146	Productivity (Efficiency)	11	55
147	Progressive Design Review	1	1
148	Project Benchmarking	1	1
149	Project Champion	4	6
150	Project Debrief	2	2
151	Project Deep Dive	1	1

#	Name	Files	References
152	Project Deliverables	3	4
153	Project Delivery	1	2
154	Project Development Experience	2	2
155	Project Direction	2	3
156	Project Feedback	8	13
157	Project Funding	1	1
158	Project Handover	2	3
159	Project Leadtime	3	3
160	Project Needs	5	15
161	Project Phase	2	4
162	Project Portfolio	1	1
163	Project Preconception	1	1
164	Project Success	4	5
165	Project Visualisation	9	13
166	Prototyping	8	12
167	Proven Systems	1	1
168	Proven Useful	2	8
169	QR Code	1	3
170	Quality Assurance and Quality Control (QAQC)	1	2
171	Quality Management	6	9
172	Quantify Savings	1	1
173	Questions and Answers (Q&A)	1	1
174	Real Time	9	21
175	Regulation	1	3
176	Reliability	5	10
177	Renewable Energy	1	7
178	Request for Proposal (RFP)	1	1
179	Requirements	1	1
180	Research Software Companies	1	2
181	Research Team	1	1
182	Resources	3	6
183	Response Time	1	1
184	Return on Investment (ROI)	2	6
185	Scope Creep	1	1
186	Scope Management	6	11
187	Self Trained	5	6
188	Set Up of Technology	4	4
189	Skill Sets	1	4
190	Social Licence	1	1
191	Software Applications	8	15
192	Software as a Service (Saas) Applications	1	1
193	Software Developers Experience	1	1
194	Software Ecosystem	1	1
195	Software Integration	8	16
196	Software Layers	1	1
197	Software Maintenance	2	4
198	Spatial Data	3	5
199	Stakeholder Alignment	3	5

#	Name	Files	References
200	Stakeholder Communication	4	15
201	Stakeholder Engagement	6	8
202	Stakeholder Satisfaction	5	6
203	Stealth Mode	1	1
204	Subject Matter Expert (SME)	1	1
205	Superimpose AR	1	2
206	Target Audience	1	2
207	Technical Perspective	1	2
208	Technology Accuracy	2	4
209	Technology Advise	1	1
210	Technology Availability	3	8
211	Technology Dependency	2	2
212	Technology Engagement	3	3
213	Technology Enthusiasts	1	1
214	Technology Insertion	1	1
215	Technology Interface	5	8
216	Technology Misconception	5	5
217	Technology Purpose	4	4
218	Technology Resistance	2	3
219	Technology Savvy	3	4
220	Time and Motion	1	1
221	Time Management	8	24
222	Trade Industry	1	1
223	Training	18	65
224	Transparency of Project Information	2	2
225	Trial Licence	3	3
226	Understanding of AR	18	30
227	Underutilised Equipment	1	1
228	User Acceptance	10	24
229	User Difficulties with AR Technology	1	1
230	User Expectation	7	11
231	User Experience	8	10
232	User Friendly Technology	4	6
233	User Support During Set Up	2	2
234	Utility	1	1
235	Validation	2	2
236	Verbal Communication	5	9
237	Virtual Asset	1	2
238	Visto	1	2
239	Visual Aids-Handover	1	1
240	Visual Communication	4	11
241	Visual Display	16	31
242	Visual Instructions	1	1
243	Web Browser Accessibility	6	6
244	Workflow	3	11
245	Wow Factor	5	6
246	Written Communication	5	11
247	You Tube	1	1
248	Younger Generation	5	6

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