

Review

# Exploring the Potential of Virtual Reality Technology to Improve Safety Practices in the Construction Sector Through Network, Loop, and Critical Path Analysis

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## Abstract

The study explores how Virtual Reality (VR) can improve safety training in the construction industry by identifying key influencing factors and analysing their interactions to enhance safety outcomes. A systematic literature review (SLR) was conducted using Scopus and ScienceDirect databases, yielding 58 relevant studies published between 2019 and 2024. Thematic analysis was employed to determine and categorise key factors influencing VR training effectiveness. Using network analysis techniques, the study generated author-factor and interrelation matrices, a causal loop diagram, and loop and critical path analyses to determine feedback mechanisms and the most influential factor sequences. The study identified 33 key factors across behavioural, cognitive, technological, social, economic, and health and safety themes. Safety and hazard awareness, immersive experiences, realism, and worker behaviour were the most dominant. These factors were found to support better engagement, learning, and safety performance. On the other hand, financial constraints, low adoption rates, communication issues, and language barriers were identified as limiting factors that reduce the overall impact and integration of VR training in construction environments. This research presents an interrelation-based framework for analysing VR training effectiveness using thematic and network analysis.



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**Keywords:** virtual reality; safety training; construction; network analysis

## 1. Introduction

Globally, the average employment rate in the construction sector is approximately 7.3%, highlighting its key role in the labour market and its impact on economic activity across various regions [1]. According to the Ministry of Business, Innovation and Employment [2], construction employment contributes to 10.7% of New Zealand's total employment, making it the third-largest employment industry in the country. This growth is reflected in approximately 17.6 billion New Zealand dollars contributed to the year's GDP, as of September 2023 [3]. Despite their significant role, the construction sector remains one of the most hazardous sectors due to the high number of fatalities and injuries on the job [4]. In 2022, the U.S. Bureau of Labour Statistics [5] reported that the construction sector had the highest number of fatal work injuries among all industry sectors (refer to Table 1). Meanwhile, the construction industry in New Zealand accounted for 38,800 work-related injury claims, representing 17% of total injury claims and the highest number among all sectors [6].

**Table 1.** Number of fatal work injuries in the private industry sector in 2022 [5].

Industry Sector	Number of Fatal Work Injuries
Construction	1069
Transportation and warehousing	1053
Professional and business services	598
Agriculture, forestry, fishing, and hunting	417
O Manufacturing	404
Leisure and hospitality	306
Retail trade	301
Other services (exc. Public admin.)	200
Educational and health services	178
Wholesale trade	171

The high injury rate underscores the need for improved safety management, particularly for construction workers. Rokooei et al. [7] stated, “The best approach to improve the industry’s safety performance is to mitigate incidents in the first place [8]. In the construction industry, safety is crucial because workers face numerous risks and hazards, including falls from heights, falling objects, and electrical hazards [9,10]. Construction safety is usually guided by regulations from organisations like OSHA in the U.S. or WorkSafe in New Zealand [11]. These standards encompass practices such as wearing proper protective equipment, conducting regular safety training, and maintaining a work area that is as safe as possible.

Despite established safety protocols and regulations, construction workers often disregard them, resulting in hazardous conditions [12]. Additionally, other studies have identified workplace stressors and insufficient training as factors that can hinder safety compliance, highlighting the ongoing challenge of achieving a safe construction environment, even with comprehensive safety standards in place [13,14]. The primary objective of safety training is to prepare workers to recognise, avoid, and handle the various hazards they encounter on-site [15]. Safety training plays a crucial role in promoting awareness and ensuring that all personnel are adequately prepared to face the unique challenges of the job [16].

Traditionally, construction industry safety practices include on-site training, lectures, slideshows, video or textbook learning and toolbox sessions [17,18] to cover topics such as hazard identification, emergency response, and personal protective equipment (PPE). Each of these methods has its advantages, which are limited maintenance costs, easy accessibility, and repeatability [7,19]. At the same time, hands-on practice allows workers to apply their knowledge with real equipment under the guidance of experienced instructors [20]. In the United Kingdom, the government-owned National Highways organisation has introduced a new Health and Safety initiative that offers realistic training, enabling workers to gain practical experience in a safe environment [21]. Traditional safety training in construction has limitations: it is often passive and may not engage participants effectively [18,19], resulting in reduced retention of safety knowledge [9,22,23]. It poses a risk of injury to workers, as they may encounter hazards in real-world environments during on-site training [24].

To address the challenges of conventional training, applying modern technology could improve productivity, efficiency, and safety practices, despite the time and effort required [25]. According to Stefan et al. [26], Virtual Reality technology could be a promising substitute for traditional training methods to overcome these challenges [13]. Numerous studies reported that VR technology is more effective than conventional methods [11,17,19]. Seo, Park and Koo [27] reported that the Korea Occupational Safety and Health Agency (KOSHA) has been providing photo- and computer-generated VR content on construction

safety to support workers' training. Szóstak et al. [28] study shows that students who trained with VR consistently performed better than those who trained with traditional methods in safety knowledge and retention. Hussain et al. [29] mentioned that VR technology enables customised learning experiences tailored to the stakeholders' needs. The study found that VR-based safety training is more effective at capturing participants' attention, improving learning enthusiasm, and enhancing hazard identification abilities [20].

Despite this, the construction sector continues to experience alarmingly high injury rates, which concern both construction workers and employers [30]. A possible explanation for these persistent safety risks is a lack of knowledge about the factors and their interrelationships that affect VR safety training. The potential of VR to enhance safety practices in the construction sector highlights the importance of understanding the factors and their interrelations that influence the effectiveness of VR-based safety training. Recognising these factors and their interrelations is crucial for developing strategies that improve training effectiveness, enhance safety management, and reduce workplace injuries. By examining these factors, we can identify feedback loops and critical paths that affect the success of VR safety training. Therefore, the main aim of this research is to define and analyse the factors influencing VR-based safety training in the construction sector by answering the following questions:

What key factors influence the effectiveness of VR-based safety training, and how do they impact safety training in the construction sector?

Which loops and critical paths exist within the interrelations of VR effectiveness factors that influence safety training outcomes?

## 2. Research Methodology

This study adopted a systematic literature review methodology with content analysis to collect, analyse, and categorise articles discussing VR-based safety training in the construction industry. It used two databases, Scopus and ScienceDirect, to identify articles focusing on virtual reality safety training in the construction industry. While Scopus covered all journals, Science Direct brought in more articles within the search area. The articles' search was restricted to 2019–2024 to ensure recency and keep the review manageable.

### 2.1. Search Strategy

The keywords from the aim were used to search for literature on virtual reality safety training in Scopus and ScienceDirect. The search results were divided into three groups: the first group is related to virtual reality (all types, including fully immersive virtual reality and desktop virtual reality), the second group is associated with the industry, and the last is related to safety training or NZ's risk. The advanced query used on Scopus after combining these three groups is as follows: *TITLE-ABS-KEY ("virtual reality" OR "VR") AND TITLE-ABS-KEY ("construction" OR "engineering") AND TITLE-ABS-KEY ("safety training" OR "safety practice")*). At Scopus, the keywords were searched in the "Article Title, Abstract, or Keywords" field, whereas in ScienceDirect they were searched in the "Find articles with these terms" field. Thus, the keywords that were used in ScienceDirect are as follows: *("virtual reality" OR "VR") AND ("construction" OR "engineering") AND ("safety training" OR "safety practice")*. The inclusion and exclusion criteria were defined to ensure that the studies selected for the review are relevant to this research, as shown in Table 2.

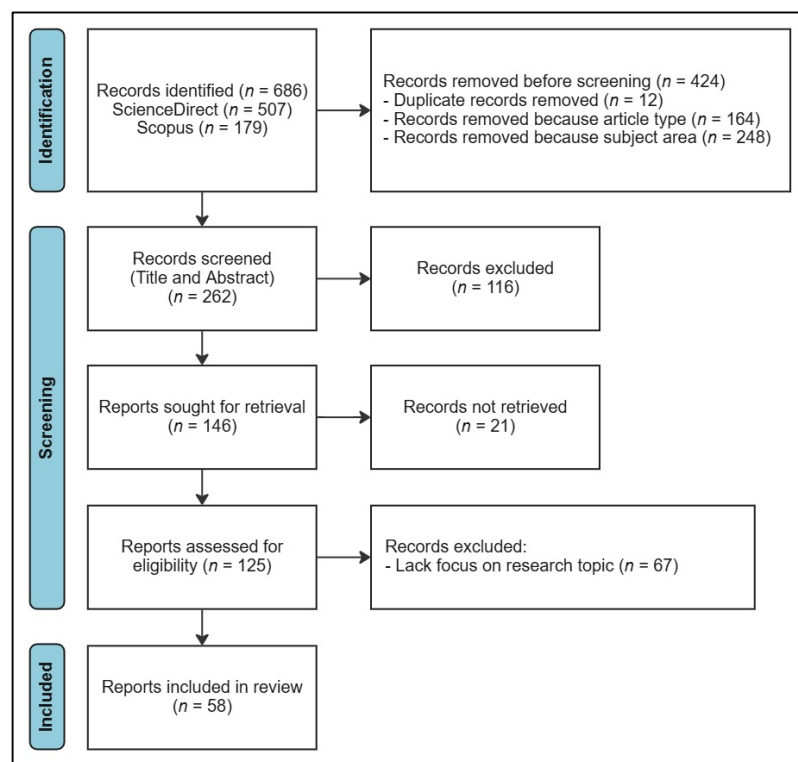
**Table 2.** Inclusion/exclusion criteria for literature search.

	Criteria
Inclusion	Articles published between 2019 and 2024 Articles written in English Articles focusing on VR applications in construction safety training
Exclusion	Document type is not research, journal, or conference papers The subject type is not engineering or construction Articles without full text

## 2.2. Screening Process

The literature selection and screening process for these systematic reviews used the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) framework. The EndNote 21 app was used to organise the records into four groups: Identification, Screening, Full-Text Screening, and Included. Additionally, the tags feature was used to categorise the documents included or excluded in each group.

As illustrated in Figure 1, the search keywords across the two databases, ScienceDirect and Scopus, yielded a total of 686 records: 507 from ScienceDirect and 179 from Scopus. Then, 424 records were removed as duplicates or did not match the required article type and subject area, leaving 262 records for screening. The first screening process involved reading the titles and abstracts and excluding articles that lacked focus on the research topic or used SLR as their research methodology. All records excluded in this phase were given the “1st screening–excluded” tag. Then, the remaining 146 records were retrieved in full text from Google Scholar and immediately attached to their respective records in EndNote. Unfortunately, 21 articles were inaccessible, and those records were given the “No Access” tag. The last screening phase involved reading the entire article and excluding those that lacked a focus on VR technology in construction safety training. Thus, after the screening phase, 58 articles were included in this research.

**Figure 1.** PRISMA diagram for literature search.

### 2.3. Data Extraction

This study's initial article analysis focused on bibliometric data to examine the trends and geographical distributions of research related to the topic, by analysing publication counts per year and the location of studies [31]. The bibliometric analysis of the records included in this study was conducted using Google Sheets. Additionally, Google Sheets was utilised to record and organise the extracted analysis data. The list of article data, such as title, author, year, and the country of the first author, was organised in a sheet titled "Data."

Following the bibliometric overview, a thematic analysis was conducted to extract and categorise key factors discussed across the selected articles. The thematic analysis had five stages: Organising Articles, Reading Process, Compilation of Factors, Theme Analysis and Coding. It began with organising articles in EndNote, ensuring each document was read at least twice for thoroughness. During this reading process, the highlighting feature in EndNote was used to mark relevant factors, and repeated readings ensured that all pertinent aspects were captured. Once the factors were identified, they were compiled into an Excel sheet, with similar factors merged to streamline the data. Since factor identification is subjective, the research team collectively examined the factors, verified their presence in articles, and correlated them with the authors' themes, identifying key themes from the compiled factors. Then, the themes and factors were discussed with fellow researchers to ensure adequacy, relevance and recency. Lastly, the factors were assigned codes based on the identified themes, facilitating a structured compilation. For assigning codes, these factors were systematically recorded in a separate sheet labelled "Factors". Each factor is categorised into themes such as behavioural, cognitive, economic, organisational, health and safety, social, technological, challenges and potential risks. Then, when the theme is chosen, the factor's code will be generated automatically by utilising the formula feature. To make this formula work, another table was made to assign short codes to each theme, such as "BHV" for behavioural and "COG" for cognitive. Finally, the formula combined the theme code with a sequential number that increments for each new factor within the same theme. For example, Worker Engagement Level under the Behavioural Theme was assigned BHV-01, and Critical Thinking and Problem-Solving under the Cognitive Theme was assigned COG-01.

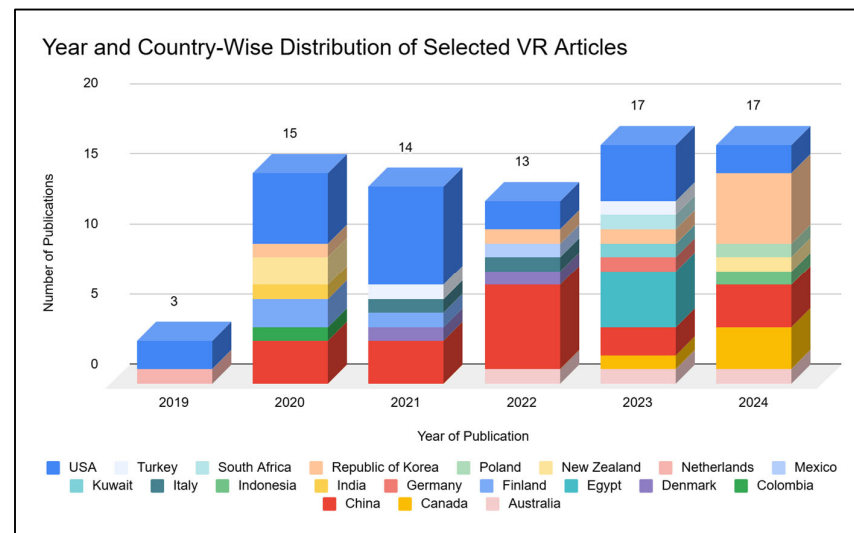
To examine the interrelationships between the factors, an additional dataset was organised in a sheet named "Relations." Each row in the relations table includes details such as the influenced factor, the relation type (positive or negative), and the affected factor. Dropdowns containing all the factors were used for the influenced and affected factors in each row. This ensured all the relations were correctly organised.

The relation type captures the nature of the interaction between each influencing and affected factor. A positive relation indicates that the influencing factor has a beneficial or enhancing effect on the affected factor. For example, if "Technology Adaptability" positively impacts "VR Sickness", this implies that as users adapt better to technology, the likelihood or severity of VR sickness may decrease. Conversely, a negative relation indicates that the influencing factor has an adverse effect on the affected factor. For instance, if "Cultural Resistance and Adaptability" negatively impacts "Worker Behaviour", it implies that resistance to cultural or technological change could hinder positive safety behaviour among workers, potentially reducing their engagement to adopt new training practices.

### 2.4. Distribution of Publications per Year

From the data table in Google Sheets, a pivot table was created to calculate the total publications for each year and country, and a graph was generated from it to show the distribution of publications. Figure 2 presents the yearly and country-wise distribution

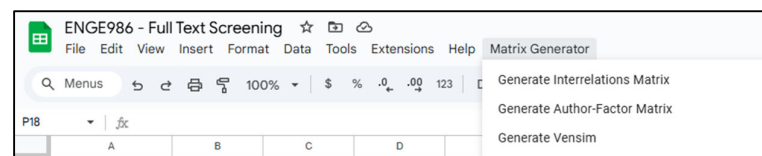
of selected VR articles from 2019 to 2024. The data reveals a general upward trend in VR research publications over the years, with notable peaks in 2023 and 2024, totalling 17 publications. The contributions came from diverse countries, with the United States and China as major contributors throughout the years. Countries such as the Republic of Korea, Canada, and Egypt have also made periodic contributions, reflecting a global interest in VR research. Overall, the chart underscores the growing focus on VR technology across multiple countries, highlighting a rising interest and recognition of its potential for construction safety training.



**Figure 2.** Year- and country-wise distribution of selected articles.

### 2.5. Matrix Generator

One of the benefits of using Google Sheets to organise data is the various features it offers. A generator code was developed using another Google feature, Apps Script, to streamline the creation of the author–factor and interrelation matrices. Using this feature (Figure 3), it is possible to process data in Google Sheets and achieve the desired outcome, provided the code is developed. Thus, this study used this feature to generate the author–factor and interrelation matrices with a click menu, as shown in Figure 3, rather than creating them manually.



**Figure 3.** Matrix Generator menu developed in Google Sheets using Apps Script.

### 2.6. Author–Factor Matrix

To generate the author–factor matrix, the code accesses the Relations sheet to determine whether each article contains specific factors. The script scans each entry in the Relations sheet to determine whether an article is associated with a particular factor, marking it as true if a match is found. This process automatically populates the author–factor matrix by placing a checkmark (✓) in the corresponding cell when an article includes the respective factor. For example, the author [32] from Egypt mentioned BHV-02, which is represented by the ✓ mark in the respective intersecting cell. By automating this verification process, the generator efficiently creates an accurate matrix that reflects the associations between articles and factors without manual input, thereby reducing the risk of human error. This

approach ensures consistency and saves time, enabling the quick visualisation of factor distribution across selected articles for further analysis.

### 2.7. Interrelation Matrix

Like the author–factor matrix, the interrelation matrix was generated by processing the data from the Factors and Relations sheet using App Script. The row and column headers were generated with the factors' codes in the Factors sheet as required for a complete interrelation matrix. Then, the script iterates over each matrix–cell and the Relations sheet to check if the given influencing-and-affected factor pair exists. When an interrelation is found, the script populates the matrix–cell at the intersection of these two factors with the authors associated with the article. If the relation type is positive, the text colour is green; if it is negative, the text is red. Cells without any recorded relationships are left blank.

### 2.8. Causal Loop Diagram

This study used the Vensim app to visualise a causal loop diagram (CLD) that shows the interdependencies among key factors identified from the selected articles. Since one of the save file formats in Vensim is the mdl format, it is possible to create a causal loop diagram generator using Apps Script and JavaScript. This generator automates the creation of the CLD by pulling data directly from the Relations sheet, where influencing and affected factors are documented.

The generator interprets each factor and relation, mapping them into the generated .mdl file to illustrate variables and connecting arrows. JavaScript libraries such as D3.js and WebCola were used to determine element positions, ensuring that the CLD elements do not overlap. Blue arrows indicate positive relations, while red arrows indicate negative relations. After the generated file was created, manual adjustments were made to improve the visualisation of CLD, such as changing variable and curve positions. Automating the creation of the .mdl file significantly reduces the time and effort required to construct diagrams in the Vensim app manually. It is worth noting that, since the multi-factor loops are discussed separately, the CLD does not represent the balancing and reinforcing loops. Also, stock flows were not visualised since they were not relevant and do not appear in the discussion.

### 2.9. Loop Analysis

This study conducted a comprehensive analysis of loops based on the interrelations among various factors. A conventional approach to gathering this data involves using the loops function in the Vensim application and recording each cycle in an Excel sheet; however, this method is often time-consuming and requires significant manual effort. To enhance efficiency and ensure data accuracy, this study developed a Python 3.12 program designed to automate the calculation of loop analysis results. This program efficiently provides both the number of loops and the list of loop cycles. This program uses NetworkX, a built-in Python library, to identify connections between factors based on the specified interrelations.

Furthermore, the analysis incorporated calculations for both unit weight and centrality weight for each cycle in the results. The type of relationship determines the unit weight in a connection: a positive relationship results in an increment of 1, and a negative relationship results in a decrement of 1. Conversely, centrality weight is calculated based on the degree of centrality associated with each factor, rather than simply assigning a value of 1. Following [33], to calculate the degree of centrality in a network, we counted the total number of relationships connected to a specific node and divided it by the maximum degree in the network. This means that the node with the most connections will have a degree centrality of 1, while the centrality of all other nodes will be represented as a

fraction of their own degree relative to the highest-degree node. Then, the results were exported to two CSV files: one containing the number of loops. At the same time, the other provides a list of identified loop cycles with unit and centrality weights, as illustrated in Figures 4 and 5.

	A	B
1	Code	Number of Loops
2	HNS-04	2
3	BHV-03	3
4	COG-04	2
5	COG-07	1

Figure 4. Screenshot of the generated number of loops data.

	A	B	C
1	Cycle	Unit Weight	Centrality Weight
2	BHV-03 -> HNS-04 -> BHV-03	0	0.090909091
3	SOC-03 -> SOC-01 -> SOC-03	0	0.181818182
4	TCH-01 -> STCK-01 -> COG-05 -> TCH-01	3	1.727272727
5	SOC-03 -> ECO-02 -> STCK-01 -> SOC-03	1	0.272727273
6	TCH-01 -> STCK-01 -> TCH-01	2	1
7	TCH-01 -> STCK-01 -> TCH-02 -> TCH-01	3	1.454545455

Figure 5. Screenshot of generated loop analysis data.

### 2.10. Critical Path Analysis

In the Vensim application, critical paths were identified using the causal chain menu after selecting two factors to obtain the results. However, this method can be even more time-consuming than loop analysis, particularly when dealing with numerous factors. To streamline this process, a Python program was developed to efficiently determine these critical paths. Similar to the loop analysis, the program calculates both unit weight and centrality weight for each path and exports the results into a CSV file, as illustrated in Figure 6.

	A	B	C
1	Critical Paths	Unit Weight	Centrality Weight
2	BHV-04 -> HNS-02 -> SOC-01 -> SOC-03 -> ECO-02	6	3.818181818
3	BHV-04 -> HNS-02 -> SOC-01 -> SOC-03 -> ECO-02	6	3.818181818
4	TCH-06 -> TCH-04 -> COG-05 -> TCH-01 -> ECO-02	4	1.454545454
5	TCH-06 -> TCH-04 -> COG-05 -> TCH-01 -> ECO-02	0	-1.636363637
6	TCH-06 -> TCH-04 -> COG-05 -> TCH-01 -> ECO-02	4	1.454545455
7	TCH-06 -> TCH-04 -> COG-05 -> TCH-01 -> ECO-02	4	1.090909091
8	TCH-06 -> HNS-02 -> SOC-01 -> SOC-03 -> ECO-02	6	4.363636364
9	TCH-06 -> HNS-02 -> SOC-01 -> SOC-03 -> ECO-02	6	4.363636364
10	BHV-04 -> HNS-02 -> STCK-01 -> TCH-02 -> COG-0	3	1.545454545
11	BHV-04 -> HNS-02 -> STCK-01 -> TCH-02 -> COG-0	3	1.545454545
12	BHV-04 -> HNS-02 -> STCK-01 -> TCH-02 -> COG-0	-1	-1.545454546

Figure 6. Screenshot of generated critical path analysis data.

### 2.11. Research Workflow

Figure 7 illustrates the research workflow, representing the culmination of the study's methodological approach. It outlines the structured sequence followed, from keyword identification to an in-depth analysis of factors and their interrelations. This process, which incorporates systematic literature screening and data processing techniques, ensures a thorough exploration of the study's critical elements.

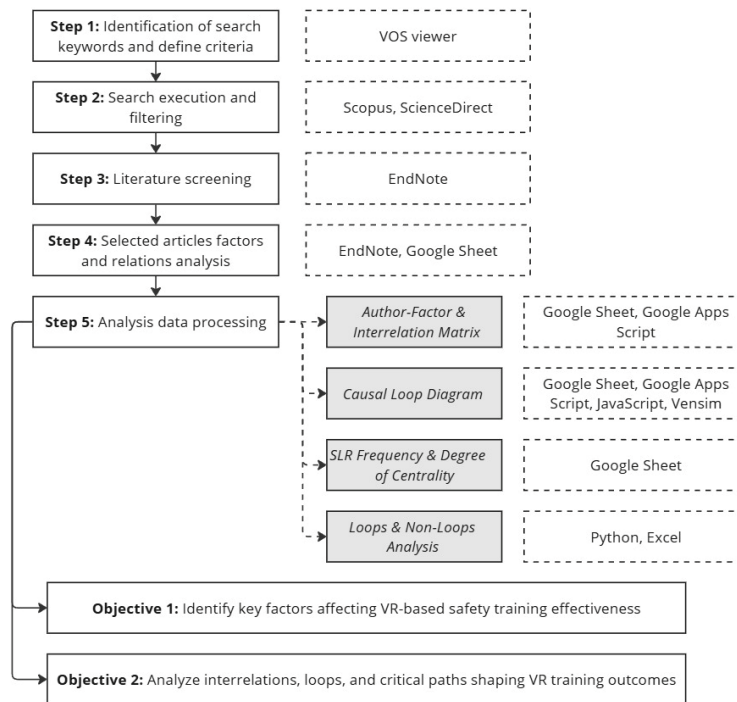


Figure 7. Research overview.

### 3. Results

This section presents the findings from the SLR and the data analysis of the factors identified in the selected articles.

#### 3.1. Factors

This study analysed key factors influencing the effectiveness of VR-based training in the construction sector. These factors, shown in Table 3, are categorised into six themes: behavioural, cognitive, economic, health and safety, and social and technological. Each factor was assigned a unique code for structured organisation and easy reference. The classification of factors is inherently subjective and should be understood in a general context. Some factors may encompass sub-factors. These sub-factors are split and highlighted to emphasise them as deemed essential. For example, one may argue that “Worker Behaviour” (BHV-03) can include “Motivation and Commitment” (BHV-02) or “Worker Engagement Level” (BHV-01). In such cases, it should be understood that Worker Behaviour” (BHV-03) is all aspects other than Motivation and Commitment” (BHV-02) or “Worker Engagement Level” (BHV-01). This categorisation provides a foundation for examining the relations and impacts of these factors within VR training applications.

Table 3. List of factors.

No.	Factor	Theme	Code
1	Worker Engagement Level	Behavioural	BHV-01
2	Motivation and Commitment	Behavioural	BHV-02
3	Worker Behaviour	Behavioural	BHV-03
4	Technology Adaptability	Behavioural	BHV-04
5	Different Learning Styles	Behavioural	BHV-05
6	Critical Thinking and Problem-Solving	Cognitive	COG-01
7	Knowledge acquisition	Cognitive	COG-02
8	Knowledge retention	Cognitive	COG-03
9	Safety and hazard awareness	Cognitive	COG-04

**Table 3.** *Cont.*

No.	Factor	Theme	Code
10	Realism and immersion	Cognitive	COG-05
11	Self-efficacy	Cognitive	COG-06
12	Stress level	Cognitive	COG-07
13	Task engagement and performance	Cognitive	COG-08
14	Ease of learning	Cognitive	COG-09
15	Educational experience	Cognitive	COG-10
16	Financial implications	Economic	ECO-01
17	VR implementation cost	Economic	ECO-02
18	Training cost	Economic	ECO-03
19	Cost-effectiveness	Economic	ECO-04
20	Incident reduction	Health & Safety	HNS-01
21	VR sickness	Health & Safety	HNS-02
22	Training risk reduction	Health & Safety	HNS-03
23	Safety management	Health & Safety	HNS-04
24	VR adoption	Social	SOC-01
25	Cultural resistance and adaptability	Social	SOC-02
26	Knowledge and communication flow	Social	SOC-03
27	Language barriers	Social	SOC-04
28	Interactive and immersive experiences	Technological	TCH-01
29	Visualisation	Technological	TCH-02
30	Scheduling and accessibility	Technological	TCH-03
31	User interaction and navigation	Technological	TCH-04
32	Customised safety training	Technological	TCH-05
33	VR framework	Technological	TCH-06

### 3.2. Author–Factor Matrix

Appendix A presents the Author–Factor Matrix, summarising the factors discussed in various VR-related studies and linking them to their respective authors, publication years, and countries. Each row represents a selected article, while each column corresponds to a specific factor relevant to VR-based training in the construction sector, such as behavioural, cognitive, and technological elements. A checkmark (✓) in a cell indicates that the corresponding factor was addressed in that article.

### 3.3. Interrelation Matrix

This study uses the interrelation matrix shown in Appendix B to map the relationships between the identified factors. When a relation exists, the cell is filled with the article’s author number in green if the relation is positive, and in red if it is negative. Positive meant the first factor aids or enhances the effect of the second factor, and negative meant the opposite.

### 3.4. Causal Loop Diagram

The Causal Loop Diagram in Figure 8 illustrates the complex interdependencies between various factors influencing VR effectiveness in construction safety training. VR Effectiveness serves as the focal point, connected to a network of factors across behavioural, cognitive, technological, organisational, economic, and environmental themes. Positive correlation, i.e., when a factor increases, the affected factor also increases, is represented in Blue, and negative correlation, i.e., if a factor increases, the affected factor decreases, is shown in red.

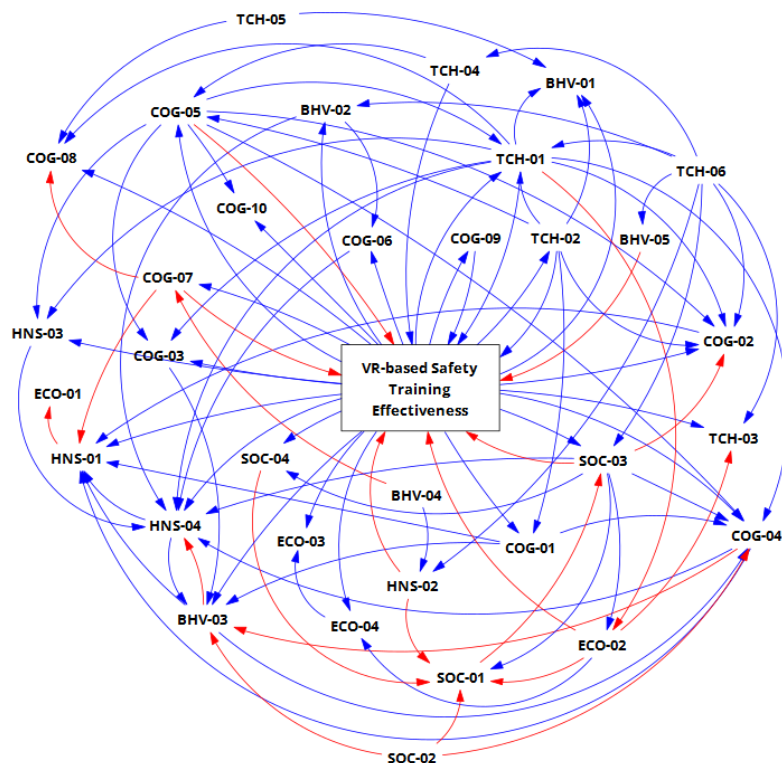


Figure 8. Causal Loop Diagram.

### 3.5. SLR Frequency

The SLR Frequency analysis presents the occurrence of factors across the systematic literature reviews, highlighting their prominence in VR. It is important to note that when a factor is repeated multiple times in a paper, the frequency is counted as one. As shown in Table 4, the top 4 factors identified by the study are Safety and Hazard Awareness (COG-04), Interactive and Immersive Experiences (TCH-01), Realism and Immersion (COG-05), and Knowledge Acquisition (COG-02).

Table 4. SLR Frequency Ranking.

Factor	SLR Frequency	Rank
COG-04	47	#1
TCH-01	30	#2
COG-05	27	#3, #4
COG-02	27	#3, #4
HNS-03	23	#5, #6
ECO-02	23	#5, #6
HNS-02	22	#7, #8
BHV-03	22	#7, #8
COG-03	20	#9
BHV-01	19	#10
HNS-01	17	#11
SOC-03	16	#12
TCH-04	15	#13, #14
HNS-04	15	#13, #14
COG-06	14	#15, #16
BHV-02	14	#15, #16
TCH-02	13	#17, #18
SOC-01	13	#17, #18
COG-01	12	#19

**Table 4.** *Cont.*

Factor	SLR Frequency	Rank
ECO-04	10	#20
COG-08	9	#21
TCH-03	8	#22
TCH-05	7	#23, #24
COG-10	7	
COG-07	6	#25
COG-09	4	#26
SOC-04	3	#27–#31
SOC-02	3	
ECO-03	3	
BHV-05	3	
BHV-04	3	
TCH-06	2	
ECO-01	1	#32
		#33

# rank number.

### 3.6. Degree of Centrality

Table 5 presents the Degree of Centrality analysis, which identifies the most influential factors within the interrelation matrix and indicates their relative importance in the network of factors affecting VR effectiveness. Interactive and Immersive Experiences (TCH-01) have the highest centrality, making them the most connected factor. Safety Management (HNS-04) and Safety and Hazard Awareness (COG-04) share second place, highlighting the critical roles of structured safety protocols and hazard recognition in improving construction site safety. This ranking provides insights into which factors drive key relationships, helping prioritise areas for intervention and further research in VR-enhanced safety practices.

**Table 5.** Degree of Centrality Ranking.

Factor	Degree of Centrality	Rank
TCH-01	1.00000	#1
HNS-04	0.81818	#2, #3
COG-04	0.81818	
TCH-06	0.72727	#4–#7
SOC-03	0.72727	
COG-05	0.72727	
BHV-03	0.72727	
HNS-01	0.63636	#8
SOC-01	0.54545	#9, #10
COG-02	0.54545	
TCH-02	0.45455	#11, #12
ECO-02	0.45455	
COG-01	0.36364	#13
SOC-02	0.27273	#14–#21
HNS-03	0.27273	
HNS-02	0.27273	
COG-08	0.27273	
COG-07	0.27273	
COG-03	0.27273	
BHV-02	0.27273	
BHV-01	0.27273	

**Table 5.** *Cont.*

Factor	Degree of Centrality	Rank
TCH-05	0.18182	
TCH-04	0.18182	
TCH-03	0.18182	
SOC-04	0.18182	#22–#28
ECO-04	0.18182	
COG-06	0.18182	
BHV-04	0.18182	
ECO-03	0.09091	
ECO-01	0.09091	
COG-10	0.09091	#29–#32
BHV-05	0.09091	

# rank number.

### 3.7. Number of Loops

The Number of Loops analysis highlights factors that reinforce feedback cycles within the interrelation matrix, revealing their role in influencing VR effectiveness and construction safety outcomes. As shown in Table 6, VR Implementation Cost (ECO-02) and Knowledge and Communication Flow (SOC-03), each present in 11 loops, indicate the substantial impact of financial constraints and effective information exchange in shaping safety training dynamics.

**Table 6.** Number of Loops Ranking.

Code	Number of Loops	Rank
ECO-02	11	#1
SOC-03	11	#1
SOC-01	9	#3
TCH-01	8	#4
COG-05	6	#5
TCH-02	6	#5
BHV-03	3	#7
SOC-04	3	#7
HNS-04	2	#9
COG-04	2	#9
COG-07	1	#11

# rank number.

### 3.8. Loop Cycles

The loop cycle analysis in Table 7 highlights key feedback loops that shape VR adoption and implementation in construction safety training. These loops reveal how interconnected factors reinforce or hinder VR effectiveness. Understanding these dynamics helps identify opportunities to optimise VR integration and improve safety outcomes.

**Table 7.** Loop Cycles Ranking.

Cycle	Unit Weight	Rank Unit Weight	Centrality Weight	Rank Centrality Weight
COG-04→HNS-04→BHV-03→COG-04	3	#1	2.363636	#1
STCK-01→TCH-02→STCK-01	2	#2	0.454545	#2
SOC-03→ECO-02→STCK-01→SOC-03	1	#3	0.272727	#3
TCH-01→ECO-02→STCK-01→TCH-02→COG-05→TCH-01	1	#3	−0.27273	#8

Table 7. Cont.

Cycle	Unit Weight	Rank Unit Weight	Centrality Weight	Rank Centrality Weight
STCK-01→TCH-02→COG-05→STCK-01	1	#3	−0.27273	#8
SOC-03→SOC-01→SOC-03	0	#6	0.181818	#4
HNS-04→BHV-03→HNS-04	0	#6	0.090909	#5
COG-04→BHV-03→COG-04	0	#6	−0.09091	#7
STCK-01→COG-07→STCK-01	0	#6	−0.27273	#8
SOC-03→STCK-01→SOC-03	0	#6	−0.72727	#13
TCH-01→ECO-02→STCK-01→COG-05→TCH-01	0	#6	−0.72727	#13
STCK-01→COG-05→STCK-01	0	#6	−0.72727	#13
TCH-01→ECO-02→STCK-01→TCH-02→TCH-01	0	#6	−1	#16
SOC-03→SOC-04→SOC-01→SOC-03	−1	#14	0	#6
SOC-03→ECO-02→SOC-01→SOC-03	−1	#14	−0.27273	#8
SOC-03→ECO-02→STCK-01→SOC-04→SOC-01→SOC-03	−1	#14	−0.45455	#12
TCH-01→ECO-02→STCK-01→TCH-01	−1	#14	−1.45455	#17
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→TCH-02→COG-05→TCH-01	−1	#14	−1.54545	#19
SOC-03→STCK-01→SOC-04→SOC-01→SOC-03	−2	#19	−1.45455	#17
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-05→TCH-01	−2	#19	−2	#20
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→TCH-02→TCH-01	−2	#19	−2.27273	#21
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→TCH-01	−3	#22	−2.72727	#22

# rank number.

### 3.9. Critical Paths

Critical paths determine the most influential linear factor sequences, illustrating progressive influence without feedback loops and highlighting the strongest reinforcing and deteriorating relationships. Similar to the loop cycles, critical paths were analysed based on two primary metrics: unit weight and centrality weight. The highest positive unit weight recorded in this analysis is 10, with several paths reaching 9, indicating intense reinforcing sequences that play a significant role in VR effectiveness and implementation. Similarly, the highest negative unit weight is  $-4$ , with multiple paths approaching it, indicating the strongest deteriorating sequences that may hinder VR adoption and training outcomes.

In addition to unit weight, centrality weight was analysed to assess the overall influence of each critical path within the network. This metric measures the centrality of each factor in the sequence, highlighting paths that pass through the most interconnected factors. The highest positive centrality weight recorded is 5.82, with several paths closely following. On the other hand, the highest negative centrality weight observed is  $-3.45$ , with multiple paths approaching it. The positive and negative critical paths are detailed in the tables presented in Appendix C.

## 4. Discussion

The discussion section analyses the research's key findings, emphasising the most interconnected factors that influence the effectiveness of VR-based safety training in the construction sector. It explores the feedback loops that reinforce or hinder training outcomes, as well as the critical paths that shape the efficacy of VR-based safety training. By examining these interrelations, this section provides insights into how VR can enhance safety training practices and address industry challenges, particularly in the construction sector.

### 4.1. Key Factors

This study identified that Safety and Hazard Awareness (COG-04), Interactive and Immersive Experiences (TCH-01), Realism and Immersion (COG-05), and Worker Behaviour

(BHV-03) are among the most dominant factors influencing the effectiveness of VR-based safety training. These factors consistently rank high in SLR frequency, degree of centrality, and number of loops, highlighting their substantial impact on construction safety training outcomes, as shown in Table 8.

**Table 8.** Top factors analysis comparison.

Code	SLR Frequency	Rank	Code	Degree of Centrality	Rank	Code	Number of Loops	Rank
COG-04	47	#1	TCH-01	1.00000	#1	ECO-02	11	#1
TCH-01	30	#2	HNS-04	0.81818	#2	SOC-03	11	#1
COG-05	27	#3	COG-04	0.81818	#2	SOC-01	9	#3
COG-02	27	#3	TCH-06	0.72727	#4	TCH-01	8	#4
HNS-03	23	#5	SOC-03	0.72727	#4	COG-05	6	#5
ECO-02	23	#5	COG-05	0.72727	#4	TCH-02	6	#5
HNS-02	22	#7	BHV-03	0.72727	#4	BHV-03	3	#7
BHV-03	22	#7	HNS-01	0.63636	#8	SOC-04	3	#7
COG-03	20	#9	SOC-01	0.54545	#9	HNS-04	2	#9
BHV-01	19	#10	COG-02	0.54545	#9	COG-04	2	#9

# rank number; colours highlight the common factors across various analyses.

The ability to identify, assess, and respond to hazards is one of the most critical factors of construction safety training. VR-based safety training has been widely recognised for its ability to improve hazard recognition, situational awareness, and knowledge retention [12,17,34–36]. Studies indicate that hazard identification is a key component of effective safety management, particularly for frontline safety supervisors who play a crucial role in maintaining site safety [37]. The use of VR-based training enhances safety performance by allowing workers to engage with realistic hazard scenarios, strengthening their ability to detect risks and take preventive actions before incidents occur [38]. For example, a study by Alzarrad [39] found that VR significantly contributes to safety by enabling trainees to practice corrective actions and safety protocols before exposure to real-world hazards. The customizability of VR training further enhances its effectiveness, allowing it to simulate various hazardous conditions specific to different construction environments [34].

Additionally, VR training has demonstrated measurable improvements in construction workers' safety consciousness and behaviour, both of which are essential for reducing workplace accidents and injuries [40]. Another study by Feng, Lovreglio, Yiu, Acosta, Sun and Li [11] showed that VR can significantly enhance workers' understanding of hazards and help them develop a proactive approach to identifying safety risks before incidents occur. These findings emphasise the effectiveness of VR-based safety training in strengthening safety and hazard awareness, making it a valuable tool for reducing incidents and improving safety outcomes in the construction industry.

While hazard awareness forms the foundation of adequate safety training, the extent to which trainees engage with the learning process is equally necessary. Interactive and immersive experiences have been recognised as key factors in making safety training more effective, as they enable workers to engage in hands-on learning rather than passively receiving information [36]. Compared to traditional lecture-based training, VR simulations create highly engaging environments that will allow trainees to interact with realistic accident scenarios, perform safety procedures, and respond to hazards dynamically [41]. This active engagement leads to higher knowledge retention and improved application of safety measures in real-world construction sites [42]. Additionally, technological advancements, such as voice communication and real-time interaction, have further enhanced training engagement, enabling workers to collaborate in virtual environments and simulate real-world teamwork [43].

However, achieving high levels of realism and immersion in VR safety training requires significant investment not only in hardware and software but also in advanced interactive features, such as sensory feedback systems, environmental simulations, and lighting effects, all of which are designed to enhance trainees' sense of presence and embodiment [32,44]. Similarly, interaction technologies such as hand tracking and motion capture enhance realism by enabling workers to engage with virtual environments that closely mimic real-world tasks [39]. However, these enhancements require additional development resources, increasing the overall cost of implementing VR safety training. The cost of high-quality VR headsets and motion-tracking systems can be a challenge for many construction companies, as well as for tiny and medium-sized enterprises.

Another challenge of adopting these high levels of realism and immersion safety training is managing its potential drawbacks. A study by Eiris et al. [45] highlighted that a highly detailed virtual environment may lead to cognitive overload, making it difficult for trainees to process information effectively. Moreover, multiple studies have reported that some users experience discomfort or VR sickness when engaging with highly immersive simulations, which may hinder training effectiveness and limit participation [12,46,47].

Lastly, worker behaviour is a critical factor in construction site safety, as unsafe actions are among the causes of workplace accidents [48]. Cheng and Liao [49] found that VR-based safety training helps mitigate this issue by immersing workers in realistic hazard scenarios, reinforcing hazard recognition, and promoting proactive safety responses. Similarly, González [46] reported that VR-trained workers exhibit greater safety consciousness and improved hazard anticipation, which may contribute to reduced accident rates. However, its effectiveness depends on continued reinforcement, as workers may revert to unsafe habits without follow-up training [50].

#### 4.2. Cycles

The analysis of loop cycles highlights key reinforcing mechanisms that influence the effectiveness of VR-based safety training. The positive cycles discussed in this section were identified based on the highest unit and centrality weights, representing the most influential feedback mechanisms driving continuous improvements in safety training outcomes. It is worth noting that the loop analysis conclusions are drawn based on the construction of the causal loop diagram, and these correlations do not necessarily imply influencing-and-affected relationships. The three most influential positive loops identified in this study are:

Safety and Hazard Awareness (COG-04)→Safety Management (HNS-04)→Worker Behaviour (BHV-03)→Safety and Hazard Awareness (COG-04)

Visualisation (TCH-02)→VR Effectiveness (STCK-01)→Visualisation (TCH-02)

Knowledge and Communication Flow (SOC-03)→VR Implementation Cost (ECO-02)→VR Effectiveness (STCK-01)→Knowledge and Communication Flow (SOC-03)

The loop Safety and Hazard Awareness (COG-04)→Safety Management (HNS-04)→Worker Behaviour (BHV-03)→Safety and Hazard Awareness (COG-04) demonstrates how improved hazard awareness strengthens safety management, which in turn encourages safer worker behaviour, ultimately reinforcing safety awareness. As workers become more aware of hazards, they are more likely to follow safety protocols, thereby contributing to a structured, proactive safety management system. Stronger safety management fosters a safer work environment, reduces unsafe practices, and further reinforces hazard recognition.

Similarly, the Visualisation (TCH-02)→VR Effectiveness (STCK-01)→Visualisation (TCH-02) loop highlights how enhanced visualisation improves VR training effectiveness. Realistic virtual environments allow workers to develop spatial awareness and hazard

recognition, making risk assessment more intuitive. As VR effectiveness improves, it further enhances visualisation, reinforcing the learning process. Meanwhile, the Knowledge and Communication Flow (SOC-03)→VR Implementation Cost (ECO-02)→VR Effectiveness (STCK-01)→Knowledge and Communication Flow (SOC-03) loop underscores how investment in VR training impacts communication and knowledge-sharing. Practical training requires collaboration among various stakeholders, and while VR enhances communication flow, the cost of implementation remains a limiting factor. Despite this, well-designed VR training strengthens knowledge exchange, reinforcing the effectiveness of safety education. Ensuring the long-term impact of these loops requires sustained investment and integration into broader safety management strategies.

The negative cycles discussed in this section were identified based on the lowest unit and centrality weight values, representing the most constraining feedback mechanisms that hinder the effectiveness of VR-based safety training. While multiple negative loops were detected, several shared similar structures and influencing factors, differing only in minor variations. To ensure a focused discussion, two representative loops were selected as they exhibited the lowest weight values while following similar patterns:

Interactive and Immersive Experiences (TCH-01)→VR Implementation Cost (ECO-02)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03)→VR Effectiveness (STCK-01)→Interactive and Immersive Experiences (TCH-01)

Knowledge and Communication Flow (SOC-03)→VR Implementation Cost (ECO-02)→VR Effectiveness (STCK-01)→Language Barriers (SOC-04)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03)

The loop Interactive and Immersive Experiences (TCH-01)→VR Implementation Cost (ECO-02)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03)→VR Effectiveness (STCK-01)→Interactive and Immersive Experiences (TCH-01) highlights how financial constraints impact VR adoption and training effectiveness. Developing VR-based training, including accurate hazard representation and interactive simulations, requires substantial investment, which can discourage organisations from fully integrating VR into their safety programs. Additionally, some companies fear that relying on VR-based training may lead to a loss of tacit knowledge typically transferred through experienced professionals. Moreover, a lack of communication between trainers and trainees might result in inadequate training outcomes. This loop demonstrates how financial and adoption barriers create a cycle that prevents VR from reaching its full potential as a training tool.

Similarly, the loop Knowledge and Communication Flow (SOC-03)→VR Implementation Cost (ECO-02)→VR Effectiveness (STCK-01)→Language Barriers (SOC-04)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03) illustrates how communication gaps and financial barriers further undermine VR training accessibility. Developing practical VR training requires structured communication between developers, trainers, and workers, but limited coordination can make VR implementation inefficient. Additionally, language barriers can hinder workers' ability to engage with VR training, reducing its overall effectiveness. This results in lower adoption rates, making it less likely for organisations to invest in VR improvements. The cycle reinforces itself as VR training remains underutilised, preventing widespread adoption and limiting its impact on construction safety.

#### 4.3. Critical Paths

Identifying the critical paths among key factors in VR-based safety training is crucial for understanding the most influential sequences that impact safety outcomes. This study identified 3981 unique critical paths, of which 3835 contain VR Effectiveness (STCK-01), demonstrating the central role of VR-based safety training in shaping safety outcomes.

Six critical paths consistently appeared among the top 10 highest-ranked sequences based on unit and centrality weight, indicating their significant influence on safety training performance. The application of unit weight and centrality weight accounts for the polarity of their interrelations and the net impact of the path. This analysis will benefit when quantifying the specific factors' effect is not possible with simple data, or when collecting data is time-consuming. Though this may not suggest a workflow, it provides specific links to target for effective training. These paths are:

- TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01
- TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01
- TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01
- TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01
- TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-04→HNS-04→BHV-03→HNS-01
- TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-04→BHV-03→COG-04→HNS-01

Across all six positive critical paths, they share a recurring sequence: VR Framework (TCH-06)→User Interaction and Navigation (TCH-04)→VR Effectiveness (STCK-01)→Visualisation (TCH-02)→Realism and Immersion (COG-05)→Interactive and Immersive Experiences (TCH-01). The sequence begins with the VR Framework (TCH-06), which provides the foundation for effective training by enabling seamless User Interaction and Navigation (TCH-04). When trainees can engage with virtual environments intuitively, VR Effectiveness (STCK-01) improves, reinforcing the role of Visualisation (TCH-02) in hazard perception. High-quality visual representations strengthen Realism and Immersion (COG-05), allowing workers to experience training scenarios as if they were on real-world construction sites. This increased realism fosters Interactive and Immersive Experiences (TCH-01), where active engagement enhances multiple factors: Safety Management (HNS-04), Worker Behaviour (BHV-03), and Safety and Hazard Awareness (COG-04). Ultimately, these positive reinforcement paths support Incident Reduction (HNS-01), highlighting how VR-based safety training could effectively improve safety outcomes.

Despite its potential, the effectiveness of VR-based safety training can be hindered by financial constraints, adaptation challenges, and communication barriers. The top two dominant negative critical paths are:

- TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-04→BHV-03→HNS-04→HNS-01
- TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-07→HNS-01

Across both negative critical paths, the chains start with recurring factors such as Interactive and Immersive Experiences (TCH-01)→VR Implementation Cost (ECO-02)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03)→VR Effectiveness (STCK-01). This sequence begins with Interactive and Immersive Experiences (TCH-01), where high-quality, realistic VR simulations are essential for effective engagement. However, achieving this level of immersion requires advanced hardware and software development, which raises implementation costs (ECO-02) and makes large-scale adoption difficult, especially for smaller construction firms. Limited VR Adoption (SOC-01) restricts access to comprehensive safety training, creating gaps in Knowledge and Communication Flow (SOC-03) and reducing the overall VR effectiveness. Poor Safety and Hazard Awareness (COG-04) and increased stress levels (COG-07) weakened workers' ability to recognise and

mitigate risks. This lack of awareness contributes to unsafe Worker Behaviour (BHV-03), ultimately increasing the likelihood of workplace incidents (HNS-01).

These findings underscore the pivotal role of VR-based safety training in shaping safety management, worker behaviour, and hazard awareness while also highlighting key barriers that may limit its effectiveness. Addressing the challenges of technology adoption, financial constraints, and communication gaps is essential to enhancing the integration and effectiveness of VR-based training in construction safety. By allowing employees to interact with realistic hazard scenarios in a safe setting, VR training serves as a more engaging and effective alternative to traditional methods. These research findings underscore essential practical benefits for the construction industry by showcasing the critical factors, its networks, loops and critical paths of VR-based safety training. This immersive approach can boost understanding of the factors affecting VR-based training, improve worker engagement, enhance hazard detection, reduce risk, and improve knowledge retention. Nevertheless, for widespread implementation, organisations need to tackle financial limitations and technological barriers to ensure it is both accessible and scalable. Additionally, strategies must be developed to alleviate VR-related discomfort and cognitive overload, ensuring that training is practical for diverse workforce groups.

The study presents a structured framework for assessing the effectiveness of virtual reality (VR) in safety training, contributing to existing literature. This systematic approach clarifies how behavioural, technological, and financial factors interact to affect training outcomes. The research uncovers key insights into the adoption and success of VR-based safety programs. The findings have significant implications for the construction sector, highlighting VR training's ability to enhance engagement, hazard recognition, and knowledge retention. This immersive approach allows workers to interact with realistic hazard scenarios in a controlled setting, offering a more effective alternative to traditional methods. However, for broader adoption, organisations must overcome financial and technological barriers to ensure VR training is accessible and scalable. It is also crucial to address VR sickness and cognitive overload to improve the training experience for diverse workforce groups. Theoretically, this research contributes to the understanding of VR's role in safety training by providing a structured framework for analysing its effectiveness. This approach not only clarifies how different factors interplay to shape training outcomes but also emphasises the significance of various determinants that influence the success of VR-based training initiatives.

## 5. Conclusions

This study examined the interrelationships among key factors that influence the effectiveness of VR-based safety training in the construction sector. In alignment with the research aim of understanding the key factors that influence VR-based safety training effectiveness and their impact on the construction sector, the study conducted a systematic literature review and interrelation analysis to determine critical elements. Among the identified factors, Safety and Hazard Awareness (COG-04), Interactive and Immersive Experiences (TCH-01), Realism and Immersion (COG-05), and Worker Behaviour (BHV-03) emerged as the most influential. These factors influence hazard recognition, user engagement, knowledge retention, and behavioural adaptation, collectively reinforcing the potential of VR-based safety training to improve safety performance within construction environments.

Furthermore, this study also examined how reinforcing loops shape VR training outcomes, either reinforcing safety training outcomes or exacerbating barriers to effective learning. The most significant positive and negative loop cycles include:

Positive Loop Cycles:

- Safety and Hazard Awareness (COG-04)→Safety Management (HNS-04)→Worker Behaviour (BHV-03)→Safety and Hazard Awareness (COG-04).
- Visualisation (TCH-02)→VR Effectiveness (STCK-01)→Visualisation (TCH-02).
- Knowledge and Communication Flow (SOC-03)→VR Implementation Cost (ECO-02)→VR Effectiveness (STCK-01)→Knowledge and Communication Flow (SOC-03).

Negative Loop Cycles:

- Interactive and Immersive Experiences (TCH-01)→VR Implementation Cost (ECO-02)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03)→VR Effectiveness (STCK-01)→Interactive and Immersive Experiences (TCH-01).
- Knowledge and Communication Flow (SOC-03)→VR Implementation Cost (ECO-02)→VR Effectiveness (STCK-01)→Language Barriers (SOC-04)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03).

In addition to determining reinforcing loops, this study revealed critical paths that significantly influence VR-based training effectiveness. The most impactful critical paths are:

- VR Framework (TCH-06)→User Interaction and Navigation (TCH-04)→VR Effectiveness (STCK-01)→Visualisation (TCH-02)→Realism and Immersion (COG-05)→Interactive and Immersive Experiences (TCH-01).
- Technology Adaptability (BHV-04)→Stress Level (COG-07)→VR Effectiveness (STCK-01)→Interactive and Immersive Experiences (TCH-01)→VR Implementation Cost (ECO-02)→VR Adoption (SOC-01)→Knowledge and Communication Flow (SOC-03).

### 5.1. Research Limitation

While this study provides valuable insights into VR-based safety training, several limitations must be acknowledged. First, reliance on secondary data from the published literature may introduce selection bias, potentially limiting the direct applicability of the findings to real-world construction environments. Second, the study focused on factors influencing VR safety training effectiveness without considering the technological constraints that could affect implementation. For example, variations in VR hardware accessibility and integration with existing safety management systems could introduce additional challenges. Third, this study employed specific inclusion and exclusion criteria, which may have influenced the scope of the findings. Most articles studied in SLR measure the factors in their studies; however, many have not investigated the effects of these factors on training effectiveness, which is acknowledged. The selection criteria prioritised studies published in English and those accessible through selected academic databases, potentially excluding relevant research from non-English sources or other databases. Lastly, Factors and themes were based on the research team's subjective judgment of the articles, and this limitation is acknowledged. However, the strict process followed and rigorous analysis offset these limitations to a greater extent.

### 5.2. Practical and Theoretical Implications

This study presents significant practical implications for the construction sector by highlighting the potential of VR-based safety training to enhance engagement, improve hazard recognition, and increase knowledge retention. By enabling workers to interact with realistic hazard scenarios in a controlled environment, VR training offers a more immersive and effective alternative to traditional training methods. However, for widespread adoption, organisations must address financial constraints and technological challenges to ensure accessibility and scalability. Additionally, strategies to mitigate VR sickness and cognitive overload must be considered to optimise training effectiveness across diverse workforce groups.

From a theoretical perspective, this research contributes to the existing body of knowledge by offering a structured interrelation analysis framework for assessing VR effectiveness in safety training. By determining key reinforcing loops and critical paths, this study provides a systematic approach to understanding how various factors interact to shape VR training outcomes. The findings offer insights into the roles of behavioural, technological, and financial determinants in shaping the adoption and effectiveness of VR-based safety programs.

### 5.3. Future Research

Future research should validate these findings through industry case studies and empirical analyses. Longitudinal studies assessing the long-term impact of specific factors and their interrelationships with VR training would provide further evidence of its effectiveness. Additionally, exploring emerging technology-related factors, such as Artificial Intelligence-driven adaptive learning and haptic feedback systems, offers opportunities to further refine and enhance VR training methodologies. Reflecting on these advancements, technology could revolutionise not just training methods but also the very culture of safety on construction sites. The potential to simulate high-risk scenarios in a controlled environment allows workers to gain valuable experience without the direct consequences of real-world errors.

Understanding the evolving relationship between VR training, AI, and construction site safety protocols will be crucial for optimising future training frameworks and ensuring widespread industry adoption. Furthermore, fostering collaboration between technology developers and industry stakeholders will be essential in creating solutions that address both practical needs and safety regulations, ultimately creating a safer work environment and improving overall efficiency. This collaborative approach could lead to continuously evolving training practices that adapt to new challenges in the construction industry.

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## Abbreviations

The following abbreviations are used in this manuscript:

VR	Virtual Reality
SLR	Systematic Literature Review
OSH	Occupational Safety and Health
KOSHA	Korea Occupational Safety and Health Agency
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
CLD	Causal Loop Diagram



AN	Author	Country	BHV-01	BHV-02	BHV-03	BHV-04	BHV-05	COG-01	COG-02	COG-03	COG-04	COG-05	COG-06	COG-07	COG-08	COG-09	COG-10	ECO-01	ECO-02	ECO-03	ECO-04	HNS-01	HNS-02	HNS-03	HNS-04	SOC-01	SOC-02	SOC-03	SOC-04	TCH-01	TCH-02	TCH-03	TCH-04	TCH-05	TCH-06		
29	Harichandran and Teizer [60]	Denmark													✓									✓			✓		✓								
30	Hussain, Sabir, Lee, Zaidi, Pedro, Abbas and Park [29]	Republic of Korea	✓	✓	✓				✓	✓	✓			✓										✓		✓	✓	✓									
31	Ismara, Supriadi and Mubarok [10]	Indonesia	✓						✓		✓								✓		✓	✓		✓					✓								
32	Jacobsen et al. [61]	China									✓	✓							✓				✓										✓				
33	Jeelani et al. [23]	USA	✓		✓				✓		✓	✓							✓						✓									✓			
34	Jiang et al. [62]	Australia						✓	✓		✓	✓							✓				✓	✓	✓							✓		✓			
35	Joshi, Hamilton, Warren, Faucett, Tian, Wang and Ma [17]	USA	✓	✓					✓	✓	✓	✓								✓	✓	✓	✓	✓						✓	✓						
36	Kang et al. [63]	Canada								✓	✓	✓															✓										
37	Kim, Ahn, Miller, Dibello, Lobello, Oh and McNamara [50]	USA	✓		✓						✓											✓	✓							✓							
38	Kwegyir-Afful and Kantola [64]	Finland							✓		✓	✓																		✓							
39	Liu and Li [20]	China	✓						✓		✓	✓					✓						✓					✓	✓								
40	Lu et al. [65]	China			✓				✓		✓	✓	✓				✓						✓														
41	Mondragón-Bernal [66]	Colombia																											✓								
42	Noghabaei and Han [37]	USA			✓						✓											✓															
43	Noghabaei and Han [67]	USA									✓	✓													✓												
44	Nykänen et al. [68]	Finland		✓							✓	✓	✓		✓								✓							✓							
45	Ouyang and Luo [69]	China			✓			✓			✓								✓				✓	✓	✓				✓								
46	Pedro et al. [70]	Republic of Korea			✓				✓	✓	✓												✓	✓	✓					✓							
47	Rey-Becerra et al. [71]	Germany	✓	✓					✓	✓	✓		✓								✓		✓	✓	✓					✓							
48	Rokoeei, Shojaei, Alvanchi, Azad and Didehvar [7]	USA	✓								✓	✓							✓							✓	✓			✓	✓				✓		
49	Seo, Park and Koo [27]	Republic of Korea		✓					✓	✓	✓	✓	✓										✓														
50	Shi et al. [72]	USA			✓							✓		✓	✓								✓						✓								
51	Shin et al. [73]	Republic of Korea									✓	✓		✓								✓															
52	Shringi, Arashpour, Dwyer, Prouzeau and Li [38]	Australia							✓		✓	✓											✓							✓							
53	Shringi et al. [74]	Australia	✓						✓	✓	✓	✓	✓										✓	✓													
54	Smuts, Manga and Smallwood [35]	South Africa	✓					✓		✓	✓	✓		✓		✓	✓						✓	✓	✓					✓							
55	Wu, Yu et al. [40]	China			✓				✓		✓											✓								✓							
56	Yu et al. [75]	China									✓													✓					✓								
57	Zhang et al. [76]	China	✓										✓				✓									✓			✓								
58	Zhang and Pan [77]	China			✓				✓	✓	✓		✓		✓							✓	✓	✓				✓		✓							





## Appendix C. Critical Paths Analysis. Authors Own Creation

### Appendix C.1. Top 16 Positive Unit Weight Critical Paths

Path	Unit Weight
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	10
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	10
TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	9
TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-04→HNS-04→BHV-03→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-04→BHV-03→COG-04→HNS-01	9
TCH-06→TCH-04→STCK-01→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	9
TCH-06→TCH-04→STCK-01→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→COG-03→BHV-03→COG-04→HNS-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	9
TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	9
TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	9
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→HNS-01	9

### Appendix C.2. Top 4 Negative Unit Weight Critical Paths. Authors Own Creation

Path	Unit Weight
BHV-04→COG-07→STCK-01→TCH-01→ECO-02→SOC-01→SOC-03→COG-04→BHV-03→HNS-04→HNS-01	-4
BHV-04→COG-07→STCK-01→TCH-01→ECO-02→SOC-01→SOC-03→COG-02→HNS-01	-4
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-07→HNS-01	-4
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-04→BHV-03→HNS-04→HNS-01	-4

### Appendix C.3. Top 10 Positive Centrality Weight Critical Paths. Authors Own Creation

Path	Centrality Weight
TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	5.82
TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	5.82
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	5.73
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	5.73
TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→COG-04→HNS-04→BHV-03→HNS-01	5.55
TCH-06→SOC-03→ECO-02→STCK-01→TCH-02→COG-05→TCH-01→HNS-04→BHV-03→COG-04→HNS-01	5.55
TCH-06→BHV-05→STCK-01→TCH-02→COG-05→TCH-01→COG-03→BHV-03→COG-04→HNS-04→HNS-01	5.45
TCH-06→BHV-05→STCK-01→TCH-02→COG-05→TCH-01→HNS-03→HNS-04→BHV-03→COG-04→HNS-01	5.45
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→COG-04→HNS-04→BHV-03→HNS-01	5.45
TCH-06→TCH-04→STCK-01→TCH-02→COG-05→TCH-01→HNS-04→BHV-03→COG-04→HNS-01	5.45

### Appendix C.4. Top 12 Negative Centrality Weight Critical Paths. Authors Own Creation

Path	Centrality Weight
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-04→BHV-03→HNS-04→HNS-01	-3.45
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-01→COG-04→BHV-03→HNS-04→HNS-01	-3.09

Path	Centrality Weight
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-07→HNS-01	−3
TCH-02→TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-04→BHV-03→HNS-04→HNS-01	−3
COG-05→STCK-01→TCH-01→ECO-02→SOC-01→SOC-03→COG-02→HNS-01	−2.91
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-04→BHV-03→HNS-01	−2.82
COG-05→TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-04→BHV-03→HNS-04→HNS-01	−2.73
COG-05→STCK-01→TCH-01→ECO-02→SOC-01→SOC-03→COG-04→BHV-03→HNS-04→HNS-01	−2.73
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→HNS-01	−2.73
TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-05→COG-04→BHV-03→HNS-04→HNS-01	−2.73
TCH-06→TCH-01→ECO-02→SOC-01→SOC-03→STCK-01→COG-04→BHV-03→HNS-04→HNS-01	−2.73
TCH-04→COG-05→STCK-01→TCH-01→ECO-02→SOC-01→SOC-03→COG-02→HNS-01	−2.73

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