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Research Article

Evaluating the Drivers of Immersive Technologies Implementation for Health and Safety Management in the Construction Industry

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Abstract

Despite immersive technologies having significant potential to enhance health and safety performance in construction, their uptake in developing countries such as Ghana remains slow due to technological, organisational, and contextual limitations. This study investigates the key drivers influencing ImTs adoption to support safer construction practices in resource-constrained settings. A two-phase approach was employed: first, 16 adoption drivers were identified through an extensive literature review and expert consultation; second, a questionnaire survey of 204 construction professionals—selected using purposive and snowball sampling—generated quantitative data for analysis. Factor analysis revealed three underlying dimensions shaping ImTs adoption decisions: Collaborative Safety Enhancement and Organisational Readiness; Technological Performance and Safety Management Capabilities; and Implementation Support and Technological Advancement. Fuzzy synthetic evaluation (FSE) was then applied to assess the criticality of these categories, identifying Technological Performance and Safety Management Capabilities as the most influential (index = 4.17), followed by Implementation Support and Technological Advancement (3.83) and Collaborative Safety Enhancement and Organisational Readiness (3.78). The study offers empirical, factor-based insights into ImTs implementation and proposes a fuzzy evaluation model for decision-making under uncertainty. The findings contribute to the limited developing-country literature and inform targeted strategies to overcome adoption barriers and strengthen construction safety management.

Keywords: Construction safety management; Fuzzy synthetic evaluation (FSE); Ghana; Health and safety; Immersive technologies; Implementation drivers

Highlights

- ImTs adoption is highly driven by safety performance gains.
- Technological capability and integration outweigh organisational and regulatory drivers.
- Human factors (training, awareness) are critical for successful uptake.

1 Introduction

The construction industry plays a central role in global socio-economic development, accounting for approximately 7% of global employment and 13% of global Gross Domestic Product (GDP) (Adami et al., 2021; Pittri et al., 2026a; Bhagwat et al., 2021). However, it also consistently ranks among the most hazardous industries worldwide, recording injury and fatality rates far exceeding those of other economic sectors (Dutta, 2017; Häikio et al., 2020). More than 100,000 workers die annually on construction sites according to the International Labour Organisation, reflecting deep-rooted concerns about ineffective hazard detection, insufficient safety communication, and limited capacity for proactive risk management (International Labour Organisation (ILO), 2015; Pittri et al., 2025a). These challenges are exacerbated by the industry's labour-intensive nature, high employee turnover, and fragmented supply chains, making robust Occupational Safety and Health (OSH) management a persistent and complex endeavour (Zhao et al., 2016). Traditional safety practices, largely reliant on manual observations, toolbox meetings, and paper-based reporting, struggle to cope with the increasing complexity, dynamism, and fragmentation of modern construction projects (Zhao et al., 2016; Williams et al., 2020). Perlman et al. (2014) recognised that about 57% of hazards in construction sites are not recognised, partly due to traditional approaches to safety training and assessment.

These global challenges are even more pronounced in developing countries such as Ghana, where construction activities are constrained by structural deficiencies, weak regulatory enforcement, poor safety culture, and chronic underinvestment in digital technologies (Osei-Asibey et al., 2021; Agyekum et al., 2022; Pittri et al., 2026b). Despite being a key driver of national development, the Ghanaian construction industry (GCI) continues to face high accident rates linked to limited hazard visibility, inadequate training, low managerial commitment, and inefficient communication pathways on site (Takyi et al., 2021; Adade-Boateng et al., 2023; Pittri et al., 2025a). As Ghana pursues broader digital transformation and seeks to strengthen OSH outcomes, there is growing interest in innovative, technology-driven approaches to safety management.

Immersive Technologies (ImTs) including Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) have emerged as transformative tools capable of reshaping construction safety management. Their ability to create realistic hazard simulations, enhance situational awareness, support interactive training, and integrate digital overlays onto physical environments positions them as a promising response to long-standing OSH challenges (Sacks et al., 2013; Afzal and Shafiq, 2021; Rauh et al., 2021). VR has demonstrated strong potential in risk-free training and behavioural improvement (Babalola et al., 2023); AR enhances on-site hazard identification through real-time visual cues (Li et al., 2018); and MR offers hybrid environments for collaborative safety planning, inspection, and design review (Rauh et al., 2021; Pittri et al., 2023). With the increasing convergence of ImTs with complementary technologies such as Building Information Modelling (BIM), eye-tracking technologies and Internet of Things (IoT) sensors, studies demonstrate significant potential for integrated, predictive, and real-time safety monitoring systems (Alizadehsalehi et al., 2020; Chung et al., 2021).

Despite these promises, ImTs adoption in developing countries remains extremely limited, fragmented, and poorly understood (Oke et al., 2023; Eiris et al., 2020). The existing literature reveals several unresolved gaps that constrain both academic understanding and industrial implementation. First, most prior studies examine isolated ImTs applications—focusing on single tools (e.g., VR for training or AR for hazard detection) (Purushothaman et al., 2025; Afzal et al., 2021; Pedram et al., 2021) and specific tasks—while overlooking the broader ecosystem of organisational, technological, socio-economic, and contextual drivers that shape adoption decisions. Second, empirical evidence is heavily skewed toward developed economies, with limited attention to the structural, cultural, and infrastructural realities of developing countries where technology uptake is influenced by resource constraints and institutional weaknesses (Adami et al., 2021; Joshi et al., 2021). As a result, it is unclear which adoption drivers are most relevant or critical in such environments. Third, within Ghana, although

digitalisation is increasingly prioritised in construction and national development policies, no study has undertaken a systematic, quantitative assessment of the drivers that enable or hinder ImTs implementation for OSH management. The absence of such knowledge limits the ability of practitioners, regulators, and policymakers to make informed decisions about investing in or supporting ImTs.

These gaps highlight a broader research problem: there is insufficient empirical and context-specific understanding of the technological, organisational, and environmental drivers that shape ImTs implementation for safety management in the GCI. Without such insights, organisations risk making misguided investments, overlooking critical readiness factors, or implementing ImTs in piecemeal ways that undermine long-term safety improvements. This study addresses these gaps by examining the full spectrum of VR, AR and MR technologies as used for Health and Safety (H&S) management. The study is guided by the following research questions:

1. What are the key drivers influencing the implementation of ImTs (VR, AR, and MR) for H&S management in the GCI?
2. What is the underlying factor structure of these drivers?
3. What is the relative criticality of the identified driver factors in the GCI?

The novelty and significance of this study lie in three key contributions. First, it provides the first quantitative, Ghana-specific evaluation of ImTs adoption drivers for OSH management, addressing a critical gap in existing literature. Second, the study develops a rigorous evaluative model that integrates Exploratory Factor Analysis (EFA) with Fuzzy Synthetic Evaluation (FSE), enabling a nuanced prioritisation of drivers under uncertainty, an approach rarely applied in technology adoption research within developing countries. A quantitative, factor-based approach is necessary to move beyond mere identification to provide actionable, evidence-based guidance for industry practitioners and policymakers. Third, the findings offer practical guidance for aligning ImTs adoption with Ghana's ongoing digitalisation efforts, OSH policy objectives, and construction industry capacity-building initiatives. By uncovering the critical drivers that influence implementation success, this study supports both academic discourse on construction digitalisation and industry efforts to modernise safety management practices.

This study holds strong relevance to global sustainability agendas by advancing safer, more resilient, and digitally enabled construction practices. By identifying the critical drivers enabling ImTs adoption for H&S management in Ghana, the research directly supports SDG 3 (Good Health and Well-being) and SDG 8 (Decent Work and Economic Growth) through its focus on reducing workplace injuries and improving labour conditions. It further contributes to SDG 9 (Industry, Innovation and Infrastructure) by promoting the uptake of advanced digital tools aligned with global Construction 4.0 priorities, while indirectly supporting SDG 11 (Sustainable Cities and Communities) through safer and more sustainable construction processes. Importantly, by addressing a major knowledge gap in a developing-country context, the study aligns with global commitments to equitable digital transformation and the broader international push—led by bodies such as the UN, ILO, and World Economic Forum—for technology-driven improvements in occupational safety and resilient infrastructure development.

2 Literature Review

2.1 Definition and Application of Immersive Technologies in H&S Management

Immersive technologies (ImTs) have emerged as powerful tools in construction H&S management, offering new approaches to address traditional safety challenges. These technologies encompass VR, AR and MR, each providing distinct capabilities for enhancing safety practices (Babalola et al., 2023). VR creates fully immersive computer-generated environments accessed through head-mounted

displays or projection systems, while AR overlays digital information onto the real world, allowing users to maintain awareness of their physical surroundings. MR represents a more sophisticated blend, enabling digital objects to interact with the real environment (Rauh et al., 2021).

The application of ImTs in construction safety management has primarily focused on training and hazard identification. VR-based safety training has demonstrated improved knowledge retention and hazard awareness compared to traditional methods, particularly in high-risk scenarios (Sacks et al., 2013). For example, Joshi et al. (2021) reported enhanced understanding of safety protocols among workers in the precast/prestressed concrete industry through VR training programs. AR applications have proven effective for real-time hazard identification during construction operations, allowing safety managers to identify and address potential risks proactively (Afzal and Shafiq, 2021). ImTs also facilitate better safety planning and communication through virtual site walkthroughs and collaborative safety reviews. These capabilities enable project stakeholders to assess and optimise safety measures before construction begins, supporting a proactive approach to safety management (Getuli et al., 2018). Emergency response training has been enhanced through virtual environments where workers can practice crisis procedures without exposure to actual dangers (Pedram et al., 2021; Pittri et al., 2023).

Recent developments have seen the integration of ImTs with Building Information Modeling (BIM) and Internet of Things (IoT) sensors, creating more comprehensive safety management solutions (Alizadehsalehi et al., 2020). These integrations enhance the ability to provide real-time safety monitoring and predictive hazard identification. However, successful implementation requires careful consideration of user acceptance, technical infrastructure, and organisational readiness (Prabhakaran et al., 2022). When properly integrated within a broader safety management framework, ImTs show significant potential for improving construction safety outcomes through their ability to provide real-time visualisation, risk-free experience, and enhanced engagement in safety practices.

2.2 Drivers of Immersive Technologies Implementation for H&S Management

The implementation of ImTs for H&S management in the construction industry is driven by several key factors. These drivers can be broadly categorised into technological, organisational, and environmental factors that facilitate the adoption of ImTs for enhancing safety practices. One of the primary drivers is enhanced stakeholder engagement in design reviews that ImTs enable (Li et al., 2018). Through virtual and AR platforms, multiple stakeholders can collaboratively review safety considerations during the design phase, leading to better hazard identification and mitigation strategies before construction begins. This increased engagement helps prevent safety issues early in the project lifecycle rather than addressing them reactively during construction.

The increasing awareness of the benefits of ImTs has played a significant role in accelerating their adoption for H&S management (Prabhakaran et al., 2022). As organisations become more informed about the capacity of ImTs to enhance hazard visualisation, improve risk communication, and deliver interactive, experience-based safety training, their perceived value becomes more tangible. This growing recognition reduces uncertainty and resistance to change, particularly in traditionally conservative construction environments. Consequently, organisations are more willing to allocate resources toward ImTs, viewing them not as experimental tools but as strategic investments capable of improving safety performance and operational effectiveness.

The proven effectiveness of ImTs in reducing workplace accidents serves as a compelling driver, with studies demonstrating improved hazard recognition and risk awareness among workers trained using immersive platforms (Sacks et al., 2013).

Another significant driver is the enhanced safety hazard identification and visualisation capabilities offered by ImTs (Park et al., 2013). These technologies allow for the realistic simulation of hazardous scenarios and safety protocols, enabling workers to experience and respond to dangerous situations without actual exposure to risks. This capability is particularly valuable for high-risk construction

activities where traditional training methods may be inadequate or impractical. The streamlined site operations and monitoring enabled by ImTs also drive their implementation (Afzal et al., 2021). Through AR overlays and virtual monitoring systems, safety managers can more effectively oversee construction activities and identify potential hazards in real-time. This enhanced operational efficiency contributes to better safety outcomes while potentially reducing supervision costs.

Improved safety-oriented design optimisation represents another key driver (Alizadehsalehi et al., 2020). ImTs facilitate better integration of safety considerations into the design process through improved visualisation and simulation capabilities. This allows designers to evaluate and optimise safety features more effectively during the planning phase.

The integration capability of ImTs with existing construction systems, particularly BIM, represents a critical driver of adoption (Wang et al., 2012). The ability to seamlessly embed ImTs within established digital workflows enhances their usability and reduces disruption to existing processes, thereby lowering implementation resistance. This interoperability allows organisations to combine visualisation, data analytics, and real-time monitoring within a unified environment, improving coordination and decision-making. Moreover, integrating ImTs with BIM and other digital tools supports more holistic and data-driven safety management, enabling proactive risk identification and more effective communication across project stakeholders.

Increasing management support and buy-in has emerged as a crucial organisational driver (Li et al., 2018). As construction industry leaders better understand the potential return on investment from ImTs implementation in terms of improved safety performance and reduced accident-related costs, they are more likely to support adoption initiatives. The limitation of traditional safety management methods in addressing modern construction challenges also drives ImTs adoption (Afzal and Shafiq, 2021). Conventional approaches often struggle to effectively address the complexity and dynamic nature of modern construction projects, creating a need for more sophisticated safety management tools. A supportive regulatory environment has also emerged as an important driver (Zhou et al., 2012). As safety regulations become more stringent and emphasise the use of advanced technologies for risk management, organisations are increasingly motivated to implement ImTs to ensure compliance and demonstrate commitment to worker safety.

The decreasing implementation costs of ImTs, driven by rapid technological advancements, increased competition among solution providers, and growing market maturity, have significantly improved their accessibility to construction organisations of varying sizes (Prabhakaran et al., 2022). As hardware becomes more affordable and software platforms more user-friendly, the initial investment barriers are gradually reduced. However, beyond upfront costs, the economic value of ImTs lies in their ability to deliver long-term savings through reduced accident rates, lower compensation claims, improved productivity, and minimised rework. Consequently, when evaluated from a lifecycle cost perspective, ImTs present a strong business case, particularly for organisations seeking to enhance safety performance while maintaining operational efficiency (Pittri et al., 2023).

2.3 Theoretical Underpinnings of Technology Adoption

To provide a robust theoretical foundation for understanding the drivers of ImTs adoption in the GCI, it is essential to situate this study within established technology adoption frameworks. Two widely recognised theoretical lenses are particularly relevant: the Technology-Organisation-Environment (TOE) framework (Tornatzky and Fleischer, 1990) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al., 2003). The TOE framework posits that an organisation's adoption of a technological innovation is influenced by three contextual dimensions: technological context (e.g., the technology's characteristics, integration capabilities, and performance), organisational context (e.g., firm size, resources, management support, and readiness), and environmental context (e.g., regulatory environment, market conditions, and competitive pressure). This multi-dimensional perspective is

particularly valuable for analysing innovation adoption in resource-constrained settings like Ghana, where organisational readiness and weak regulatory enforcement significantly shape implementation outcomes (Pittri et al., 2026b; Agyekum et al., 2022). Similarly, UTAUT emphasises key determinants of user acceptance and behaviour, including performance expectancy (the perceived benefit of the technology), effort expectancy (ease of use), social influence, and facilitating conditions (e.g., infrastructure and training). In developing-country contexts, where user familiarity with digital tools may be limited (Pittri et al., 2025b), these factors critically influence the uptake and sustained use of technologies such as VR, AR, and MR for safety management (Pittri et al., 2023; Agyekum et al., 2022).

Building on these theoretical foundations, this study adopts an integrated perspective that aligns with the TOE and UTAUT constructs. The drivers identified in this study, such as integration capability with existing construction technologies (technological context), increasing management support and buy-in (organisational context), and supportive regulatory environment (environmental context), directly map onto the TOE framework. Likewise, drivers such as enhanced safety hazard identification and visualisation (performance expectancy), streamlined site operations (effort expectancy), and growing awareness of ImTs benefits (social influence) resonate with the core tenets of UTAUT. By grounding the empirical investigation in these established theories, this study not only enhances the conceptual clarity of the drivers under examination but also facilitates cross-contextual comparison with technology adoption research in other developing economies. Furthermore, this theoretical grounding enables a more nuanced interpretation of the FSE results in this study.

3 Materials and Methods

3.1 Research Design

To achieve a comprehensive understanding of the drivers influencing the implementation of ImTs for H&S management in the construction industry, this study adopted a quantitative research approach. This approach is particularly suitable for enabling the generalisation of findings to a broader population and relies on structured data collection methods, such as questionnaire surveys (Burrell and Morgan, 2019). In this study, a structured questionnaire incorporating interval Likert-type scales was employed to systematically capture respondents' perceptions of the identified drivers. This facilitated the application of descriptive and inferential statistical techniques for data analysis, thereby enhancing the robustness and reliability of the findings. Moreover, the use of questionnaires supports quantifiability and objectivity, allowing for consistent measurement and comparison across respondents (Ackroyd and Hughes, 1992). Consequently, this approach is well-suited to examining patterns and drawing generalisable conclusions among construction professionals within the GCI.

3.2 Identification of the Drivers to Immersive Technologies Implementation for H&S Management

The identification of relevant drivers influencing ImTs implementation for H&S management in the construction industry followed a systematic two-phase quantitative approach. The initial phase involved a comprehensive review of scholarly literature through established academic databases including Scopus, Web of Science, and Google Scholar. The literature search employed key search terms such as “immersive technologies,” “health and safety management,” “construction industry,” and “technology adoption.” The second phase involved conducting a pilot study with industry experts to validate and refine the identified drivers. The pilot study engaged 15 carefully selected experts, comprising both academic researchers and industry practitioners with substantial experience in ImTs adoption and familiarity with the GCI. These experts were tasked with evaluating the comprehensiveness and relevance of the identified drivers, assessing their significance within the local context, and suggesting additional factors that might have been overlooked in the literature review. The feedback gathered through the pilot study was instrumental in refining the final list of drivers. This

process involved eliminating redundant or less relevant factors while incorporating new ones based on expert recommendations. The rigorous qualitative approach, combining scholarly evidence with practitioner insights, resulted in the identification of 16 distinct drivers relevant to ImTs implementation in construction H&S management. These drivers encompass various dimensions including technological capabilities, organisational readiness, economic considerations, social factors, and policy frameworks that constitute the construction safety innovation ecosystem.

3.3 Questionnaire Survey and Participants

A structured questionnaire was developed to collect quantitative data regarding the drivers influencing the implementation of ImTs for H&S management in the GCI. The questionnaire design was informed by the 16 drivers identified through the literature review and pilot study. To assess the criticality of each driver, respondents were asked to rate them using a 5-point Likert scale, where 1 represented "not critical (NC)," 2 "fairly critical (FC)," 3 "critical (C)," 4 "very critical (VC)," and 5 "extremely critical (EC)." This rating scale approach has been widely validated in construction management research, as evidenced by similar studies (Pittri et al., 2024a; Ameyaw and Chan, 2015). The scale provided respondents with sufficient flexibility to evaluate each driver while ensuring the data would be suitable for subsequent statistical analysis.

The survey targeted construction industry practitioners in Ghana using a purposive sampling technique to identify qualified experts. Participant selection was based on two primary criteria: (1) extensive working experience in the GCI, and (2) in-depth knowledge of technological innovations for improving H&S management. These criteria ensured that respondents possessed substantial practical experience and were well-versed in H&S concerns within Ghanaian construction projects, enabling them to provide reliable assessments.

To expand the participant pool, snowball sampling was subsequently employed, wherein initial respondents were requested to recommend other qualified professionals who met the study's criteria. The online nature of the survey instrument facilitated nationwide distribution through email and other digital platforms, enabling broader geographical coverage. Given the diverse nature of the construction industry and its professionals and the lack of databases for the targeted population (Oduro et al., 2025; Agyekum et al., 2025), determining the exact population size proved challenging. Therefore, the sample size was calculated using Cochran's formula for an infinite population (Cochran, 1977):

$$n = \frac{z^2 p(1 - p)}{(e)^2}$$

$$n = \frac{1.96^2 \times 0.5(1 - 0.5)}{(0.07)^2}$$

$$n = 196$$

From the equation above, n represents the sample size, z denotes the confidence score (1.96), p signifies the estimated proportion of the population possessing the characteristic of interest (0.5 is employed as a cautious estimate), and e indicates the desired level of accuracy (0.07 for 7%). The application of the formula at a 7% precision level yielded a sample size of about 196. The sample size was augmented by 30% to accommodate probable non-response and incomplete questionnaires, yielding a final sample size of 255.

3.4 Data Collection

Data was collected through the distribution of the questionnaire to the targeted respondents. Out of the 255 questionnaires distributed, 204 responses were received, indicating an 80% response rate. The sample size is therefore considered sufficient for data analysis, as it exceeds the typical response rate of 20-30% in the construction industry (El-Gohary, 2012; Oyewobi et al., 2015).

3.5 Data Analysis

The data analysis encompassed pretesting the dataset, mean score ranking, one-sample t-test, normalisation, EFA, and FSE. The Statistical Package for the Social Sciences (SPSS) version 27.0 was utilised to conduct the analyses. Mean score ranking, one-sample t-test, and normalisation were subsequently conducted to assess the relative significance and criticality of the drivers. EFA was performed to classify the drivers (DR) into principal components (PDRs). The dataset's appropriateness for factor analysis was confirmed by the Kaiser-Meyer-Olkin (KMO) test (0.749) and Bartlett's test of sphericity ($p < 0.000$) (Field, 2005; Osie-Kyei et al., 2017). Finally, FSE was utilised to evaluate the overall criticality of key components. The FSE process entailed determining the weightings for each variable and principal component, calculating the membership functions for each variable and principal component, and assessing the influence of the principal components through criticality indices (Ameyaw and Chan, 2015; Osei-Kyei et al., 2017; Xu et al., 2010; Pittri et al., 2025c).

4 Results

4.1 Respondent Demographic

This section presents the demographic characteristics of the survey respondents, including their professional roles, organisational classifications, years of experience, and educational qualifications as shown in Table 1. These characteristics help establish the credibility and representativeness of the responses gathered for this study.

Table 1. Demographic Information (Source: Authors).

Demographic information	Frequency	Percentage(%)
Profession		
Architect	16	7.8
Client	10	4.9
Engineer (Civil/Structural/MEP)	29	14.2
Project Manager	23	11.3
Quantity Surveyor	43	21.1
Researcher	4	2.0
Safety Officer/Manager	61	29.9
Site Manager	18	8.8
Category of firm		
N/A	7	3.4
Micro (1–9 employees)	11	5.4
Small (10–49 employees)	37	18.1
Medium (50–249 employees)	59	28.9
Large (≥ 250 employees)	90	44.1
Years of Experience		
1 – 5 years	92	45.1
6 – 10 years	35	17.2
11 – 15 years	34	16.7
16 – 20 years	11	5.4
More than 20 years	32	15.7

Level of education		
Higher National Diploma (HND)	25	12.3
Bachelor Degree	69	33.8
MBA/MSc. /MPhil	85	41.7
PhD	25	12.3
Total	204	100.0

Source: Table created by authors.

The results of the demographic data reveal a diverse representation of construction industry professionals. Safety Officers/Managers constituted the largest professional group (29.9%), followed by Quantity Surveyors (21.1%) and Engineers (14.2%). Project Managers and Site Managers accounted for 11.3% and 8.8% respectively, while Architects represented 7.8% of respondents. The smallest groups were Client (4.9%) and Researchers (2.0%), providing a comprehensive cross-section of industry perspectives. Regarding organisational size, the majority of respondents were from large firms (44.1%), followed by medium (28.9%) and small (18.1%) firms, with micro firms representing 5.4%. A small portion (3.4%) were not affiliated with any classified firm or not sure of the size. This distribution indicates that the findings predominantly reflect the perspectives of professionals from larger construction organisations. In terms of industry experience, 45.1% of respondents had 1-5 years of experience, while 17.2% had 6-10 years, and 16.7% had 11-15 years. Notably, 21.1% of respondents possessed over 15 years of experience, with 15.7% having more than 20 years in the industry. The educational background of respondents was predominantly postgraduate level, with 41.7% holding MBA/MSc. /MPhil degrees and 12.3% having PhD qualifications. Bachelor's degree holders constituted 33.8% of respondents, while 12.3% held HND. This educational profile indicates that the respondents possessed the requisite knowledge to provide informed assessments of ImTs implementation drivers.

4.2 Statistical Pretesting of Data Set

The Cronbach's alpha test was to test the reliability of the scale. The instrument demonstrated a high level of reliability, as indicated by the overall alpha coefficient of 0.934, with 21 items, well above the recommended 0.70 (Field, 2005; Agyekum et al., 2022; DeVellis and Thorpe, 2021).

4.3 Descriptive and Inferential Analysis of the Drivers

The analysis of drivers to ImTs implementation for H&S management was conducted through both descriptive and inferential statistical approaches to provide robust insights into the current situation in the GCI. The analysis employed mean scores to rank the relative importance of the drivers, one-sample t-test to assess statistical significance using a test value of 3.5, and normalisation values to identify critical drivers (See Table 2). The normalisation values were calculated using the formula below;

$$NV = \frac{(\text{Mean value} - \text{Min. mean value})}{(\text{Max. mean value} - \text{Min. mean value})}$$

An $NV \geq 0.60$ was used to detect the critical items (Pittri et al., 2024b). This value corresponds to the third level on a five-point Likert scale. The results revealed that seven (7) out of the sixteen (16) drivers were identified as critical based on their normalisation values. The findings, presented in Table 2, indicate that ImTs adoption for H&S management in the GCI is primarily driven by human-centred performance benefits, particularly stakeholder engagement, safety training, and hazard visualisation. The top-ranked drivers (enhanced stakeholder engagement in design reviews (mean = 4.39, $NV = 1.00$), increased engagement in safety training (mean = 4.29, $NV = 0.83$), and enhanced hazard identification (mean = 4.26, $NV = 0.78$)) suggest that ImTs are valued less for their technological novelty and more for their ability to enhance cognitive processes, situational awareness, and proactive decision-making. The prominence of design-phase engagement and safety-oriented optimisation further reflects a shift from

reactive to preventive safety management, positioning ImTs as tools for early hazard mitigation and collaborative safety planning rather than merely operational support systems.

Notably, although all drivers are statistically significant ($p < 0.000$), only a subset is considered critical ($NV \geq 0.60$), highlighting a clear prioritisation of high-impact, practice-oriented factors over others such as cost and regulatory support. The relatively lower importance of economic and institutional drivers suggests that adoption is less constrained by financial or policy pressures and more influenced by functional relevance and organisational readiness. This points to a context where weak regulatory enforcement and evolving digital maturity place greater responsibility on firms to drive adoption internally. The findings emphasise that successful ImTs implementation depends on aligning technological capabilities with organisational processes and human factors, reinforcing the socio-technical nature of innovation adoption in construction.

Table 2. Ranking of Drivers to Immersive Technology Implementation H&S Management (Source: Authors).

Code	Drivers	Mean	t-value	p-value	SS	NV	Critical	Rank
DR1	Enhanced stakeholder engagement in design reviews	4.39	17.261	.000	Yes	1.00*	Yes	1 st
DR2	Increased engagement in safety training	4.29	13.839	.000	Yes	0.83*	Yes	2 nd
DR3	Enhanced safety hazard identification and visualisation	4.26	13.296	.000	Yes	0.78*	Yes	3 rd
DR4	Growing awareness of ImTs benefits	4.25	10.840	.000	Yes	0.76*	Yes	4 th
DR5	Streamlined site operations and monitoring	4.20	15.441	.000	Yes	0.68*	Yes	5 th
DR6	Improved safety-oriented design optimisation	4.17	12.323	.000	Yes	0.63*	Yes	6 th
DR7	Improved defect detection and quality control	4.16	11.957	.000	Yes	0.61*	Yes	7 th
DR8	Improved stakeholder collaboration	4.13	10.821	.000	Yes	0.56	No	8 th
DR9	Rapid advancement in ImTs capabilities	4.12	11.766	.000	Yes	0.54	No	9 th
DR10	Enhanced knowledge retention through interactive learning experiences	4.00	9.118	.000	Yes	0.34	No	10 th
DR11	Integration capability with existing construction technologies	4.00	8.725	.000	Yes	0.34	No	11 th
DR12	Proven effectiveness of ImTs in reducing workplace accidents	3.97	7.985	.000	Yes	0.29	No	12 th

DR13	Increasing management support and buy-in	3.92	9.388	.000	Yes	0.20	No	13 th
DR14	Supportive regulatory environment	3.90	6.863	.000	Yes	0.17	No	14 th
DR15	Decreasing implementation costs	3.90	7.175	.000	Yes	0.17	No	15 th
DR16	Limited effectiveness of traditional safety management methods	3.80	4.509	.000	Yes	0.00	No	16 th

Note: NV= Normalisation Value; *represent NVs ≥ 0.60 is critical: SS = Statistically Significant

Source: Table created by authors.

4.4 Exploratory Factor Analysis - Categorisation of Drivers

Factor analysis is a factor reduction statistical method that has the power to group correlated variables into clusters. Research involving the quantitative evaluation of several factors widely uses factor analysis to conduct structure detection (Osei-Kyei et al., 2017; Zhang, 2005; Agyekum et al., 2023). However, some conditions must be satisfied before factor analysis can be used for the dataset. The first requirement is reliability in the dataset. A Cronbach’s alpha of 0.934 indicated that the first criterion was satisfied. The Kaiser-Meyer-Olkin (KMO) Test for Sampling Adequacy was conducted on the dataset. The analyses generated a statistic of 0.749, which is higher than the 0.6 threshold adopted in previous studies (Osei-Kyei et al., 2017). This means the dataset is suitable for structure detection. The Bartlett’s test of sphericity was conducted to determine whether the factors are related and suitable for structure detection. The analyses generated an approximate Chi-square of 2508.752. And a p-value less than 0.000, indicating that the correlation matrix is not an identity matrix; hence, the dataset is suitable for factor analysis.

Although several other techniques are used to measure the suitability of a dataset for factor analysis, the consistent affirmative results of the above statistical indicators are considered adequate to justify the suitability of the dataset for factor analysis. As a result, EFA was conducted using principal component analysis as the factor extraction method and variance with Kaiser normalisation as the factor rotation method. The criteria for factor extraction included the eigenvalue > 1 rule and the percentage of variance explained by the retained factors. Principal Component Analysis was chosen as the extraction method due to its ability to reduce the dimensionality of the data while retaining the maximum variance in the dataset (Pittri et al., 2025c). Varimax rotation was chosen because it simplifies interpretation as the principal component factor is represented by a small number of variables (Abdi, 2003). The rotation converged in 6 iterations and generated a 3-factor solution, which formed the basis for the FSE analysis. Table 3 displays the results of the exploratory factor analysis. Hereafter, the factor groupings are referred to as the Principal Components (PCM), and DRs represent the drivers.

Table 3. Factor extraction and their loadings (Source: Authors).

SN.	Factor groupings (PMC)	Factor Loadings	Eigenvalue	% of variance explained	Cumulative % variance explained
PDR1	Collaborative Safety Enhancement and Organisational readiness		7.521	47.004	47.004
DR1	Enhance stakeholder engagement in design reviews	0.623			
DR5	Streamlined site operations and monitoring	0.598			
DR8	Improved stakeholder collaboration	0.853			

DR14	Supportive regulatory environment	0.488			
DR6	Improved safety-oriented design optimisation	0.775			
DR2	Increased engagement in safety training	0.675			
DR4	Growing awareness of ImTs benefits	0.662			
PDR2	Technological Performance and Safety Management Capabilities		1.648	10.301	57.305
DR16	Limited effectiveness of traditional safety management methods	0.831			
DR11	Integration capability with existing construction technologies	0.562			
DR12	Proven effectiveness of ImTs in reducing workplace accidents	0.705			
DR7	Improved defect detection and quality control	0.715			
DR3	Enhance safety hazard identification and visualisation	0.481			
PDR3	Implementation Support and Technological Advancement		1.429	8.928	66.234
DR10	Enhanced knowledge retention through interactive learning experiences	0.580			
DR9	Rapid advancement in ImT capabilities	0.760			
DR13	Increasing management support and buy-in	0.803			
DR15	Decreasing implementation costs	0.784			

Source: Table created by authors.

4.5 Fuzzy Synthetic Evaluation

FSE is a powerful tool for multi-criteria decision-making problems, particularly when dealing with complex systems involving uncertainties and subjective judgements (Ameyaw and Chan, 2015; Liu et al., 2013; Pittri et al., 2025c). The FSE approach offers several advantages over other similar statistical tools, making it more suitable for this study. FSE can handle inherent fuzziness and uncertainty associated with subjective evaluations provided by experts. In the context of examining the drivers influencing ImTs implementation for H&S management in the construction industry, the perceptions and opinions of construction professionals may be influenced by their individual experiences, knowledge, and biases. FSE addresses these challenges by using membership functions to quantify the degree of belonging of each driver to a particular critical level, thereby capturing the fuzziness in the evaluation process (Ameyaw and Chan, 2015). The FSE was implemented using a comprehensive methodology that consisted of three levels. The initial step involves calculating the weightings for each variable and determining the principal factors or components. Next, the membership function is computed for each variable and the principal factors. Finally, the impact of the Principal Factors are quantified using the criticality indices. The criticality index obtained for each Principal factors (PCM) are interpreted based on a predefined scale. In this study, a five-point scale was adopted, where 1 represents "not at all critical" and 5 represents "extremely critical". The criticality threshold was set at 3, which corresponds to the linguistic term "critical" on the five-point scale. This threshold has been widely used in previous studies employing FSE judgements (Ameyaw and Chan, 2015; Liu et al., 2013). PCM with criticality index greater than or equal to 3.0 are considered critical and required prioritised attention.

4.5.1 Determining the Appropriate Weightings

The weightings for 16 drivers and 3 principal components are established based on the mean score values obtained from the questionnaire survey. Given the mean values, the weightings are computed using the following equation:

$$W_i = \frac{M_i}{\sum M_{ii}}$$

Where W_i is the weightings of the DRs and PDRs; M_i is the mean score value of a DRs/PDRs, M_{ii} is the summation of the mean score value of all the DRs/PDRs. The results for the weightings are shown in Table 4.

4.5.2 Determining the Membership Function

To determine the membership of each PDRs, the membership function of each DRs must be established first. This establishes the foundation for calculating the membership of each PDR. The membership function of driver is determined through expert evaluation, where grades are assigned to indicate the level of criticality (ranging from 1 - Not critical to 5 - extremely critical). As an illustration, the survey findings showed that a small percentage of experts considered "Enhance stakeholder engagement in design (DR1)" to be not critical, while a larger percentage rated it as fairly critical, critical, very critical, or extremely critical. Regarding this matter, the membership function for this specific factor can be expressed by the following equation:

$$MF_{(DR1)} = \frac{0.00}{NC(1)} + \frac{0.02}{FC(2)} + \frac{0.09}{C(3)} + \frac{0.36}{VC(4)} + \frac{0.52}{EC(5)}$$

This is also written as (0.00, 0.02, 0.09, 0.36, 0.52). Using the same approach, the membership functions of the remaining DRs are computed and this is shown in Table 4. The membership function of the DRs is further used to compute the membership functions of each PDR. The PDRs are determined using the equation.

$$D = W_i \circ R$$

Where D represents the final evaluation matrix; W_i is the weightings for all the DRs under each PDRs; R is the fuzzy evaluation matrix for each PDRs; and \circ is a fuzzy composition operator.

Using PDR2 (Factor grouping 2) as an example, the weightings for all the DRs under this factor are expressed as:

$$W_i = (0.188, 0.198, 0.197, 0.206, 0.211) \text{ and } R = \begin{pmatrix} 0.03 & 0.05 & 0.21 & 0.48 & 0.23 \\ 0.00 & 0.07 & 0.13 & 0.54 & 0.26 \\ 0.00 & 0.05 & 0.21 & 0.46 & 0.28 \\ 0.00 & 0.02 & 0.18 & 0.42 & 0.38 \\ 0.00 & 0.03 & 0.13 & 0.37 & 0.46 \end{pmatrix}$$

Therefore, the membership function of PDR2 (Factor grouping 2) is calculated as follows:

$$D_{PDR2} = (0.188, 0.198, 0.197, 0.206, 0.211) \times R = \begin{pmatrix} 0.03 & 0.05 & 0.21 & 0.48 & 0.23 \\ 0.00 & 0.07 & 0.13 & 0.54 & 0.26 \\ 0.00 & 0.05 & 0.21 & 0.46 & 0.28 \\ 0.00 & 0.02 & 0.18 & 0.42 & 0.38 \\ 0.00 & 0.03 & 0.13 & 0.37 & 0.46 \end{pmatrix}$$

$D_{PDR2} = (0.01, 0.05, 0.17, 0.45, 0.33)$ as shown in Table 4.

Using the same approach, the membership functions of PDR1 and PDR3 were derived and shown in Table 4. After determining the membership of each PDR, the criticality (index) for each PDR (factor grouping) is calculated.

Table 4. Weighting and Membership Function of each Variable and Principal Components (Source: Authors).

Weighting functions of each variable (DR) and Principal component (PDR)					
SN.	Factor groupings (PMC)	Factor Loadings	Eigenvalue	% of variance explained	Cumulative % variance explained
PDR1	Collaborative Safety Enhancement and Organisational Readiness			29.33	0.448
DR1	Enhance stakeholder engagement in design reviews	4.39	0.150		
DR5	Streamlined site operations and monitoring	4.20	0.143		
DR8	Improved stakeholder collaboration	4.13	0.141		
DR14	Supportive regulatory environment	3.90	0.133		
DR6	Improved safety-oriented design optimisation	4.17	0.142		
DR2	Increased engagement in safety training	4.29	0.146		
DR4	Growing awareness of ImTs benefits	4.25	0.145		
PDR2	Technological Performance and Safety Management Capabilities			20.19	0.308
DR16	Limited effectiveness of traditional safety management methods	3.80	0.188		
DR11	Integration capability with existing construction technologies	4.00	0.198		
DR12	Proven effectiveness of ImTs in reducing workplace accidents	3.97	0.197		

DR7	Improved defect detection and quality control	4.16	0.206	
DR3	Enhance safety hazard identification and visualisation	4.26	0.211	
PDR3	Implementation Support and Technological Advancement			15.94 0.244
DR10	Enhanced knowledge retention through interactive learning experiences	4.00	0.251	
DR9	Rapid advancement in ImT capabilities	4.12	0.258	
DR13	Increasing management support and buy-in	3.92	0.246	
DR15	Decreasing implementation costs	3.90	0.245	
Membership Function of the DR and PDR				
SN.	DR and PDR	Weightings for DR	Membership function for DR	Membership function for PDR
PDR1	Collaborative Safety Enhancement and Organisational Readiness			(0.00, 0.03, 0.12, 0.37, 0.34)
DR1	Enhance stakeholder engagement in design reviews	0.150	(0.00, 0.02, 0.09, 0.36, 0.52)	
DR5	Streamlined site operations and monitoring	0.143	(0.00, 0.00, 0.13, 0.55, 0.32)	
DR8	Improved stakeholder collaboration	0.141	(0.00, 0.05, 0.13, 0.45, 0.37)	
DR14	Supportive regulatory environment	0.133	(0.00, 0.07, 0.18, 0.51, 0.23)	
DR6	Improved safety-oriented design optimisation	0.142	(0.00, 0.04, 0.11, 0.49, 0.36)	
DR2	Increased engagement in safety training	0.146	(0.02, 0.00, 0.11, 0.40, 0.47)	
DR4	Growing awareness of ImTs benefits	0.145	(0.02, 0.03, 0.17, 0.23, 0.55)	
PDR2	Technological Performance and Safety Management Capabilities			(0.01, 0.05, 0.17, 0.45, 0.33)
DR16	Limited effectiveness of traditional safety management methods	0.188	(0.03, 0.05, 0.21, 0.48, 0.23)	
DR11	Integration capability with existing construction technologies	0.198	(0.00, 0.07, 0.13, 0.54, 0.26)	

DR12	Proven effectiveness of ImTs in reducing workplace accidents	0.197	(0.00, 0.05, 0.21, 0.46, 0.28)
DR7	Improved defect detection and quality control	0.206	(0.00, 0.02, 0.18, 0.42, 0.38)
DR3	Enhance safety hazard identification and visualisation	0.211	(0.00, 0.03, 0.13, 0.37, 0.46)
PDR3	Implementation Support and Technological Advancement		(0.00, 0.02, 0.24, 0.49, 0.26)
DR10	Enhanced knowledge retention through interactive learning experiences	0.251	(0.00, 0.03, 0.21, 0.48, 0.28)
DR9	Rapid advancement in ImT capabilities	0.258	(0.00, 0.00, 0.23, 0.42, 0.35)
DR13	Increasing management support and buy-in	0.246	(0.00, 0.00, 0.25, 0.59, 0.16)
DR15	Decreasing implementation costs	0.245	(0.00, 0.03, 0.26, 0.47, 0.23)

4.4.3 Quantifying Criticality of the PDRs (Factor Groupings)

After determining the membership function of each PDR, the criticality index for each factor grouping (PDR) is calculated using the equation below:

$$\text{Criticality index (CI) for each PCR} = \sum_{i=1}^5 D \times E$$

Where D denotes the final evaluation matrix of a given PDR and E denotes the grade alternatives of the 5-point rating scale.

From Table 4, the following outcomes can be derived:

$$D_{PDR1} = (0.00, 0.03, 0.12, 0.37, 0.34)$$

$$D_{PDR2} = (0.01, 0.05, 0.17, 0.45, 0.33)$$

$$D_{PDR3} = (0.00, 0.02, 0.24, 0.49, 0.26)$$

Therefore, the criticality indices (see Table 5) of the PDRs are computed as follows:

$$PDR1_{CI} = D_{PDR1} \times E = (0.00, 0.03, 0.12, 0.37, 0.34) \times (1, 2, 3, 4, 5) = 3.78$$

$$PDR2_{CI} = D_{PDR2} \times E = (0.01, 0.05, 0.17, 0.45, 0.33) \times (1, 2, 3, 4, 5) = 4.17$$

$$PDR3_{CI} = D_{PDR3} \times E = (0.00, 0.02, 0.24, 0.49, 0.26) \times (1, 2, 3, 4, 5) = 3.83$$

Table 5. Critical indices of the Principal Components (PCM) (Source: Authors).

Code	Principal Components (PCM)	Index	Description	Rank
PDR1	Collaborative Safety Enhancement and Organisational Readiness	3.78	Critical	3 rd

PDR2	Technological Performance and Safety Management Capabilities	4.17	Critical	1 st
PDR3	Implementation Support and Technological Advancement	3.83	Critical	2 nd

Source: Table created by authors.

5 Discussion

The FSE analysis identified three critical principal components influencing ImTs implementation for H&S management in the GCI as shown in Table 5. Technological Performance and Safety Management Capabilities (PDR2) emerged as the most critical with an index of 4.17, followed by Implementation Support and Technological Advancement (PDR3) with 3.83, and Collaborative Safety Enhancement and Organisational Readiness (PDR1) with 3.78. Each component represents distinct but interrelated aspects requiring strategic attention.

5.1 PDR1 – Collaborative Safety Enhancement and Organisational readiness

Collaborative Safety Enhancement and Organisational Readiness ranked third with an index of 3.78, though it accounted for the largest variance explanation at 47.004%. This grouping emphasises the human and organisational factors essential for ImTs implementation. "Improved safety-oriented design optimisation" (0.775) highlights ImTs' potential to enhance safety considerations during the project planning phase. As noted by Alizadehsalehi et al., this capability allows for better integration of safety features into project designs, potentially reducing safety risks before construction begins. The factor's high loading suggests strong recognition of ImTs' value in proactive safety planning. "Increased engagement in safety training" (0.675) and "growing awareness of ImTs benefits" (0.662) underscore the importance of stakeholder participation and understanding. These factors suggest that successful implementation requires both effective training programs and clear communication of ImTs' benefits to all stakeholders. The loadings indicate that organisations recognise the need to build both capability and buy-in among users. The "supportive regulatory environment" factor (0.488), while showing lower loading, suggests that regulatory frameworks influence implementation decisions. This factor indicates that while regulatory support can facilitate adoption, internal organisational factors and technological capabilities are more critical drivers of successful implementation. Empirical studies in Ghana consistently demonstrate that digital construction uptake is constrained by deficiencies in skills, training, and knowledge systems, with Pittri et al. (2025b) finding that gaps in technical competencies and training infrastructure significantly limit the adoption of emerging technologies. Similarly, Agyekum et al. (2022) showed that although awareness of safety-related technologies exists, their practical utilisation remains low due to inadequate training and organisational preparedness. These findings directly reinforce the strong loadings observed in this study for stakeholder engagement, safety training, and awareness of ImTs benefits. Furthermore, research on smart building technologies in Ghana identifies people, processes, and organisational readiness as the most influential determinants of implementation success, suggesting that without internal capability development, technological innovations are unlikely to be effectively deployed (Ghansah et al., 2024).

Furthermore, the significance of PDR1 reinforces Statista (2026) emphasis on capacity and readiness gaps in developing regions. While developed countries benefit from mature digital ecosystems and institutional support, the findings of this study show that in Ghana, like many other developing countries, adoption is still heavily dependent on awareness, training, management support, and cost considerations. This supports the argument that adoption in developing contexts is largely organisation-driven rather than system-driven, with firms compensating for weak external environments through internal initiatives. At the same time, the identification of factors such as decreasing implementation costs and increasing awareness as drivers suggests a gradual transition consistent with global trends, where improving affordability and accessibility are beginning to lower adoption barriers.

The findings align with the organisational dimension of the TOE framework, which emphasises management support, resource readiness, and organisational culture as key determinants of innovation uptake (Tornatzky and Fleischer, 1990). The strong loadings for increased safety training engagement and growing awareness of ImTs benefits further reflect UTAUT constructs of social influence and facilitating conditions, highlighting the importance of stakeholder alignment and institutional support in shaping adoption (Venkatesh et al., 2003). Conversely, the relatively weaker influence of regulatory support suggests that, in the GCI, internal organisational readiness outweighs external pressures, consistent with evidence from developing countries where weak enforcement shifts responsibility to firm-level initiatives (Darko et al., 2018; Agyekum et al., 2022).

5.2 PDR2 – Technological Performance and Safety Management Capacities

Technological Performance and Safety Management Capabilities emerged as the most critical driver grouping with an index of 4.17, accounting for 10.301% of the total variance. This component encompasses factors that directly influence the operational effectiveness of ImTs in safety management. The high loading (0.831) of "limited effectiveness of traditional safety management methods" underscores the industry's recognition that conventional approaches are increasingly inadequate for modern construction challenges (Afzal and Shafiq, 2021). "Integration capability with existing construction technologies" (0.562) highlights the importance of seamless incorporation with established systems, particularly BIM. The significant loading (0.715) for "improved defect detection and quality control" emphasises ImTs' potential to enhance safety monitoring precision. Similarly, the substantial loading (0.705) for "proven effectiveness in reducing workplace accidents" reflects growing confidence in ImTs' ability to improve safety outcomes through enhanced hazard identification and risk mitigation (Sacks et al., 2013). "Enhanced safety hazard identification and visualisation" (0.481) complements other factors by highlighting ImTs' capability to provide clearer, more intuitive representations of safety risks. This visualisation capability enables better understanding and communication of safety concerns among project stakeholders, supporting more effective preventive measures. This finding is strongly supported by Agyekum et al. (2022), who found that construction stakeholders in Ghana prioritise technologies that directly improve safety performance, hazard detection, and operational efficiency. Similarly, Pittri et al. (2025a) identified that the adoption of digital technologies in construction is largely influenced by their ability to deliver measurable performance improvements, particularly in safety and sustainability outcomes. However, these studies also highlight a critical limitation: despite recognising the value of such technologies, adoption remains constrained by technical complexity, lack of integration capabilities, and infrastructural limitations. This supports the interpretation that while technological capability is a key driver, it also represents a conditional factor, where its influence is dependent on the availability of supporting systems and expertise.

Consistent with Statista (2026), which highlights that developing countries remain in the early and fragmented stages of adoption due to economic, infrastructural, and skills-related constraints, the results of this study similarly show that adoption in developing countries is not yet driven by external systems such as advanced infrastructure or regulatory frameworks, but rather by internal organisational and functional considerations.

The dominance of PDR2 aligns closely with the performance expectancy construct within the UTAUT, which posits that users are more likely to adopt a technology when they perceive it as effective in enhancing job performance (Venkatesh et al., 2003). In this study, drivers such as proven effectiveness in reducing workplace accidents, improved defect detection, and enhanced hazard visualisation reflect a strong perception among Ghanaian construction professionals that ImTs deliver tangible safety improvements over traditional methods. This finding also resonates with the technological context of the TOE framework, which emphasises that a technology's relative advantage and compatibility with existing systems are critical determinants of adoption (Tornatzky and Fleischer, 1990). The high loading of integration capability with existing construction technologies further confirms that for ImTs to gain

traction in the GCI, they must seamlessly complement established tools such as BIM, thereby reducing implementation friction and reinforcing their perceived value.

5.3 PDR3 – Implementation Support and Technological Advancement

Implementation Support and Technological Advancement ranked as the second most critical component with an index of 3.83, explaining 8.928% of the total variance. This grouping reflects the organisational and technological support mechanisms necessary for successful ImTs implementation. "Increasing management support and buy-in" emerged with the highest factor loading (0.803), highlighting the crucial role of leadership commitment in driving ImTs adoption. This aligns with Li et al. (2018) observation that management understanding of ImTs' potential return on investment significantly influences implementation success. "Rapid advancement in ImT capabilities" showed strong loading (0.760), indicating the industry's awareness of evolving technological possibilities. The considerable loading (0.784) for "decreasing implementation costs" suggests that economic considerations remain a significant driver, supporting Prabhakaran et al. (2022) findings about technology accessibility improving with market maturation. "Enhanced knowledge retention through interactive learning experiences" (0.580) emphasises the importance of effective training and learning systems in maximising ImTs' benefits for safety management. Darko et al. (2018) found that management support and strategic commitment are among the most influential drivers of green technology adoption in Ghana, as they determine resource allocation and organisational prioritisation. This is consistent with the strong loading of management support in this study. In addition, Pittri et al. (2026b) emphasise that beyond awareness, the adoption of emerging technologies requires institutionalised support mechanisms, including training programmes, technical guidance, and organisational investment. While this study identifies decreasing implementation costs and technological advancement as enabling factors, existing literature suggests that these alone are insufficient to drive widespread adoption. Agyekum et al. (2022) show that even where technologies become more affordable, adoption remains limited without corresponding improvements in skills, infrastructure, and organisational systems. This indicates that PDR3 represents a transitional dimension, where technological progress and cost reduction can facilitate adoption, but only when reinforced by strong organisational and institutional support.

This component aligns with both the organisational and technological dimensions of the TOE framework, where top management support, cost considerations, and technological maturity are critical determinants of adoption feasibility (Tornatzky and Fleischer, 1990; Pittri et al., 2025a). The strong loading of management support reinforces its role as a key enabler in resource-constrained settings, while decreasing implementation costs and rapid technological advancement reflect the importance of economic viability and innovation readiness (Kissi et al., 2023; Pittri et al., 2025d). From a UTAUT perspective, these factors correspond to facilitating conditions, encompassing the organisational and technical infrastructure necessary to support effective technology use (Venkatesh et al., 2003). This suggests that successful ImTs implementation in developing contexts depends on aligning leadership commitment with accessible, evolving technological capabilities to reduce adoption barriers and sustain utilisation.

6 Implications of Research Findings

The findings of this study have several implications for the adoption of ImTs in H&S management within the GCI and similar developing countries. Firstly, the identification of Technological Performance and Safety Management Capabilities as the most critical component suggests that organisations should prioritise developing robust technological infrastructure and integration capabilities. This includes establishing clear protocols for incorporating ImTs into existing safety management systems and conducting pilot projects to demonstrate their effectiveness. The high criticality of Implementation Support and Technological Advancement indicates the need for comprehensive change management

strategies and dedicated resources. Organisations should establish structured training programs and specialised teams responsible for implementing and maintaining ImTs systems. Additionally, the findings suggest that policymakers should develop flexible regulatory frameworks that encourage innovation while maintaining safety standards, potentially including incentive schemes for early adopters. For educational institutions, the emphasis on improved stakeholder collaboration and enhanced knowledge retention suggests a need to update curricula to incorporate ImTs training. Universities and technical institutions should develop programs that combine construction management with digital technology skills, preparing professionals for an increasingly technology-driven industry.

The findings also suggest that organisations should prioritise ImTs applications that directly enhance safety performance, particularly in areas such as hazard identification, safety training, and site monitoring. These technologies should be selected and implemented based on their practical impact on reducing risks and improving decision-making, rather than their novelty. However, beyond technological capability, the results emphasise that successful implementation depends on aligning these tools with organisational readiness, stakeholder engagement, and continuous training systems.

From an economic standpoint, although cost was not ranked as the most critical driver, financial feasibility remains important, especially for SMEs. Adoption should therefore be guided by a cost-benefit perspective, focusing on reduced accidents, improved productivity, and long-term operational gains. Policy support through incentives and funding mechanisms can further lower entry barriers.

A phased implementation approach is recommended. Organisations can begin with pilot applications (e.g., VR-based safety training), followed by integration with existing systems such as BIM, and ultimately scale up and institutionalise ImTs within standard safety practices. This staged strategy reduces risk, builds internal capacity, and supports sustainable adoption.

7 Conclusion, Limitations and Future Research Directions

This study systematically evaluated the drivers influencing ImTs implementation in H&S management within the GCI. Through factor analysis and fuzzy synthetic evaluation, the study identified sixteen critical drivers and categorised them into three principal components: Collaborative Safety Enhancement and Organisational Readiness, Technological Performance and Safety Management Capabilities, and Implementation Support and Technological Advancement. The FSE analysis revealed Technological Performance and Safety Management Capabilities as the most critical component, highlighting how enhanced safety hazard identification, improved defect detection, and integration capabilities significantly influence successful ImTs implementation.

The study has several limitations that should be acknowledged. First, the study is subject to sample composition bias, which may influence the interpretation and generalisability of the findings. The respondent profile is dominated by professionals from large organisations (44.1%) and individuals with higher educational qualifications (over 50% holding postgraduate degrees). While this enhances the reliability and technical depth of responses, it may not fully reflect the perspectives of SMEs and less formally trained practitioners, who constitute a significant proportion of the construction workforce in Ghana. SMEs often operate under more severe financial, technological, and institutional constraints, and their adoption drivers may differ substantially from those identified in this study. Consequently, the findings may be skewed toward organisations with relatively greater access to resources, digital awareness, and innovation capacity, potentially overestimating the readiness and perceived importance of certain drivers across the broader industry.

Moreover, the study adopts a cross-sectional research design, capturing perceptions of ImTs implementation drivers at a single point in time. Technology adoption, however, is inherently dynamic and evolutionary, influenced by changes in technological maturity, market conditions, regulatory

frameworks, and organisational learning. As such, the study does not account for how the relative importance of drivers may shift over time as organisations progress from awareness to implementation and eventual institutionalisation of ImTs. For example, factors such as cost and technical complexity may be more critical in early adoption stages, while integration and performance optimisation may become more salient in later stages. The cross-sectional nature of the data therefore limits the ability to capture causal relationships, temporal changes, and adoption trajectories, and the findings should be interpreted as a snapshot rather than a longitudinal representation of adoption dynamics.

Furthermore, the study is conducted within the specific context of the GCI, which presents unique institutional, economic, and socio-cultural characteristics. These include weak regulatory enforcement, limited digital infrastructure, skills shortages, and fragmented industry structures, which collectively shape technology adoption patterns. While these conditions are representative of many developing countries, they may not be directly transferable to contexts with stronger institutional frameworks, higher digital maturity, or different market dynamics. Therefore, the external validity and generalisability of the findings may be limited, particularly when applied to developed economies or regions with more advanced construction ecosystems. At the same time, the Ghanaian context provides important insights into under-researched environments where digital transformation is emerging but constrained, highlighting the need for context-sensitive interpretation of the results.

Although the study employs robust quantitative techniques, including EFA and FSE, it relies on self-reported perceptual data, which may be subject to response bias, including overestimation of awareness or perceived importance of certain drivers. Future research could address these limitations by incorporating mixed-method approaches, including case studies, longitudinal analyses, and objective performance data, to provide a more comprehensive understanding of ImTs implementation.

Future research could address these limitations and expand the knowledge base in several directions. Longitudinal studies could track how the importance of different drivers changes as organisations progress in their ImTs implementation journey. Comparative studies across different developing countries could provide insights into contextual factors affecting ImTs adoption. Research employing structural equation modeling could investigate the relationships between identified drivers and implementation outcomes. Future studies could also examine the economic implications of ImTs implementation, including cost-benefit analyses and return on investment metrics specific to construction safety applications.

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Data Availability Statement

The data presented in this study are available on reasonable request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ImTs	Immersive Technologies
ImT	Immersive Technology
VR	Virtual Reality
AR	Augmented Reality
MR	Mixed Reality
FSE	Fuzzy Synthetic Evaluation
GDP	Gross Domestic Product
OSH	Occupational Safety and Health
GCI	Ghanaian Construction Industry
BIM	Building Information Modelling
IoT	Internet of Things

SPSS	Statistical Package for the Social Sciences
KMO	Kaiser-Meyer-Olkin
DR	Driver
PDR	Principal Driver
PCM	Principal Component
SDG	Sustainable Development Goal
H&S	Health and Safety
CM	Criticality Measure
HND	Higher National Diploma
EFA	Exploratory Factor Analysis
MEP	Mechanical, Electrical and Plumbing
ILO	International Labour Organisation
UN	United Nations
SS	Statistically Significant
MBA	Master of Business Administration
MSc	Master of Science
MPhil	Master of Philosophy

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