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Investigating the Interrelationships between Advanced Technologies and Safety Performance Factors: The Case of Higher Education Construction Projects

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Abstract: The architecture, engineering, and construction (AEC) industry faces ongoing challenges in enhancing safety performance. Despite the availability of advanced technologies for enhancing safety, there is limited understanding of the inter-relationships among safety factors and advanced technologies for enhancing safety performance. This study aims to investigate the inter-relationships among factors affecting safety performance and advanced technologies. A questionnaire survey was disseminated to construction professionals to assess the criticality of factors and strategies. The data were analyzed using descriptive statistics, correlation analysis, and exploratory factor analysis (EFA). The findings indicate that 16 factors and eight advanced technologies are critical for enhancing safety. The EFA grouped 11 critical factors into four underlying groupings: safety planning and hazard prevention, workplace environment and supervision, employee safety support, and medical readiness and site protection. Moreover, the EFA grouped the eight critical advanced technologies into two underlying groupings: advanced digital technologies and personal and site monitoring technologies. The correlation analysis demonstrates measurable but weak associations between the factors and advanced technologies, indicating the need for future research to explore additional variables that may impact these relationships. The findings help construction professionals prioritize resources to address the specific groupings of critical factors and advanced technologies.

Keywords: construction projects; construction safety; safety performance; advanced technologies; higher education construction projects

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1. Introduction

The construction industry is one of the most hazardous sectors globally, characterized by alarmingly high rates of accidents and fatalities [1]. This industry is responsible for over 60,000 fatalities each year [2], highlighting its status as a significant contributor to workplace fatalities worldwide. In the United States, construction-related injuries and accidents exceed those of any othertab industry by 50% annually [3]. Construction-related accidents account for 40%, 50%, and 25% of workplace incidents in Japan, Ireland, and the United Kingdom, respectively [4], underscoring the industry's pervasive safety challenges. Efforts to enhance safety and practices are crucial to mitigate these statistics and ensure a safer working environment in construction.

Among these efforts, the construction industry has increasingly adopted innovative solutions to address safety challenges on job sites. Advanced technologies have proven effective in mitigating safety risks and enhancing safety performance [5]. These technologies help overcome challenges, such as difficulties in tracking compliance with safety protocols and limitations in real-time hazard detection [6]. Advanced technologies enable more efficient monitoring and analysis of safety data, allowing for quicker responses to potential hazards [7]. Moreover, the integration of various technologies can significantly enhance the accuracy of hazard prediction and prevention [1]. With improvements in safety performance, the benefits of implementing advanced technologies become evident.

However, the complexity and costs associated with implementing these technologies can impede the effective allocation of resources to address specific safety needs. Although previous works, such as Ref. [8], provided insights into significant technologies for enhancing safety, relying solely on descriptive statistics introduces limitations in data comprehension [9]. Descriptive statistics can oversimplify complex relationships and fail to capture deeper patterns or interactions between variables, leading to an incomplete understanding of the factors affecting safety performance and advanced technologies. Moreover, previous works, such as Ref. [10], did not account for the inter-relationships among technologies, potentially concealing how different groupings influence safety performance. By treating all technologies as a single grouping, Ref. [10] may have overlooked the distinct contributions of different technology clusters. In contrast, using exploratory factor analysis (EFA) enables the identification of the underlying groupings, providing a more nuanced understanding of the inter-relationships among technologies and how these interactions collectively influence safety performance [11]. This approach offers a foundation for developing targeted and effective interventions.

This study aims to investigate the inter-relationships among factors affecting safety performance and advanced technologies. To achieve this aim, the objectives are to (1) investigate the critical factors affecting safety performance and advanced technologies; (2) examine the correlation between the critical factors and advanced technologies; and (3) explore the underlying groupings of factors and advanced technologies. A questionnaire survey was used to assess the criticality of the factors and advanced technologies for enhancing safety performance. The data were analyzed using descriptive statistics, correlation analysis, and EFA. This study contributes to understanding the inter-relationships among factors and advanced technologies for enhancing safety performance, providing useful insights into how these elements interact and influence each other. Unlike previous studies that often consider factors and technologies in isolation, this research identifies distinct groupings, offering a comprehensive approach to developing targeted safety interventions. By understanding which factors and technologies tend to cluster together, strategies can be developed that address these groupings comprehensively, enhancing the effectiveness and efficiency of safety management practices in the AEC industry. The findings advance theoretical knowledge and offer practical guidance for industry stakeholders, setting a foundation for future research to enhance safety practices and improve industry efficiency at large.

2. Literature Review

2.1. Factors Affecting Safety Performance

Safety performance in the construction industry is influenced by several factors, as shown in Table 1. For example, safety policies and procedures are vital for maintaining a safe construction environment. A well-documented emergency and safety plan ensures a structured approach to handling potential crises, thereby minimizing the impact of unexpected incidents [12–14]. The implementation of safety policies and procedures is crucial for consistent safety practices across all project levels [12,13,15,16]. Regular safety inspections identify hazards and verify compliance with safety standards, helping to reduce the risk of accidents before they occur [16–18]. Effective safety supervision ensures adherence to protocols and provides necessary guidance to workers [15,19,20]. Medical insurance policies also support worker safety by providing necessary medical coverage [12]. Historical accident records and safety inspections help track safety performance and identify areas for improvement [17,21,22]. Together, these elements foster a culture of safety and preparedness, reducing risks and enhancing overall safety performance. The availability of appropriate safety resources and equipment is fundamental to protecting workers on construction sites. Safety signs and boards communicate critical safety information, promoting safer behaviors and awareness on-site [23,24]. First aid kits and medical measures provide immediate care in case of injuries, mitigating the severity of accidents [17,25]. High-quality safety tools and equipment are vital for shielding workers from potential hazards [19,26,27]. Measures to prevent falls, such as guardrails and securing the site from falling objects, are crucial for worker safety [28,29]. Safe storage areas prevent accidents caused by improperly stored materials [25]. Additionally, fire protection and prevention measures are essential to safeguard against fire-related hazards [13]. These resources collectively ensure that workers have the necessary protection and support to carry out their tasks safely. The work environment and conditions significantly impact safety performance on construction sites. Electric shock protection is critical for preventing severe injuries and fatalities [30,31]. Weather conditions can affect safety, requiring measures to mitigate adverse effects [26,28]. Effective housekeeping practices help maintain a clean and organized worksite, reducing trip hazards and other risks [18,28]. Ensuring sufficient illumination and noise control creates a conducive environment for safe operations [21,26]. The regular maintenance of tools and equipment prevents accidents caused by faulty or poorly maintained items [20,27]. Sufficient ventilation and proper hygiene contribute to a healthy work environment, enhancing workers' ability to perform their tasks safely [30]. Resting areas allow workers to take necessary breaks, reducing fatigue-related accidents. These factors are essential for fostering a safe and productive construction site. Worker characteristics and training are crucial factors affecting safety performance. Comprehensive education and training programs equip workers with the necessary knowledge and skills to perform their tasks safely, reducing the likelihood of accidents [15,24]. Worker attitudes and negligence significantly influence safety outcomes, as a positive safety culture and diligent behavior can prevent many incidents [17,21,29]. Experience and skills are critical, with more experienced workers typically being better able to identify and mitigate risks [19,28]. Factors such as worker age and external influences also impact their ability to adhere to safety protocols [15]. Overworking employees can lead to fatigue and an increased risk of accidents [14,20]. By addressing these characteristics through targeted training and support, organizations can significantly improve safety performance. Effective management and collaboration are essential for ensuring a safe construction site. Management support for safety initiatives, including guidance, incentives, and motivation, is critical for fostering a strong safety culture [18,23]. Open communication and acceptance of employee feedback on safety issues help identify potential risks and improve safety practices [19,23]. Collaboration among workmates enhances safety by promoting teamwork and mutual support [27]. The size of the project can also influence safety management, with larger projects often requiring more structured and comprehensive safety strategies [13]. The use of well-designed and maintained temporary structures ensures stability and safety during construction activities [31]. By prioritizing management support and fostering collaboration, construction sites can achieve higher safety performance and protect their workers more effectively.

Table 1. Factors affecting safety performance.

ID	Factors Affecting Safety Performance	Source
FA01	Availability of safety signs and boards on site	[23,24]
FA02	Electric shock protection	[30,31]
FA03	Availability of an emergency and safety plan	[12–14]
FA04	Implementation of safety policies and procedures	[12,13,15,16,23,24]
FA05	Availability of a first aid kit and medical measures	[15,17,25,30]
FA06	Quality of safety resources, tools, and equipment	[12,13,21,25,28]
FA07	Education and training	[12,13,15,16,19,23,24]
FA08	Weather conditions	[12,24,26,28]
FA09	Availability of personal protective equipment	[12,17,19,21,23,26,27]

Table 1. *Cont.*

ID	Factors Affecting Safety Performance	Source
FA10	Housekeeping	[13,16,18,23,28]
FA11	Fire protection and prevention on site	[13,15]
FA12	Quality and safety of the work environment	[12,15–17,21,23]
FA13	Guardrails and measures for preventing workers from falling	[13,17,28–30]
FA14	Securing the site from falling objects	[13,15]
FA15	Availability of resting areas	[30]
FA16	Maintenance of tools and equipment	[17,20,21,27]
FA17	Use of well-designed and maintained temporary structures	[23,28,31]
FA18	Sufficient ventilation	[16,23,28]
FA19	Safety inspections	[12–14,16–18,24]
FA20	Sufficient illumination	[16,21]
FA21	Attitude and negligence	[12,15,17,19–21,23,26,27,29]
FA22	Safety supervision level	[12,13,15,19,20,23,24]
FA23	Sufficient hygiene	[28,30]
FA24	Medical insurance policy	[12,15]
FA25	Worker experience and skills	[12,13,15–17,19,21,23,24,26–28]
FA26	Company acceptance of employee feedback and complaints on safety	[18,19,23]
FA27	Availability of a safe storage area	[25,30]
FA28	Overworking employees	[12–14,17,19,20,24–26]
FA29	Worker age	[15,17,23,24,26]
FA30	Ensure permissible noise exposure on site	[16,26]
FA31	History of accidents on site and safety records	[12,14,15,17,21,22,24]
FA32	Communication	[15–17,19,24,25,27]
FA33	External influences on employees	[19]
FA34	Management support for worker safety guidance, incentives, and motivation	[12,14–21,23,24]
FA35	Availability of a smoking area	[13]
FA36	Workmate collaboration	[16,17,20,21,23,27]
FA37	Project size	[13,17,30]

2.2. Enhancing Construction Safety with Advanced Technologies

Construction work is an inherently dangerous business as it involves a complex and challenging process [32]. Workers are exposed to various hazards, such as working at heights, operating heavy machinery, and handling hazardous materials [33]. Thus, minimizing safety risks in construction projects is fraught with uncertainty and can be a difficult task [8]. Advancements in safety technologies have enhanced process efficiency and incident response, leading to significant improvements in overall construction site safety [6]. Technological advancements have transformed safety management from a reactive to a proactive approach, allowing for the prediction and prevention of potential hazards [34].

Recent research has unveiled the expanded potential of advanced technologies to significantly enhance safety management [35]. These technologies safeguard workers and empower them to proactively identify potential hazards [10]. For instance, sensors and Internet of Things (IoT) devices can continuously monitor environmental conditions, alerting workers to dangerous levels of dust, noise, or toxic gasses [36]. Using technological advancements in safety management offers more robust control measures for hazard identification and response than traditional approaches [5]. Advanced data analytics and machine learning algorithms can analyze patterns in safety data to predict and mitigate risks more effectively [37]. Technologies are employed for diverse safety applications, including real-time data acquisition, timely information dissemination, comprehensive data storage, and advanced analytics for risk assessment and predictive modeling [38]. Many advanced technologies are capable of interacting across multiple assets and processes [8]. The integration of physical and digital technologies can significantly enhance project comprehension and reliability [1]. These technologies enable real-time monitoring and data collection, offering insights into site conditions that help prevent accidents [39].

By improving communication and access to information, they ensure that workers are better informed and coordinated, reducing the likelihood of accidents caused by miscommunication or lack of awareness [7]. Therefore, the adoption of advanced technologies is essential for improving safety in construction projects. Table 2 shows the list of advanced technologies for enhancing safety.

Table 2. Advanced technologies for enhancing safety.

ID	Advanced Technologies	Source
AT01	Building information modeling (BIM)	[6,40]
AT02	Wearable sensing devices (WSDs)	[32,41]
AT03	Mobile devices on site	[42,43]
AT04	Radio frequency identification (RFID)	[44,45]
AT05	Light detection and ranging (LiDAR) and laser scanning	[46,47]
AT06	Quick response codes (QR codes)	[48,49]
AT07	Digital signage	[50,51]
AT08	Camera network systems	[7,39]
AT09	Photogrammetry	[52,53]
AT10	Exoskeleton/exo-suit	[54,55]
AT11	Artificial intelligence (AI)	[35,37]
AT12	Unmanned aerial vehicles (UAVs)	[56,57]
AT13	Virtual and augmented reality (VR/AR)	[58,59]
AT14	Automation and robot	[60,61]
AT15	Internet of things (IoT)	[36,62]

2.3. Research Gap

Advanced technologies have proven effective in mitigating safety risks and addressing factors affecting safety performance. Therefore, implementing these technologies to enhance safety performance is essential. However, the literature lacks sufficient investigation into the inter-relationships among factors and advanced technologies for enhancing safety. Most existing studies focus on individual factors or technologies in isolation, without exploring how these elements interact and influence one another. By neglecting these inter-relationships, existing works have failed to identify the high-priority factors and advanced technologies necessary to maximize the use of resources and optimize safety outcomes. This gap limits the ability to develop comprehensive strategies that leverage the interactions between factors and technologies. This study bridges this gap by investigating the inter-relationships among factors affecting safety performance and advanced technologies

3. Methodology

3.1. Survey Development

This study utilized a questionnaire survey to collect opinions on the criticality of factors affecting safety performance and advanced technologies. A questionnaire survey is well-suited for gathering a wide range of opinions from professionals and is appropriate for quantitative analysis [11]. Surveys are frequently employed in construction management research to obtain professionals' opinions on specific topics [63,64]. They are effective for conducting EFA, which captures the underlying groupings representing theoretical constructs [65]. Previous studies with similar objectives have used this method to investigate underlying groupings [12,64].

The list of factors affecting safety performance was adopted from Ref. [66] for several reasons. First, this work is recent, ensuring that the factors identified are relevant to current industry conditions. Second, the work was conducted in Saudi Arabia, making it contextually relevant to the research location. This alignment ensures that the factors are specifically tailored to the unique challenges and conditions within the Saudi Arabian construction industry. Third, the list of factors was identified using a systematic literature review, indicating a rigorous and comprehensive methodological approach. This method ensures that the factors are derived from a thorough analysis of existing literature, enhancing the reliability and validity of the findings. Therefore, this work may have affectively captured all factors affecting safety performance. Similarly, the list of advanced technologies was adopted from Ref. [8]. The work was conducted in 2024, indicating that the identified technologies are highly relevant to the current state of the construction industry.

The survey had three sections. Section 1 asked about the respondent profile. This section mainly uses single-choice questions, where respondents select only one answer. However, for the question on project type, respondents can choose multiple options to reflect their involvement in different types of projects. Section 2 aimed to assess the criticality of the factors affecting safety performance using a five-point Likert scale (1 = not critical, 2 = slightly critical, 3 = moderately critical, 4 = critical, and 5 = very critical). Section 3 aimed to assess the criticality of the advanced technologies in enhancing safety performance using the same scale.

3.2. Data Collection

This study's population comprises architecture, engineering, and construction industry (AEC) professionals from consulting firms in Saudi Arabia with substantial knowledge and hands-on experience in higher education buildings projects. A purposive sampling technique was used to select eligible respondents [11]. Five key professionals, including architectural engineer, civil engineer, electrical engineer, mechanical engineer, and project manager, were identified as the most likely professionals to offer useful input. Information about consulting firms was obtained through one of the public universities in Riyadh (through one of the author's networks). Since 2009, there have been 28 building projects, with some already completed and others still ongoing. As a result, the total population in this study was 140 (5 professionals $\times$ 28 projects). The minimum sample size was computed using the Krejcie and Morgan table for a known population based on a 5% margin of error, a 90% confidence level, a 50% response distribution, and a population of 140 [67]. As a result, the minimum sample size was 93. Accordingly, 140 questionnaire surveys were distributed among the selected professionals using an online survey platform and hard copy formats using the industry contacts established by one of the authors. The study collected 105 responses in total. However, four responses were excluded from the analysis due to missing values, leaving 101 valid responses, which accedes the calculated minimum sample size of 93.

3.3. Data Analysis

3.3.1. Reliability Testing

Cronbach's alpha coefficient was used to evaluate the internal consistency of the factors and advanced technologies. The value ranges from 0.00 to 1.00, with higher values representing greater consistency among the variables. A higher value closer to 1.00 suggests that a survey participant who chooses a certain Likert-scale score for one item is likely to assign similar scores to other items within the same section. Conversely, a low value suggests the need for survey improvement to enhance internal consistency among the variables [68]. Generally, a value greater than 0.70 indicates that the scale is reliable [9].

3.3.2. Ranking Analysis

Following the reliability testing, this study used the normalized value (NV) technique to identify the critical factors and advanced technologies. Unlike the mean score, which tends to select nearly half of the variables, the normalized value technique aggregates the respondents' perceived criticality toward each variable [69]. Therefore, the NV technique is more effective in identifying the critical variables. Previous works in the construction management domain with similar objectives have used this technique to identify critical government strategies for implementing building information modeling [11] and identify the critical causes of cost overrun in building projects [65]. This technique begins by calculating the mean score to rank the factors and advanced technologies. During the mean calculation, the standard deviation (SD) was used to differentiate between variables with identical means. A lower SD indicates a higher rank due to data being more concentrated around the mean. After the ranking analysis, the NV technique was used to identify the critical factors and advanced technologies. Factors or advanced technologies with an NV above 0.50 are considered critical [65].

3.3.3. Correlation Analysis

A correlation analysis was conducted to examine the relationships between the critical factors affecting safety performance and the critical advanced technologies using Spearman's rank-order correlation. This analysis assesses the strength of the association between two variables based on ordinal or non-normally distributed data. Unlike Pearson's correlation, which assumes linear relationships and requires interval or ratio scales, Spearman's correlation is more flexible as it does not require the data to be normally distributed or have linear relationships [9]. The correlation coefficients were calculated and interpreted as follows: 0.00 to 0.29 indicates little to no correlation; 0.30 to 0.49 indicates low correlation; 0.50 to 0.69 indicates moderate correlation; 0.70 to 0.89 indicates high correlation; and 0.90 to 1.00 indicates very high correlation [70].

3.3.4. Exploratory Factor Analysis (EFA)

After identifying the critical factors and advanced technologies, EFA was utilized to explore the underlying groupings. EFA is an effective method for revealing representative connections among sets of interrelated variables [71]. It is powerful for consolidating variables into a more critical set of groupings based on their factor scores [72]. It helps identify to variables that are strongly correlated with each other and to evaluate the strength of the connections between the observed variables and the extracted latent factors [9]. Therefore, this study employed EFA to uncover the underlying groupings among the factors and advanced technologies. During EFA, principal component analysis (PCA) with varimax rotation was used to categorize the factors and advanced technologies. Previous works in the construction management domain have adopted EFA to uncover the underlying groupings among variables [11,65].

4. Results and Discussion

4.1. Respondent Profile

Figure 1 shows the respondent profile. In terms of age, most fall between the ages of 41–50 years (34.65%) and 31–40 years (27.72%). The majority hold bachelor's degrees (92.08%). Civil engineers represent 30.69% of the total sample, followed by architects (23.76%) and mechanical engineers (21.78%). Approximately 42% of the respondents have 16–20 years of experience (41.58%), followed by 19.80% with 11–15 years of experience. Respondents involved in over 10 projects account for 43.56% of the total, followed by those involved in 6–10 projects (38.61%), while those involved in 2–5 projects constitute 17.82%. Non-high-rise buildings are the most common project type (88.12%), followed by infrastructure projects at 46.53%. High-rise buildings and industrial projects each constitute 27.72%. Respondents working in medium-to-large companies represent 60.40%, followed by those working in large companies (39.60%). The majority of the respondents are employed in private sector companies (89.11%), while those working public and semi-public sectors contribute to 8.91% and 1.98% to the survey, respectively. In terms of company size, 60.40% of the respondents work in medium-to-large companies, followed by professionals working in large companies (39.60%). Most companies aged over 20 years represent 43.56% of the total, followed by those aged 16–20 years at 26.73%, and those aged 11–15 years 21.78%.

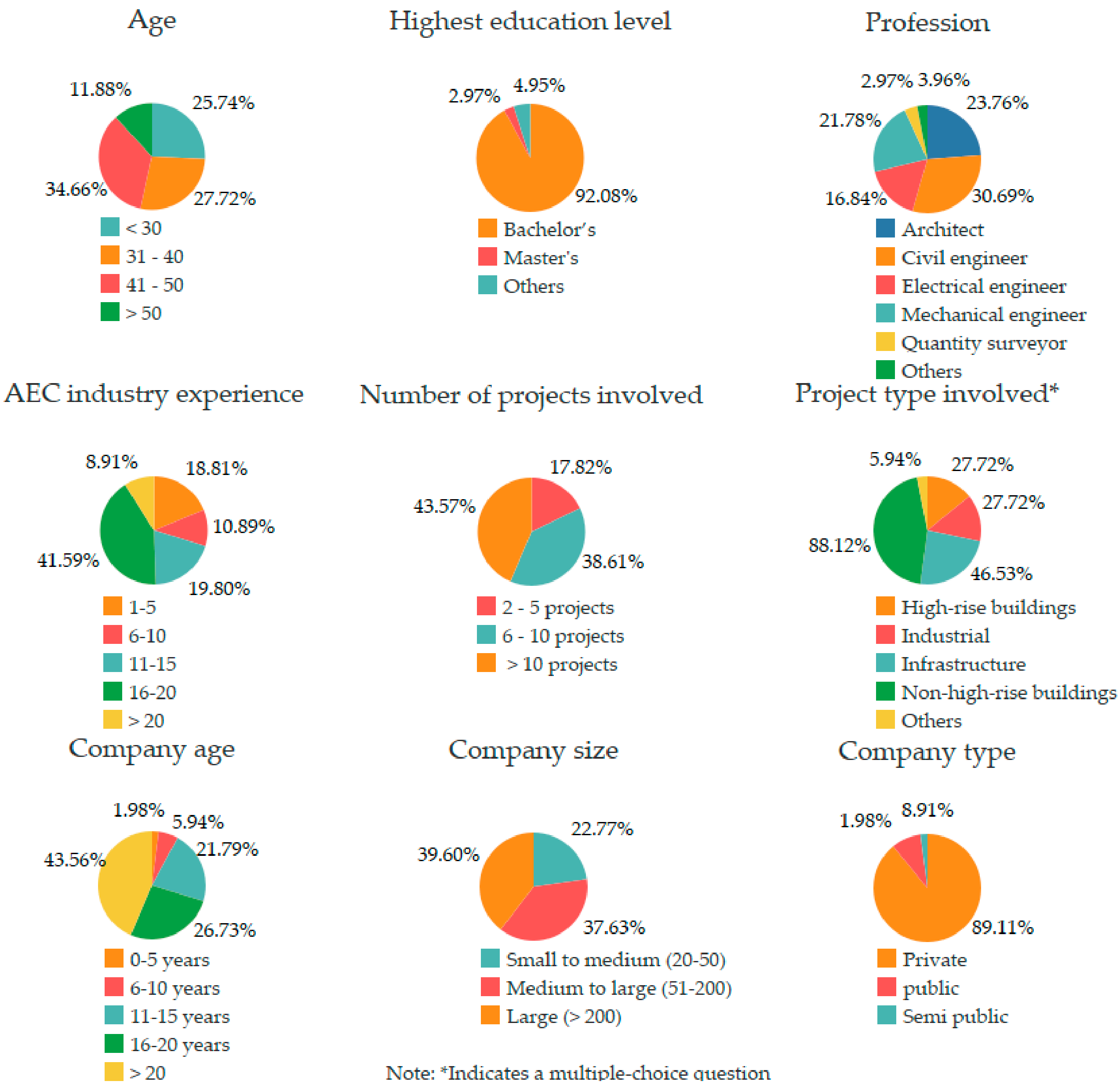

Figure 1. Respondent profile.

4.2. Results for the Reliability Testing

The reliability test was conducted using Cronbach's alpha coefficient. The results showed a coefficient value of 0.926 for factors affecting safety performance and 0.948 for advanced technologies, both exceeding the threshold of 0.60, indicating high internal consistency and reliability [68].

4.3. Results for the Ranking Analysis

Before performing the ranking analysis, the data were processed using the two standard deviations technique to identify any potential outliers in the factors or advanced technologies. This involved computing the intervals of two standard deviations. Variables with means outside of these intervals were considered outliers. For example, the factor 'availability of a smoking area' (FA35, mean = 3.802) was outside the intervals of 3.984 and 4.758. Therefore, this factor was considered an outlier and excluded from the ranking analysis. In terms of advanced technologies, the mean scores for all technologies fell within the intervals of 3.243 and 3.486. Therefore, all advanced technologies were included in the ranking analysis.

Table 3 shows the ranking of factors affecting safety performance. The results illustrate that the mean scores range between 4.089 and 4.703. Out of the 36 factors evaluated, 16 have NVs higher than 0.50. This indicates that there are 16 critical factors affecting safety performance. The top-ranked factor affecting safety performance is 'guardrails and measures for preventing workers from falling' (FA13, mean = 4.703). The second most critical factor is 'fire protection and prevention on site' (FA11, mean = 4.663), followed by 'securing the site from falling objects' (FA14, mean = 4.644). The fourth and fifth critical factors are 'electric shock protection' (FA02, mean = 4.634) and 'availability of personal protective equipment' (FA09, mean = 4.624).

Table 4 shows the ranking of advanced technologies for enhancing safety performance. The results illustrate that the mean range is between 3.248 and 3.485. Out of the 15 technologies evaluated, 8 have NVs higher than 0.50. This indicates that there are eight critical advanced technologies for enhancing safety performance. The top-ranked advanced technology is BIM (AT01, mean = 3.485). The second most critical technology is mobile devices on site (AT03, mean = 3.455), followed by AI (AT11, mean = 3.406). The fourth and fifth critical technologies are camera network systems (AT08, mean = 3.396) and photogrammetry (AT09, mean = 3.396). Figure 2 displays an overview of the ranking of factors and advanced technologies for enhancing safety performance.

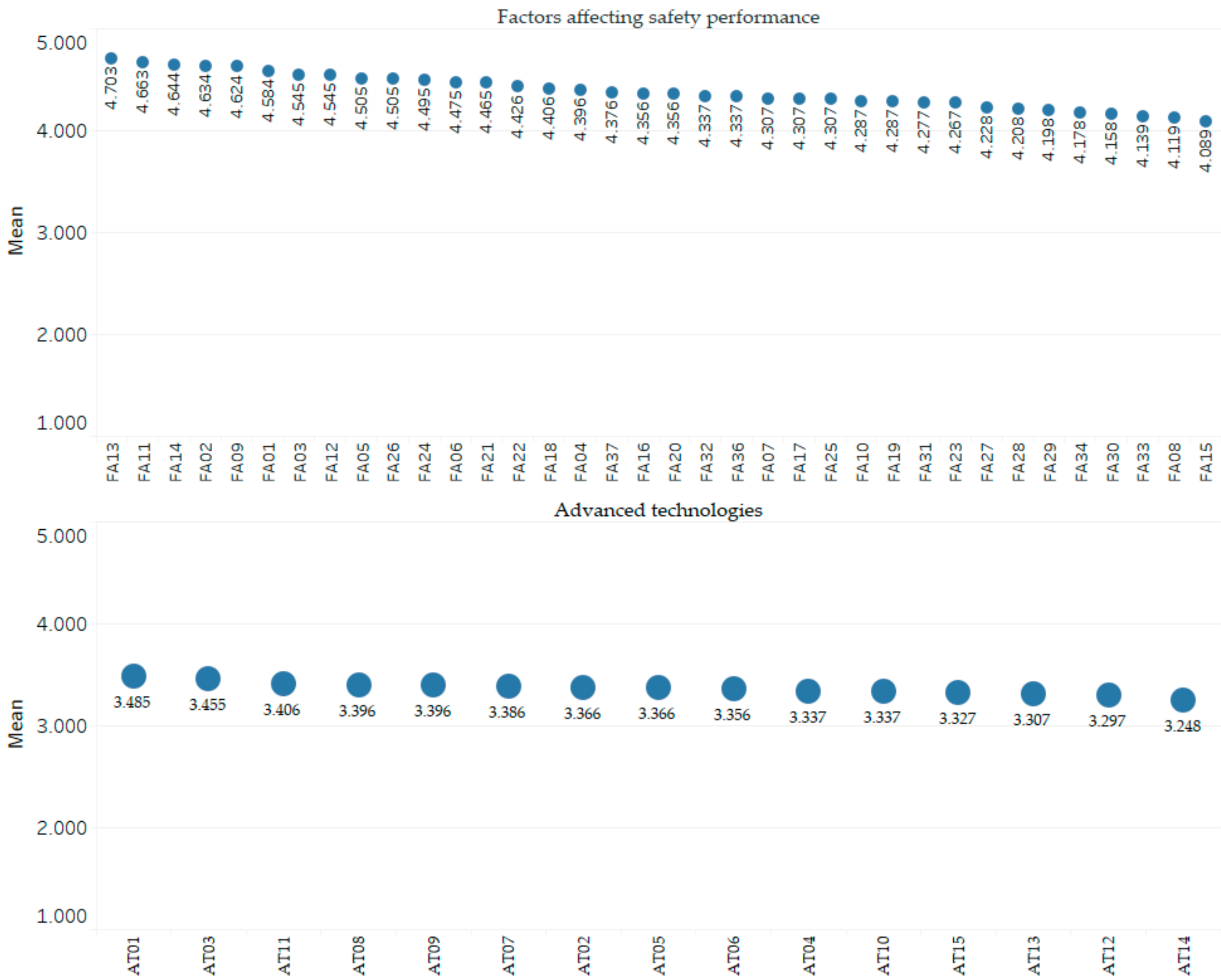

Figure 2. Overview of the ranking of factors and advanced technologies for enhancing safety performance.

4.4. Results for the Correlation Analysis

Table 5 shows that all correlations between factors and advanced technologies exhibit low negative or low positive relationships, with a few having significant negative relationships. FA01, FA1, and FA26 exhibit low negative relationships with all advanced technologies. In contrast, FA03 and FA22 exhibit low positive relationships with all advanced technologies. Positive relationships suggest that an increase in the implementation of advanced technologies is associated with a slight decrease in the related factors. Also, the statistically significant correlations confirm the presence of measurable associations, though the relationships are predominantly weak. This implies that while the adoption of advanced technologies may influence certain factors, the effects are not strong, highlighting the need for further research to explore additional variables that may impact these relationships. Figure 3 provides an overview of the correlation analysis results.

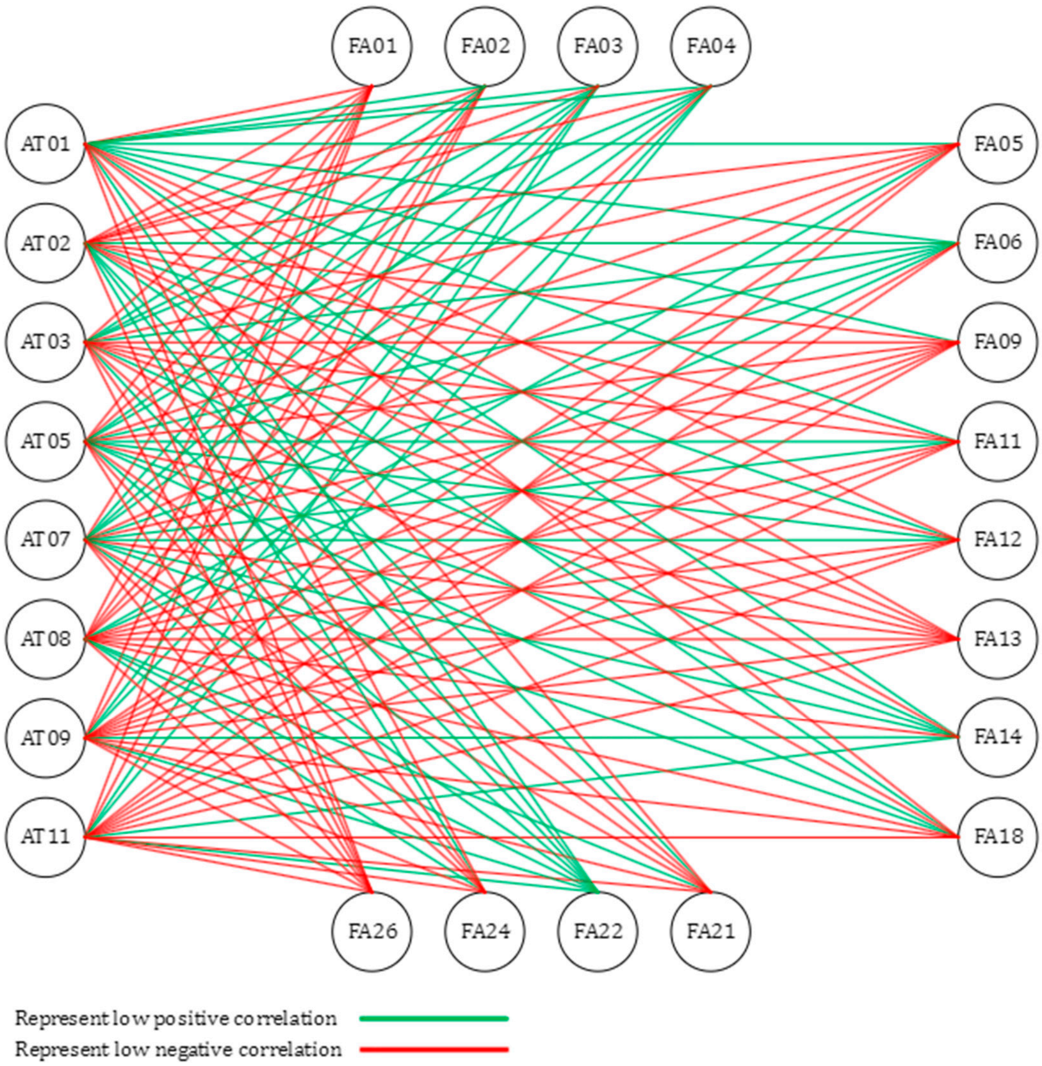

Figure 3. Overview of the correlation analysis results.

4.5. Results for Exploratory Factor Analysis (EFA)

The sample size ratio to the number of variables was used to determine the sufficient sample size for the EFA. Ref. [73] recommends a sample–variable ratio between 5:1 and 20:1. In this study, the ratio of the sample size (101) to the number of the critical factors (16) and the critical advanced technologies (8) was 6.31 and 12.63, exceeding the minimum ratio of 5:1.

Table 3. Ranking of factors affecting safety performance.

ID	Factors Affecting Safety Performance	Mean	SD	NV	Rank
FA13	Guardrails and measures for preventing workers from falling	4.703	0.4805	1.000 *	1
FA11	Fire protection and prevention on site	4.663	0.6046	0.935 *	2
FA14	Securing the site from falling objects	4.644	0.5583	0.903 *	3
FA02	Electric shock protection	4.634	0.7173	0.887 *	4
FA09	Availability of personal protective equipment	4.624	0.6140	0.871 *	5
FA01	Availability of safety signs and boards on site	4.584	0.6967	0.806 *	6
FA12	Quality and safety of the work environment	4.545	0.5390	0.742 *	7
FA03	Availability of an emergency and safety plan	4.545	0.6859	0.742 *	8
FA26	Company acceptance of employee feedback and complaints on safety	4.505	0.6265	0.677 *	9
FA05	Availability of a first aid kit and medical measures	4.505	0.8322	0.677 *	10
FA24	Medical insurance policy	4.495	0.6265	0.661 *	11
FA06	Quality of safety resources, tools, and equipment	4.475	0.6418	0.629 *	12
FA21	Attitude and negligence	4.465	0.6718	0.613 *	13
FA22	Safety supervision level	4.426	0.6978	0.548 *	14
FA18	Sufficient ventilation	4.406	0.7096	0.516 *	15
FA04	Implementation of safety policies and procedures	4.396	1.0008	0.500 *	16
FA37	Project size	4.376	0.7050	0.468	17
FA16	Maintenance of tools and equipment	4.356	0.5930	0.435	18
FA20	Sufficient illumination	4.356	0.5930	0.435	19
FA36	Workmate collaboration	4.337	0.6823	0.403	20
FA32	Communication	4.337	0.7110	0.403	21
FA25	Worker experience and skills	4.307	0.6123	0.355	22
FA17	Use of well-designed and maintained temporary structures	4.307	0.7035	0.355	23
FA07	Education and training	4.307	0.7582	0.355	24
FA10	Housekeeping	4.287	0.6532	0.323	25
FA19	Safety inspections	4.287	0.7394	0.323	26
FA31	History of accidents on site and safety records	4.277	0.7365	0.306	27
FA23	Sufficient hygiene	4.267	0.6912	0.290	28
FA27	Availability of a safe storage area	4.228	0.8818	0.226	29
FA28	Overworking employees	4.208	0.7116	0.194	30
FA29	Worker age	4.198	0.6785	0.177	31
FA34	Management support for worker safety guidance, incentives, and motivation	4.178	0.8988	0.145	32
FA30	Ensure permissible noise exposure on site	4.158	0.6743	0.113	33
FA33	External influences on employees	4.139	0.7075	0.081	34
FA08	Weather conditions	4.119	0.8401	0.048	35
FA15	Availability of resting areas	4.089	0.8729	0.000	36

NV (normalized value) = mean–minimum mean/maximum mean–minimum mean; * indicates that the factor is critical.

Table 4. Ranking of advanced technologies for enhancing safety performance.

ID	Advanced Technologies	Mean	SD	NV	Rank
AT01	Building information modeling (BIM)	3.485	0.7696	1.000 *	1
AT03	Mobile devices on site	3.455	0.7813	0.875 *	2
AT11	Artificial intelligence (AI)	3.406	0.7507	0.667 *	3
AT08	Camera network systems	3.396	0.7222	0.625 *	4
AT09	Photogrammetry	3.396	0.7222	0.625 *	5
AT07	Digital signage	3.386	0.7344	0.583 *	6
AT02	Wearable sensing devices (WSDs)	3.366	0.7032	0.500 *	7
AT05	Light detection and ranging (LiDAR) and laser scanning	3.366	0.7311	0.500 *	8
AT06	Quick response codes (QR codes)	3.356	0.7292	0.458	9
AT10	Exoskeleton/exo-suit	3.337	0.7110	0.375	10
AT04	Radiofrequency identification (RFID)	3.337	0.7249	0.375	11
AT15	Internet of Things (IoT)	3.327	0.7760	0.333	12
AT13	Virtual and augmented reality (VR/AR)	3.307	0.7841	0.250	13
AT12	Unmanned aerial vehicles (UAVs)	3.297	0.7286	0.208	14
AT14	Automation and robot	3.248	0.7669	0.000	15

NV (normalized value) = mean–minimum mean/maximum mean–minimum mean; * indicates that the advanced technology is critical.

Table 5. Results for the correlation analysis.

ID	FA01	FA02	FA03	FA04	FA05	FA06	FA09	FA11	FA12	FA13	FA14	FA18	FA21	FA22	FA24	FA26
AT01	−0.046	0.024	0.125	0.125	0.024	0.035	0.003	0.029	−0.023	−0.006	0.046	−0.031	−0.093	0.095	−0.158	−0.196
AT02	−0.098	−0.055	−0.199 *	−0.079	−0.005	0.040	−0.075	−0.103	0.025	−0.043	−0.109	0.029	0.139	0.088	0.099	−0.053
AT03	−0.069	0.006	0.142	0.154	−0.052	0.003	−0.083	−0.002	−0.023	−0.081	0.060	−0.078	−0.088	0.018	−0.269 **	−0.149
AT05	−0.095	−0.020	0.068	0.096	−0.066	0.030	−0.040	0.002	0.048	−0.075	0.062	0.013	−0.068	0.054	−0.216 *	−0.138
AT07	−0.045	0.021	0.150	0.173	−0.010	0.060	−0.024	0.045	0.045	−0.033	0.103	0.024	−0.082	0.085	−0.178	−0.109
AT08	−0.207 *	−0.132	−0.221 *	−0.056	0.028	0.010	−0.220 *	−0.162	−0.056	−0.087	−0.129	−0.084	0.021	0.024	0.063	−0.095
AT09	−0.142	−0.073	0.016	0.090	−0.052	−0.024	−0.089	−0.040	−0.031	−0.085	0.023	−0.050	−0.093	0.015	−0.273 **	−0.196 *
AT11	−0.125	−0.081	0.004	0.078	−0.056	−0.054	−0.106	−0.047	−0.046	−0.071	0.015	−0.061	−0.096	0.040	−0.259 **	−0.207 *

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

PCA with varimax rotation was used to extract the underlying groupings. Ref. [68] suggests retaining indicators with factor loadings greater than 0.50, as they substantially contribute to the interpretation of the factor group. Regarding factors affecting safety performance, 'sufficient ventilation' (FA18), 'implementation of safety policies and procedures' (FA04), 'quality of safety resources, tools and equipment' (FA06), and 'availability of personal protective equipment' (FA09) had loadings of less than 0.50, prompting their removal from the analysis. Moreover, 'guardrails and measures for preventing workers from falling' (FA13) had substantial loading in two different underlying groupings, promoting its removal from the analysis [74]. As a result, 11 factors were deemed eligible for another round of EFA. Tables 6 and 7 illustrates that four and two underlying groupings for the factors and strategies explained 70.756 and 88.410 of the total variance, respectively, which is above the minimum threshold of 50% [68]. Each underlying grouping was given a unique label to represent the underlying meaning. Accordingly, the four underlying groupings for factors affecting safety performance were named as follows: (1) safety planning and hazard prevention, (2) workplace environment and supervision, (3) employee safety support, and (4) medical readiness and site protection. The two underlying groupings for advanced technologies were named as follows: (1) advanced digital technologies and (2) personal and site monitoring technologies. Figure 4 provides an overview of the results of EFA. The percentage of each underlying grouping was calculated by dividing the total mean of the variables within a specific grouping by the overall mean of all variables included in the EFA.

Tables 6 and 7 illustrate that four and two underlying groupings were extracted based on eigenvalues ($\geq$1.00) [11]. All loadings were higher than 0.50, ranging between 0.659 and 0.861 for the factors and between 0.883 and 0.952 for advanced technologies. The KMO values for the factors and advanced technologies were 0.779 and 0.749, exceeding the minimum acceptable value of 0.60 [75]. The results of Bartlett's test of sphericity for the factors and advanced technologies were 363.291 and 1036.085, with a significance level of 0.000, suggesting that the correlation matrix is not an identity matrix, reinforcing the appropriateness of the EFA. Tables 6 and 7 illustrates that four and two underlying groupings for the factors and strategies explained 70.756 and 88.410 of the total variance, respectively, which is above the minimum threshold of 50% [68]. Each underlying grouping was given a unique label to represent the underlying meaning. Accordingly, the four underlying groupings for factors affecting safety performance were named as follows: (1) safety planning and hazard prevention, (2) workplace environment and supervision, (3) employee safety support, and (4) medical readiness and site protection. The two underlying groupings for advanced technologies were named as follows: (1) advanced digital technologies and (2) personal and site monitoring technologies. Figure 4 provides an overview of the results of the EFA. The percentage of each underlying grouping was calculated by dividing the total mean of the variables within a specific grouping by the overall mean of all variables included in the EFA.

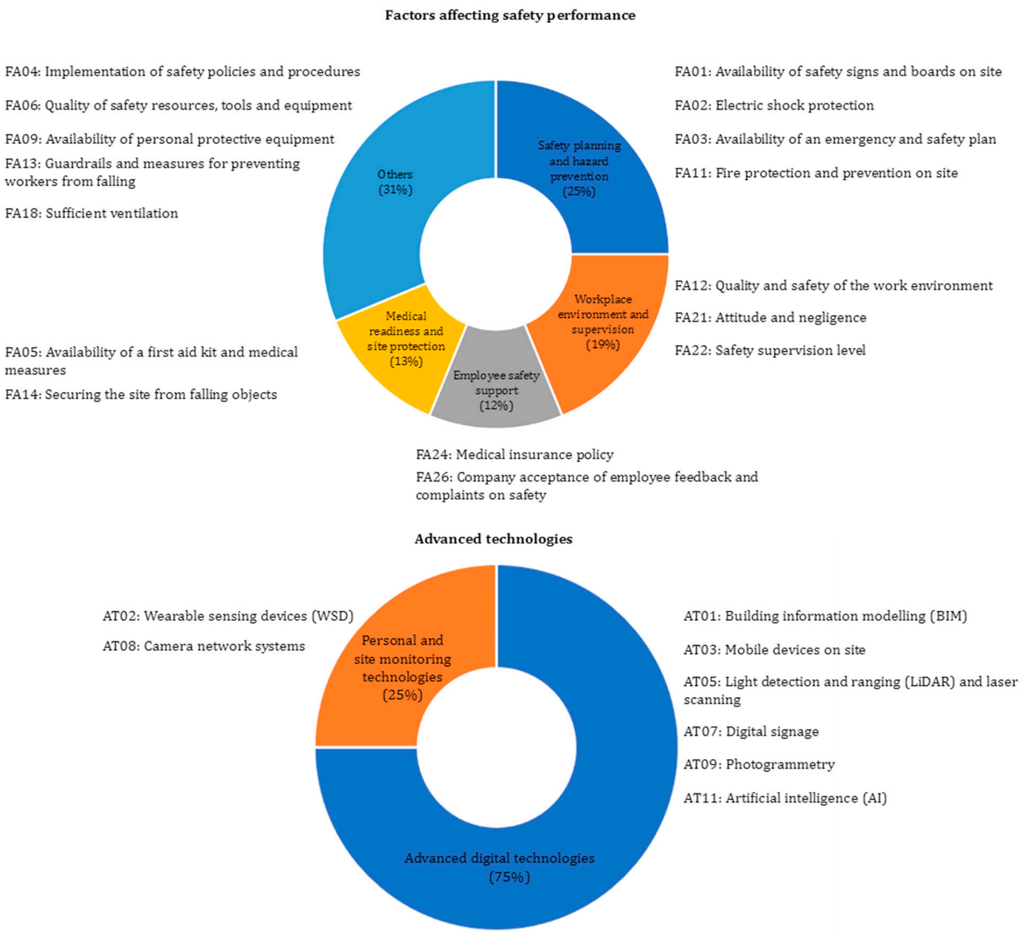

Figure 4. Overview of the factor analysis results.

Table 6. Factor analysis results for factors affecting safety performance.

ID	Description	Loadings			
		1	2	3	4
	Underlying grouping 1: Safety planning and hazard prevention				
FA03	Availability of an emergency and safety plan	0.840			
FA02	Electric shock protection	0.839			
FA11	Fire protection and prevention on site	0.827			
FA01	Availability of safety signs and boards on site	0.659			
	Underlying grouping 2: Workplace environment and supervision				
FA21	Attitude and negligence		0.801		
FA22	Safety supervision level		0.773		
FA12	Quality and safety of the work environment		0.691		
	Underlying grouping 3: Employee safety support				
FA24	Medical insurance policy			0.795	
FA26	Company acceptance of employee feedback and complaints on safety			0.766	
	Underlying grouping 4: Medical readiness and site protection				
FA05	Availability of a first aid kit and medical measures				0.861
FA14	Securing the site from falling objects				0.767
	Eigenvalues	3.963	1.531	1.238	1.051
	Variance explained (%)	25.935	18.152	13.412	13.257
	Cumulative (%)	25.935	44.088	57.500	70.756

Extraction method: PCA. Rotation method: varimax with Kaiser normalization.

Table 7. Factor analysis results for advanced technologies for enhancing safety performance.

ID	Description	Loadings	
		1	2
	Underlying grouping 1: Advanced digital technologies		
AT09	Photogrammetry	0.952	
AT05	Light detection and ranging (LiDAR) and laser scanning	0.947	
AT07	Digital signage	0.930	
AT11	Artificial intelligence (AI)	0.927	
AT03	Mobile devices on site	0.904	
AT01	Building information modeling (BIM)	0.883	
	Underlying grouping 1: Personal and site monitoring technologies		
AT08	Camera network systems		0.936
AT02	Wearable sensing devices (WSDs)		0.931
	Eigenvalues	5.558	1.514
	Variance explained (%)	64.704	23.706
	Cumulative (%)	64.704	88.410

Extraction method: PCA. Rotation method: varimax with Kaiser normalization.

4.5.1. Underlying Groupings of Factors Affecting Safety Performance

Underlying Grouping 1: Safety Planning and Hazard Prevention

Safety planning and hazard prevention are foundational to successful construction project management, ensuring both worker protection and project efficiency [12]. A comprehensive safety plan includes a thorough site assessment to identify potential hazards, such as unstable structures, electrical risks, and fire dangers [14]. This proactive identification allows for targeted control measures, such as reinforcing structures, ensuring proper electrical insulation, and safely storing flammable materials [15]. Integral to this strategy are regular site inspections and risk assessments, conducted weekly by qualified safety officers, which help to continually monitor and address safety concerns [28]. An effective safety plan also includes structured emergency response protocols, detailing specific evacuation procedures, designated safe zones, and communication channels with emergency services [24]. Regular drills and training sessions, including fire drills and first aid training, familiarize workers with these procedures, ensuring they know evacuation routes, assembly points, and how to use emergency equipment [13]. This preparedness mitigates the impact of emergencies and instills confidence among workers [25]. Furthermore, maintaining a well-documented emergency plan that undergoes regular review and updates ensures that all personnel are fully informed of their roles and responsibilities during a crisis, thereby facilitating coordinated and efficient responses. This preparedness enhances the effectiveness of the emergency plan and fosters a culture of safety and readiness through continuous education and engagement initiatives [66]. By embedding these practices into daily operations, construction projects can minimize accidents, ensure regulatory compliance, and improve productivity. This approach of safety planning and hazard prevention underscores the importance of creating a secure and efficient work environment, where workers are aware of potential hazards and equipped with the knowledge and tools to prevent accidents [22]. By prioritizing safety planning and hazard prevention, construction firms protect the workers and enhance their operational success.

Underlying Grouping 2: Workplace Environment and Supervision

Creating a safe workplace environment in construction projects hinges on worker attitudes and behaviors, and the effectiveness of supervision [17]. A supportive working environment significantly influences individuals' attitudes and behaviors, shaping how workers perceive and engage with safety protocols [26]. Many construction accidents stem from workers' negligent behaviors and irresponsible attitudes, such as leaving hazardous materials like wood with protruding nails in walkways or using makeshift scaffolding supports instead of proper assembly [12]. This negligence underscores the critical need for a robust safety culture within the working environment, where safety is prioritized and reinforced through continuous education and engagement [59]. Safety-conscious supervisors who actively engage with workers significantly contribute to safer practices on-site [76]. Effective supervision involves monitoring and enforcing safety regulations while fostering a culture of safety through communication, support, and education. Previous works illustrate that competent supervision leads to enhanced safety outcomes and reduced accidents. Supervisors' attitudes and behaviors can positively or negatively impact workers' safety attitudes and practices, with poor communication and inadequate managerial support cited as significant causes of unsafe behaviors among workers [23]. In addition, employee motivation plays a crucial role in safety compliance, as motivated workers are more likely to adhere to safety protocols [66]. For example, when workers see that a safe workplace leads to fewer accidents, they may feel more engaged and committed to maintaining safety standards, indirectly benefiting from a safer work environment [17]. Thus, construction companies are encouraged to invest in comprehensive and context-specific training programs addressing the unique risks and challenges of the work environments [19]. In conclusion, creating a supportive working environment and supervision is crucial for minimizing safety risks and decreases the likelihood of accidents.

Underlying Grouping 3: Employee Safety Support

Insurance policies play a crucial role in enhancing safety in construction projects by providing a financial safety net and ensuring prompt medical care for injured workers [12]. For instance, health insurance covers medical treatments, such as surgeries or physical therapy, which are crucial for workers recovering from on-site injuries [15]. This can speed up recovery, reduces the financial burden on workers, and also improves overall worker well-being and productivity. These policies contribute to a safer workplace culture by incentivizing proactive health management and preventive care. Simultaneously, fostering acceptance and active response to employee feedback and complaints can improve safety practices [18]. Encouraging workers to report hazards and suggest improvements without fear helps identify and mitigate risks promptly, preventing accidents [19]. Therefore, it is essential for companies to be open to receiving complaints and suggestions from workers, as this collaborative approach can significantly enhance workplace safety and foster a culture of continuous improvement [23].

Underlying Grouping 4: Medical Readiness and Site Protection

The presence of a first aid kit and accessible medical measures on-site is critical for an immediate response in case of injuries [30]. Quick and effective medical intervention can prevent minor injuries from becoming major ones, thereby reducing downtime and maintaining productivity [15]. Furthermore, the availability of first aid resources reassures workers that their health and safety are prioritized, fostering a safer and more conscientious work environment [25]. Moreover, protective measures, such as installing barriers and guardrails around elevated work areas, prevent objects from falling and causing injuries [17]. Regular inspections of these barriers for stability and integrity are necessary to maintain their effectiveness. The use of tool lanyards to secure equipment and the installation of safety nets below elevated areas can further mitigate the risk of falling objects [13]. Clear warning signs in high-risk areas alert workers to potential dangers, while alarm systems can provide immediate warnings, allowing workers to take protective action [42]. Integrating these measures with a comprehensive safety strategy involves regular safety drills that simulate real-life scenarios, such as a falling object incident followed by a medical response, ensuring workers are well-prepared for both preventive and reactive safety protocols [8]. Continuous evaluation and improvement of these measures can further strengthen the overall safety on construction sites.

4.5.2. Underlying Groupings of Advanced Technologies

Underlying Grouping 1: Advanced Digital Technologies

Photogrammetry and LiDAR technologies have shown considerable promise in enhancing safety by simplifying work processes. The combination of photogrammetry and LiDAR methods significantly improves hazard recognition and safety planning, while also aiding in the identification of defects and potential hazards through precise measurements and visuals [77]. LiDAR is notable for its application in blind spot detection, preventing construction site accidents [10]. Emerging AI technologies further bolster construction safety by minimizing risks through advanced warning systems and visual processing algorithms [78]. AI-based models have proven effective in predicting serious incidents, such as fatalities, and providing early warnings for occupational heat stress, ensuring that workers are protected from environmental hazards [35]. These technologies enable proactive measures, allowing for timely interventions and improved risk management on construction sites. Digital signage, as an administrative control, enhances safety communication with real-time updates and strategic messaging, offering a cost-effective alternative to traditional signage [50]. This technology improves safety communications by delivering critical messages more efficiently and effectively, thereby raising awareness and enabling quicker responses to potential threats [51]. Additionally, the use of various colors and strategically placed safety symbols can significantly influence workers' risk perceptions and behaviors. The use of mobile devices has revolutionized safety monitoring on construction sites. Equipped with multiple sensors, ultrasound, and infrared capabilities, these devices can be deployed in hazardous zones to automate safety monitoring, reducing reliance on labor-intensive and error-prone manual observations [8]. For example, in Korea, a mobile sensing device with hybrid sensors was developed to detect workers approaching risky areas, thereby reducing accident rates [42]. Mobile tracking sensors facilitate real-time safety oversight, ensuring the prompt identification and mitigation of potential hazards. Moreover, BIM significantly enhances construction safety performance through its collaborative environment, advanced visualization, and information-sharing mechanisms [10]. BIM tools, such as the safety risk calculation plug-in for Autodesk Revit, enable the optimization of construction safety by evaluating design alternatives to minimize fatality risks [79]. BIM interfaces that provide near-miss visualizations allow construction personnel to detect and report hazardous areas and near-miss incidents, thereby improving safety awareness and communication [80]. Integrating safety management tasks into the 4D BIM model fosters early and detailed safety planning, facilitating the incorporation of safety features, such as guardrails and safety harness anchor points from the project's inception [6].

Underlying Grouping 2: Personal and Site Monitoring Technologies

Construction projects require ongoing attention and monitoring of operations progress [39]. Monitoring technologies play a critical role in preventing accidents and injuries. Camera networks, strategically placed throughout the site, provide continuous surveillance of critical areas, such as scaffolding and crane operations [7]. These systems monitor ongoing activities and serve as powerful tools for incident investigation and safety audits [10]. For instance, cameras can capture and record unsafe behaviors, such as unauthorized access to restricted areas or improper use of equipment, facilitating immediate corrective actions [5]. Moreover, in the event of an accident or near-miss incident, camera networks provide valuable insights for root cause analysis and improving safety training programs [8]. Intelligent video surveillance allows for remote safety inspections, thereby increasing the effectiveness and efficiency of managing site safety risks [81]. Sensor-based and wearable technologies for safety monitoring can also support and improve safety. Ref. [10] found that wearable devices are one the most important technologies impacting safety performance. Ref. [82] listed several applications of wearable technologies, including measuring kinetic movement, skin response, cardiac activity, muscle engagement, and eye movement, all of which are vital for worker health and safety. The work also suggested that sensors could help prevent falls. WSDs can improve worker safety by efficiently collecting and analyzing data, providing personnel with real-time information on safety and health risks [83].

5. Limitations and Future Directions

Notwithstanding the contributions of this study, several limitations should be noted. Firstly, EFA relies on subjective interpretation when identifying and naming the underlying constructs, which may introduce bias. In addition, EFA assumes linear relationships among variables, potentially overlooking more complex interactions. Future studies should consider using complementary analytical methods, such as confirmatory factor analysis, to validate the findings and explore more complex relationships. Secondly, this study is perception-based, relying on survey responses to assess the criticality of factors and technologies. This approach may be subject to individual biases and perceptions, which might not fully capture the realities of safety performance in construction. Future research could benefit from conducting case studies or integrating empirical data, such as incident reports or field observations, to triangulate the findings and provide a more robust evaluation of safety performance factors. Finally, the study did not explore the interactions between the latent constructs of factors and advanced technologies. Incorporating advanced data analysis techniques, such as structural equation modeling, could enhance the understanding of these interactions by examining the complex relationships and the effects of advanced technologies on safety performance factors.

6. Conclusions

This study investigates the inter-relationships among factors affecting safety performance and advanced technologies. A questionnaire survey was used to assess the criticality of these factors and technologies in enhancing safety. The data were analyzed using descriptive statistics, correlation analysis, and EFA. The findings illustrate that 16 factors affecting safety performance are critical. Of these, 11 factors can be grouped into four underlying groupings: safety planning and hazard prevention, workplace environment and supervision, employee safety support, and medical readiness and site protection. Improving safety requires coordinated efforts across these areas, such as enhancing planning processes, ensuring robust supervision, fostering a supportive work culture, and maintaining readiness for medical emergencies. Policymakers can use these groupings to enhance safety by developing targeted regulations and training programs. Addressing these categories collectively can lead to more significant and sustainable improvements in construction safety. Moreover, the findings highlight that eight advanced technologies are critical for enhancing safety. These technologies can be grouped into two underlying groupings: advanced digital technologies, and personal and site monitoring technologies. This study encourages the integration of both types of technologies to create a robust safety management system. Practitioners should adopt these technologies to improve safety management, while policymakers should support their development and implementation. This can lead to more effective safety interventions and better overall safety outcomes in construction projects. Finally, the results of the correlation analysis indicate that the statistically significant correlations between factors and advanced technologies confirm measurable but weak associations. This suggests that while advanced technologies may influence certain factors, the effects are limited. Further research can explore other variables that may impact these relationships.

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