

## Article

# A Research Framework of Mitigating Construction Accidents in High-Rise Building Projects via Integrating Building Information Modeling with Emerging Digital Technologies

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**Abstract:** The construction of high-rise building projects is a dangerous vocation due to the uniqueness and nature of the activities, as well as the complexity of the working environment, yet safety issues remain crucial in the construction industry. Digital technologies, such as building information modeling (BIM), have been identified as valuable tools for increasing construction productivity, efficiency, and safety. This research aimed to mitigate the accident safety factors in high-rise building projects via integrating BIM with emerging digital technologies in the construction industry, such as photogrammetry, GPS, RFID, augmented reality, (AR), virtual reality (VR), and drone technology. Qualitative research was conceived in the ground theory approach. Forty-five online interviews with construction stakeholders and qualitative data analysis were carried out using the NVivo 11 software package. According to the findings, interviewees were more motivated to use photogrammetry and drone technologies in high-rise building projects in order to increase construction safety. Positive, negative, and neutral attitudes about BIM integration with emerging digital technologies were discovered. Furthermore, a research framework was developed by consolidating research findings that articulate the measures and future needs of BIM integration with other digital technologies to mitigate construction accidents in high-rise building projects. The framework also renders practical references for industry practitioners towards effective and safer construction.

**Keywords:** building information modeling; high-rise buildings; construction projects; safety; accidents



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## 1. Introduction

With the passage of time, the demand for high-rise buildings is continuously increasing, which has led to a rise in accident and fatality rates [1]. In many countries, the construction of high-rise buildings is well known for being high risk due to accidents [2,3]. Accidents not only result in project delays and permanent disability [4] but also have huge personal, social, and financial costs [5,6]. Accident and fatality rates are still higher compared to other industries [7,8]. In Europe, approximately, 20% of accidents happen in the construction sector [9]. Similarly, in Malaysia, the Department of Occupational Safety and Health (DOSH) stated that in 2019, 7984 accident cases were recorded, which is the highest number of accident cases as compared to previous years. Numerous practices have been implemented in the construction industry over the past few decades to reduce the high number of incidents and injuries in the workplace, but safety remains a key concern [7].

Modern construction always adopts advanced digital technologies, and one technology is building information modelling (BIM) [10]. BIM serves as a digital information management system that is one of the most informative technologies in the construction industry [11]. With the utilization of BIM, construction projects are able to manage and produce data-rich models that help in shifting the trend from vision towards realization [12].

Furthermore, BIM has the potential to integrate data from different capturing technologies like photogrammetry, global positioning system (GPS), geographic information system (GIS), radio frequency identification (RFID), augmented reality (AR), and virtual reality (VR), laser scanning, and quick response (QR) coding to produce a variety of comprehensive data and information about a project, particularly for improving the construction site safety [13,14]. By using modeling software, architects and engineers can construct n-D models that not only have parametric and object-oriented features, but that also provide the information necessary for current and prospective construction [15]. From the perspective of high-rise buildings, BIM has been integrated with a safety-rule checking platform, which shows the potential of using digital building models in construction [16]. In addition, unmanned aerial vehicles (UAVs) can enable safety managers to minimize the time needed to visit construction sites and strengthen the identification and inspection of risks in high-rise buildings [17]. The potential uses of digital technologies can significantly improve the safety practices in high-rise buildings. With the support of digital technologies, construction information can be exchanged between workers and management staff in order to collaborate in an effective way [18].

In the U.S., the *National Fire Protection Association* regarded high-rise buildings as being higher than 75 feet (23 m) or about 7 stories [19]. A high-rise building is generally defined as one that extends higher than the greatest reach of existing fire-fighting equipment. In absolute terms, this has been placed at various heights ranging from 75 (23 m) to 100 feet (30 m), or around 7 to 10 stories (depending on the slab-to-slab distance between floors) [20].

Related studies have shown that BIM has been integrated with other emerging technologies to effectively control the evacuation regulation of BIM data in high-rise buildings [21,22]. In addition, the BIM-based intelligent fire prevention and disaster relief system has been proposed to incorporate personal location information on evacuation/rescue route optimization with Bluetooth-based technology and a mobile guidance device to build a smart two-way fire disaster prevention system that displays real-time and interactive fire information in three dimensions (3-D) [23]. In addition, the BIM cloud-based radio frequency identification (RFID) location system has tremendous potential for practical applications, such as site protection control, safety management, asset management, and productivity tracking [24].

Several studies have been performed to determine accidental safety factors [25,26]; however, high fatalities among construction workers remain a major global concern for policy makers [27]. A recent case study or prototype was conducted to integrate certain digital technologies for construction safety monitoring and inspection [28]. However, very limited empirical studies have integrated BIM with other digital technologies for construction safety management, where the current approaches or studies have mainly focused on BIM-based AR and VR applications for data exchange and improved safety performance through case studies and prototypes [29]. In addition, BIM-based 4-D modeling has been used to establish the rule checking platform for construction safety [30]. Likewise, the machine learning-based object detection technique offers a platform for construction safety and surveillance through cloud fuse point, semantic data, and computer vision [31]. Furthermore, numerous researchers have made major contributions to the field of high-rise building construction safety, but there are some limits. For example, Manzoor et al. [26] identified the safety factors that cause accidents in high-rise building projects but were unable to suggest mitigating solutions. A recent study conducted by Thinakaran et al. [32] identified the safety elements affecting the safety performance of high-rise building projects but did not suggest mitigation measures. Therefore, the aim of this study was to mitigate accidental safety factors in high-rise building projects by integrating BIM with other emerging digital technologies for construction safety improvement. Qualitative research was conducted via interviews with related stakeholders to investigate the in-depth knowledge of this relative new integration of BIM and other emerging digital technologies for improving the construction safety in high-rise building projects. The research thus explored and uncovered new knowledge gaps and the practical needs of this integration for construction

safety management in high-rise building projects. It also serves as a theoretical foundation for improving safety performance in future digitalized construction projects.

The remainder of the paper is organized as follow. Section 2 presents a literature review and the rationale for this research. Section 3 describes the research methodology. Section 4 provides the results. Subsequently, Section 5 elaborates on the discussion and research framework followed by Section 6, which contains the conclusion, limitations, and future directions.

## 2. Literature Review

A significant number of research studies have been conducted that integrate BIM with emerging digital technologies in order to boost modern construction [33,34]. With the advancement of construction technologies, the BIM concept consists of 3-D-Model, 4-D-Time, 5-D-Cost, 6-D-Facility Management, 7-D-Sustainability [35,36], and 8-D-Safety [37]. It indicates that “this technology has no limit since it is possible to add as many data as you want” [38]. Due to the unsafe nature of the building environment, construction safety management is considered to be an important part of the performance criteria of the project [26,39]. Construction safety management includes safety practices and the duty of construction managers to ensure the safety of construction workers and construction firms’ resources. The construction environment (construction firms and construction sites) possesses a socio-technical nature that requires construction safety management to be strongly based mostly on a construction safety culture [40]. As a result of the constant movement of construction workers and construction activities between construction firms and construction sites, the construction safety culture is seen as an integral part of construction safety management and encourages an awareness of safety management performance [41,42]. More significantly, there is a lack of awareness of how construction safety management elements can be integrated into the construction safety culture [43]. It is therefore known that the use of emerging technologies, such as BIM, has the potential to integrate construction safety management into the construction safety culture [43]. From previous studies, BIM can help practitioners by optimizing visualization, communication, and integration in construction projects [44,45]. However, some practitioners are still hesitant to adopt these innovative tools.

Recently, BIM integrated with other digital technologies in construction safety management practices has gained worldwide attention due to object orientation and is being promoted as an appropriate method to improve the quality and efficiency of construction safety management practices [46]. In addition, the implementation of BIM in building design is evolving rapidly. Over time, BIM-based modeling and 4-D simulation (3-D and schedule) have provided distinct advantages for both construction safety and logistics applications [47]. For instance, in scaffolding work, 4-D BIM simulation can be used as a safety management tool to track and mitigate safety hazards [48]. BIM has the ability to enhance design efficiency by reducing conflict and eliminating rework for building quality control [49,50]. Moreover, 4-D BIM applications provide designers with a tool to analyze construction safety concerns during design phases in order to resolve issues for smooth construction in high-rise building projects. By using this tool, proactive measures could be taken during the design and planning phases to reduce site hazards [51,52]. During the facility management phase, a BIM-based framework was presented to promote secure maintenance and repair activities with the use of safety attribute identification/classification, data analysis, and rule-based decision making [53]. Accordingly, the BIM literature review found that the literature is largely optimistic about the potential of BIM and other emerging digital technologies. A brief overview of relevant works in the field of construction safety and BIM, accompanied by rationale and research gaps, has been addressed.

### 2.1. Related Works

The summary of current research work and results on the integration of BIM with other emerging digital technologies for construction safety is discussed in this section. Due

to the inappropriate performance of safety measures, numerous accidents have affected the construction sector [54]. Consequently, BIM is now considered to be the most promising technology in the construction sector [55]. BIM can be correlated with other emerging technologies in the construction sector to streamline project phases and improve productivity and efficiency. The construction sector is criticized for being the slowest to embrace digital innovation despite being one of the largest industries, contributing a 10th of the overall gross domestic product of the world (GDP). Moreover, BIM has played a significant role in construction safety in existing studies [47], such as visualization of scaffolding and safety facilities for accident prevention [56], development of an RFID-based real-time location system to observe construction workers [57], and establishment of databases of near-miss on-site events [58]. Similarly, a cloud-based safety information and communication system has been developed for visualization and processing of construction site safety conditions through remote sensing and VR [59]. A tremendous effort has been made by several researchers in the field of BIM integrated with digital technologies and construction safety. The overview of related works is shown in Table 1.

**Table 1.** Overview of related works.

Related Works	Types of Research	Types of Integrations	Research Implications
J Ratajczak et al. [60]	AR4C application prototype	BIM-based and AR application	To provide daily progress and performance data of construction work by visualizing construction progress in AR, AR4C application prototype was verified with laboratory experiment Improved safety performance
V Getuli et al. [29]	Real case study	BIM-based immersive VR	Representation in health and safety plan
SS Martins et al. [61]	Case study	BIM-based 4-D model	4-D BIM tools Construction planning efficiency
A Braun et al. [31]	Machine-based object-detection method	Geometric-semantic Building Information Model information	Fusing clouds, semantic information, and computer vision Improving construction monitoring and safety
Y Ji et al. [30]	Prototype system	Rule-based checking and 4-D modeling	4-D BIM and rule-based checking system Introduced prototype system. Rule checking platform
L Ding et al. [62]	BIM application framework	3-D to computable n-D models,	BIM-based 3-D to computable an n-D framework To quantify and analyze quality, safety on construction projects
Dadashi Haji et al. [63]	An empirical study	4-D simulation performance	The relationship between the performance of 4-D simulation and various phases of development was examined
Tran et al. [64]	HISTEA prototype	4-D BIM simulation	To prevent severe injuries and fatalities on building sites caused by spatial-temporal situations
Hou et al. [65]	Literature review	Digital twins applications in construction workforce safety	This review sheds light on technological clustering, improvement initiatives, and workforce safety, all of which can benefit from the development of effective digital technology paradigms

In addition, construction stakeholders are more focused on construction safety policies and are thus becoming relevant topics for research [66]. However, few studies have attempted to quantify the global construction safety research [60]. After the development of a safety regulation checking system, the construction safety practices have been applied in real case studies for validation. Moreover, CSC Ontology (Construction Safety Checking Ontology) was designed to check the construction safety and a real-world example was shown to demonstrate the proposed safety management mechanism [67]. Likewise, the social network system (SNSS) focuses on sharing construction safety and health knowledge and was tested in a fall accident case study [68]. An ontology-based framework developed for construction safety practices may be able to identify job hazard analysis (JHA) [69]. In addition, the virtual prototyping (VP) conceptual framework was developed to enhance construction safety in large-scale construction projects [70].

## 2.2. The Rationale and Research Gaps

In high-rise buildings, safety remains a global challenge in terms of construction site injury, accident and fatality rates. Throughout the project life cycle, construction safety needs consideration and preparation from the design phase to the maintenance phase [71]. The implementation of BIM is currently experiencing exponential growth in the areas of construction, planning, and management, as well as safety management [72]. However, previous studies show that there are various barriers and limitations in using BIM [73]. Therefore, there is a need to explore further work on BIM-related digital technologies and to strengthen construction practices effectively. Furthermore, more studies are focused on fall hazard identification in construction safety [74–76]. Hence, there is a need to explore more safety factors in high-rise building projects, such as personal protective equipment (negligence to wear a safety hat), personal protective equipment (negligence in using safety belts at heights) [77,78], falls from roofs/floor (working on unsafe scaffolding/scaffolding failure) [79], scaffolding and ladder failure (scaffolds not fastened/tightened properly) [80,81], safety sign (no warning signs), safety sign (no on-site monitoring system of workers), falls from roofs/floor (working at heights or open edges without using fall protection systems) [82–84], safety sign (no safety sign location plans) [26], safety sign (no identification of potential safety hazards), and safety sign (no erection of signs as required) [37,85,86].

In addition, Mohammadi et al. [87] carried out a detailed review on safety factors and revealed that there is a need to incorporate safety factors with digital tools to enhance safety performance in construction projects. However, there is a lack of research efforts that systematically examine the safety factors integrated with BIM and digital technologies to make construction safer and increase safety performance in high-rise building projects. For instance, Arifuddin et al. [88] used a questionnaire survey to identify the safety factors but failed to clarify the mitigation measures. Likewise, Abulhakim and Adeleke [89] used the partial least square structural equation modeling technique to investigate the safety factors but were unable to explain the mitigation steps to address the safety factors in high-rise buildings. A recent study by Elsebaei et al. [90] examined the causes and influences of site accidents by highlighting factors but did not suggest effective solutions. However, the ability to handle a reliable initiative depends on transformative technologies, such as BIM. Furthermore, few studies have explored systematic methods to resolve these limitations in a rigorous manner. Therefore, to fill the aforementioned research gap, this study aimed to develop a framework to address accidental safety factors from a holistic perspective and to propose an attainable way to mitigate accidents in high-rise building projects. A summary of the rationale and research gaps is shown in Table 2.

**Table 2.** Summary of the rationale and research gaps.

Research Works	Contributions	Gap/Limitations
Jürgen Melzner et al., 2013, Qi et al., 2014, Wang et al., 2015 [74–76]	Fall hazard identification in construction safety	Need to explore more safety factors in construction safety
Mohammadi et al. [87]	Carried out a detailed review on safety factors	There is a need to incorporate safety factors with digital tools to enhance safety performance in construction projects
Arifuddin et al. [88]	Used questionnaire survey to identify the safety factors	Failed to clarify the mitigation measures
Abulhakim and Adeleke [89]	Used partial least square structural equation modeling technique to investigate the safety factors	Unable to explain the mitigation steps to address the safety factors in high-rise buildings
Elsebaei et al. [90]	Examined the causes and influences of site accidents by highlighting factors	Cannot suggest effective solutions

### 3. Research Methodology

The research methodology comprises of the ground theory approach, interviews, research design, interview questions design, procedure, participants, and data analysis. The details of each section are as follows:

#### 3.1. Ground Theory Approach

In order to understand the different viewpoints, qualitative research, such as ground theory, is considered useful and not only helps to obtain people's views, opinions, practices, experiences, predictions, and behaviors, but also offers insights into how people view the world. In addition, the ground theory is used to transform qualitative data, such as transcripts and images, into a theoretical and conceptual context and is considered to be the best qualitative research method for the systematic discovery of data theory [91]. A number of researchers have also employed ground theory in safety management to investigate the significance of the findings [77,92,93]. Ground theory is a method of constructing theories that is "based on data that has been collected and analyzed in a systematic manner" [94]. The principal function of this theory is to summarize and sort primary sources according to "coding" in order to extract the core information or the most significant influencing variables of a situation. During the data analysis process, there are three levels or types of coding that can be used, including open coding, axial coding, and selective coding. The primary data can be conceptualized and categorized using this process.

Open coding is the process of looking through qualitative data (such as interview transcripts) and breaking it down into smaller pieces of information in qualitative data analysis [95]. Based on the properties of the data, each item of data should be evaluated and labelled. The following measures should be done to ensure that any two pieces of data relating to the same subject are labelled with the same codes [96].

In axial coding, it is necessary to develop the linkages and connections that exist between the various codes. It is recommended to look for causal conditions, the context behind observations, and the consequences of phenomena. Finally, the wider categories that connect the codes are determined [97]. Selective coding, on the other hand, is the process of choosing one core category that captures the substance of qualitative data. It should be a single overarching concept that represents a repeating pattern in the data analysis process [98].

Hence, empirical data is fragmented in the ground theory approach for adding codes to these fragments and collecting fragments with common codes into categories and then

theorizing based on the interactions between these categories. The method of gathering codes into categories is often referred to as thematic analysis, as it focuses on the interview themes [99]. The trend of utilizing the ground theory approach is now apparent in the construction sector [100].

### 3.2. Interviews

Due to the COVID-19 pandemic, it was not possible to perform a face-to-face interview, so online interviews with the aid of the ZOOM meeting were conducted. The collection of the data via the qualitative approach is also widely adopted in many fields like construction safety [101], nursing [54], and public health [102]. It allows a wider discussion with the interviewees within the defined area. Interviews help to gather rich data that are accessible to the decision of the participants about what is significant and relevant to the discussion. Therefore, this research study used the qualitative approach of individual ZOOM interviews to gain a wide range of people's experience in the field of digital technologies and construction safety and to discover how it can be helpful to reduce accidents in high-rise building projects with the aid of BIM and other emerging digital technologies.

### 3.3. Research Design

The flowchart of the research methodology is shown in Figure 1. The first stage of the research methodology was a literature review and interview arrangement with the ZOOM software application. The second stage of the research methodology started after the ZOOM software was successfully mounted on the laptop. The second stage comprised the collection of qualitative data, including 45 safety and BIM experts with realistic knowledge of BIM implementation in the construction industry. The third step of the study approach consisted of qualitative data analysis with the aid of the NVivo software package. The qualitative data were analyzed by open coding, axial coding, and selective coding as part of the coding process. In the fourth and final stage of the research methodology, an explanation of the data outcomes and results with conclusions, limitations, and future directions was illustrated.

### 3.4. Interview Questions Design

Interview questions were formulated through a literature review of appropriate and recent articles, including research gaps in the previous section, safety factors, construction accidents, site safety, digital technologies [103,104], and BIM [49,105]. Appendix A explains the details of the interview guide. In order to establish an integrated framework, interview questions were essential, which could help to obtain a thorough understanding of the phenomenon and mitigate possible steps to address the effects of accidents in high-rise building projects. Furthermore, demographic information, such as gender, education qualification, and previous experiences in construction industry, was collected.

Before conducting the ZOOM individual interview session, a semi-structured interview was designed to make sure that all details related to the safety accidental factors and injuries in high-rise building projects could be obtained. In the pilot study, the feedback from five participants was used to further refine the questions prior to the actual ZOOM individual interview session. The five participants were two assistant professors, two professors, and one postgraduate student involved in the pilot study.

### 3.5. Procedure and Participants

The sample size of 45 was chosen for this qualitative study because several researchers in different studies revealed that the minimum sample size for qualitative studies was 15 [106]. For instance, Boddy [107] stated that the acceptable sample size for qualitative analysis was 21. In addition, a recent qualitative analysis was conducted by Winge et al. [108] in the field of safety management with a sample size of 22. Hence, in this study, 45 was considered as acceptable and reliable. Moreover, the 45 BIM and construction safety experts had experience working in different companies, academia, and different projects in

Malaysia and voluntarily participated. The respondents were chosen based on their work experiences with high-rise buildings, skyscrapers, and BIM projects. Furthermore, in order to obtain more dependability and authenticity, only respondents with more than five years of work experience were preferred. Before the interview started, participants received a short introduction to the study and were informed of the anonymity and confidentiality of the information collected. Furthermore, assurance was given to the participants that the data collected in this interview were utilized merely for academic purposes. The interviewees were interviewed as per the designed interview questions and after every answer, additional follow-up questions were put up as required.

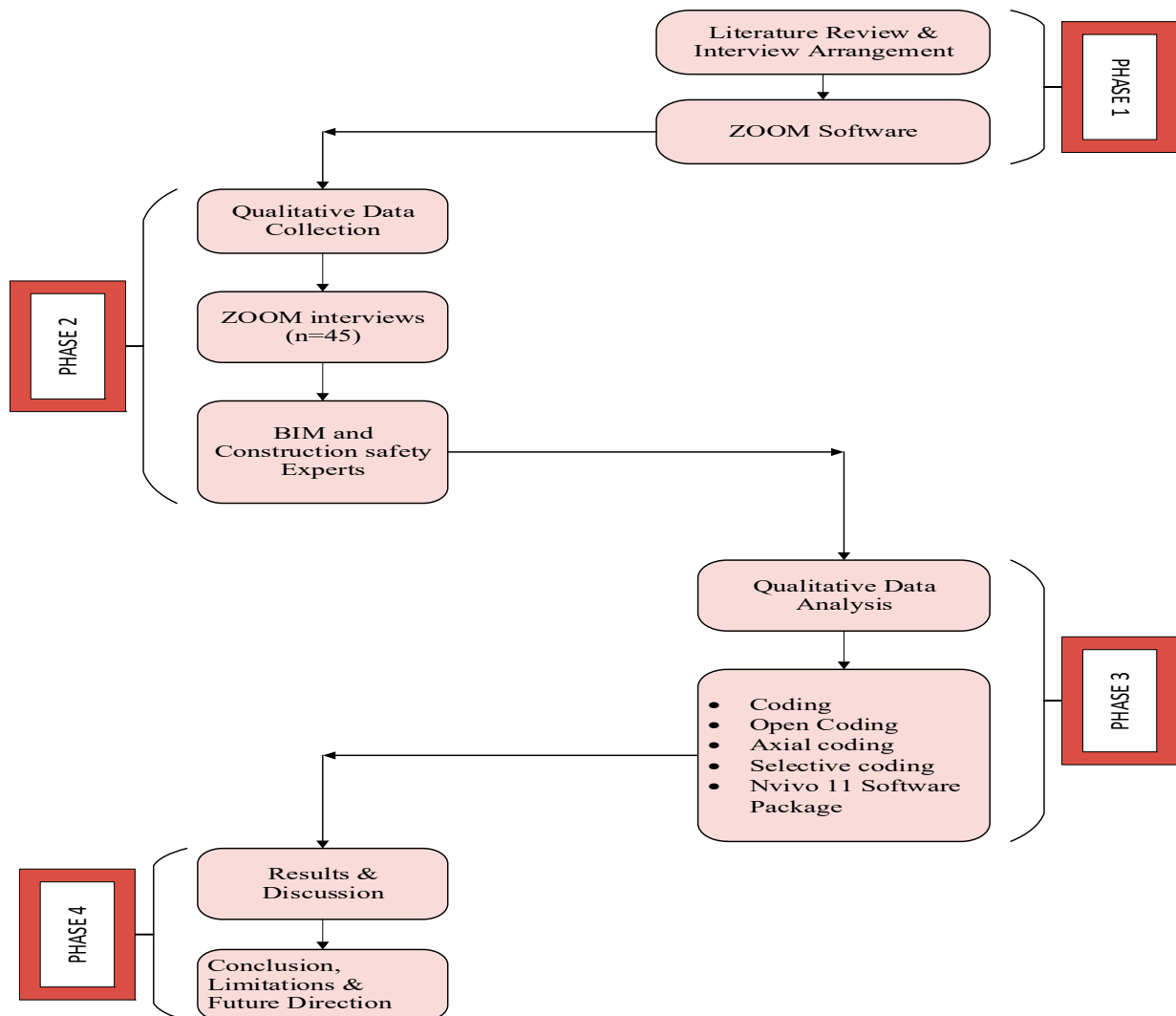


Figure 1. Research methodology flowchart.

### 3.6. Data Analysis Tool

The information collected was analyzed through the NVivo 11 software package. For this reason, a coding scheme was introduced in the qualitative study, such as open coding, axial coding, and selective coding.

#### (i). Open Coding

In open coding, after examining the data of interviewees, it was divided into the theme of concepts and allocated specific codes. For instance, the data regarding construction site activities can be monitored with the approach of taking images by utilizing drone technology. This theme and concept was broken down into ‘photogrammetry’. It selected



the phrases and social phenomena that emerged regularly in the interview based on the “fit and relevance” criteria of grounded theory to compare, screen, and refine repeatedly [95]. The goal was to investigate the phenomenon, define the concept, and identify the categories. Therefore, 593 codes were developed on the basis of open coding.

(ii). Axial Coding

Following intensive open coding, this study began to bring together the categories and to establish the relationship and connections between the codes. These categories resemble themes and are generally new ways to observe and understand the phenomenon under study. It is generally used to conduct a continuous comparison and cluster analysis of open coding in order to make it more directive and theoretical in its application. Therefore, the 593 codes were further categorized on the basis of axial coding to connect the relationships among the codes.

(iii). Selective Coding

The ground theory approach was applied to qualitative data to re-examine all categories and consolidate them into a single core category. This was accomplished through the use of selective coding and the ground theory approach. As a result, the categories were further refined into core categories, such as the virtual environment, photogrammetry, GPS, RFID, laser scanning approach, and simulation.

#### 4. Results Analysis

This section comprises respondents’ demographic analysis followed by an overview of the coding scheme, analysis of the coding scheme, BIM integration with simulation, BIM integration with photogrammetry, BIM integration with GPS and RFID, BIM integration with the virtual environment, BIM integration with the laser scanning and sensors.

##### 4.1. Respondents’ Demographic Analysis

Before selecting the respondents, it was kept in mind that the respondents should be rich in experience, industrial knowledge, and excellent knowledge of building projects, industrial construction projects, BIM know-how, and related digital technologies. Therefore, the criteria for the selection of participants depends upon: (a) having working experience of more than five years, (b) having at least one hands-on experience in high-rise building projects, and (c) possessing good knowledge of BIM and its related technologies. The demographics of the participants are shown in Table 3.

**Table 3.** Participant demographics (n = 45).

Item	Description	Number of Participants	Percentage (%)
Gender	Male	40	89
	Female	5	11
Educational qualification	Bachelors	12	27
	Masters	20	44
	PhD	10	22
	Professional engineers	03	7
Working experience	5–7 years	12	27
	8–9 years	14	31
	More than 10 years	19	42
Projects	Infrastructure	8	18
	High-rise buildings	11	24
	Skyscraper	14	31
	BIM	12	27

It is shown that 89% of the participants were male, while 11% of them were females. Similarly, 27% of the participants were Bachelor’s degree holders, while 44%, 22%, and 7%

of the participants were Master's degree holders, PhD holders, and professional engineers, respectively. In addition, 42% of the participants had career experience of more than 10 years. Moreover, 31% were involved in skyscraper projects, 24% were involved in high-rise building projects, 27% were involved in BIM-based projects, and 18% were involved in infrastructure projects. The demographic analysis indicates that the participants have broad working experience, qualifications, and skills. Thus, they were considered as suitable interviewees for this research study.

#### 4.2. Coding Scheme

On the basis of the interviews, a coding scheme was developed as shown in Table 4. The coding scheme for each category or subcategory was used to illustrate how frequently participants responded to these concepts.

**Table 4.** Coding theme.

Codes	Categories	Core Categories
Safety supervision Increase productivity Safety management tool	Augmented reality (AR) Virtual reality (VR)	Virtual environment
Safety inspection Positive attitude Neutral attitude	Drone technology Images Vision cameras	Photogrammetry
Safety training Safety rules Accident prevention Danger Positive attitude	Exact location Tracking Record information	GPS, RFID
Human error Safety consciousness Safety knowledge Positive attitude Negative attitude	Capturing Monitoring	Laser scanning approach
Safety performance improvement Time saving Less effort Visualization Positive attitude Neutral attitude	Digital modeling Computer vision-based methods	Simulation

#### 4.3. Analysis of Coding Scheme

A thorough description of the coding scheme is shown in Figure 2. It is illustrated that a total of 593 codes were obtained. The division of codes offers evidence that the highest number of codes refers to the 'safety management tool', while the lowest number of codes refers to 'negative attitudes'. This scenario shows that a picture of utilizing 'safety management tools' is necessary for enhancing safety performance.

#### 4.4. BIM Integration with Simulation

The interviewer asked, "Construction workers are working in heights in high-rise building projects, how with the help of BIM can make the impact of accidents minimal 'fall from roofs/floor (working at height or open edges without using fall-protection systems)?" The interviewees elaborated on the information with the ability of their working experiences and knowledge. Most of the interviewees believed that BIM incorporated with various types of simulation techniques could help to overcome falls from roofs/floors. For instance, Bluetooth low-energy (BLE) devices can reduce the impact of accidents in high-rise buildings. BLE is a low-power wireless communication technology that allows construction

workers to communicate with one another by connecting smart devices over a short distance. Accidents can occur during the construction of high-rise buildings but employing BLE devices to communicate efficiently reduced the danger of such events to a bare minimum. Furthermore, simulation can be used to create escape routes, arrange fire safety equipment maintenance, model safe worker behavior, and develop safety measures. The creation of an algorithm for automatic BIM-enabled fall hazard assessment and planning, as well as the development of an algorithm for BIM-enabled simulation of the safe construction of high-rise buildings, is a practical application of simulation.

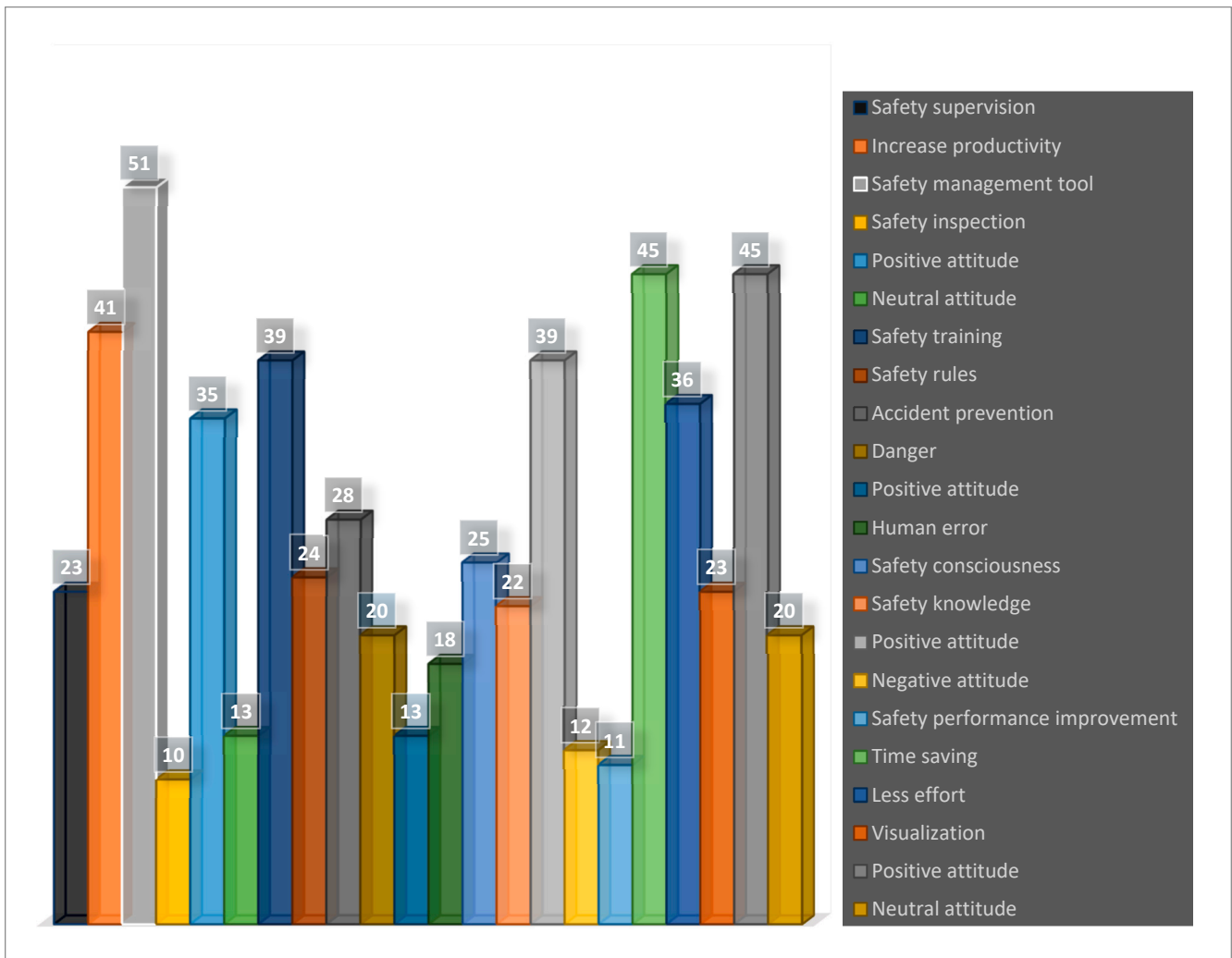


Figure 2. Coding scheme.

Furthermore, computer vision-based methods are the most appropriate solution for identifying safety problems and enhancing safety performances. Responses included ‘I think using BIM alone cannot mitigate the accidents in high-rise buildings’ and ‘I think to use BIM with other digital technologies can make it possible’. When the interviewer asked him ‘How is it?’, participants provided responses, such as ‘through simulation and algorithm approach would be useful’ and ‘developing BIM-Based frameworks’.

However, some interviewees claimed that it is difficult to detect falls from roofs/floors with the BIM integration techniques. They strongly stressed that during the pre-construction phase, the BIM integration techniques were useful for efficient construction, but during the construction phase, it was difficult, so their attitude towards BIM integration with simulation techniques was neutral. Moreover, they believed that modular construction is a much safer and smooth way of construction. They provide strong logic to support their

claim that in on-site construction, more construction workers are needed and there is a high chance of accidents and injuries during construction as compared to modular construction.

#### 4.5. BIM Integration with Photogrammetry

The interviewers asked 'Personal protective equipment make the construction effective, however, some construction workers do not use personal protective equipment (negligence to wear safety hat on, negligence in using safety belts in height)', how with the help of BIM can monitor and track the construction workers? Is it possible? If yes, what are the effective techniques used to overcome the accidents by using BIM?' According to the interviewees, most of them believed that using PPE when working in heights was very useful and protective. They have good support for the use of photogrammetry to track and monitor construction workers. With the advantage of drone technology, photographs and videos of entire construction sites can be made and from these videos and images it is possible to detect which construction worker is not wearing a safety hat and safety belt. Moreover, automatic safety monitoring that uses photogrammetric point clouds and 4-D BIM may be the effective way to reduce the accidents. The primary goal is to employ standard camera equipment on construction sites to capture the current level of work by photographing the complete facility under construction at regular intervals. When a large number of images from diverse angles are available, photogrammetric methods can be used to reconstruct a 3-D point cloud from the data. Using this point cloud, each aspect of the construction progress (as-built) can be compared element by element against the geometry of the BIM (as-planned), producing a more accurate picture of the building progress. In this way, using camera and image processing techniques for the detection of construction workers in high-rise buildings can be useful for safer construction. Responses include 'I think the use of photogrammetry techniques through drone technology will be useful and effective' and 'I think the images and videos will make it easier for construction workers to monitor'.

Moreover, the interviewer asked them, 'Do you think that with the help of photogrammetry, 'no identification of potential safety hazards in high-rise buildings' can be minimized?' 'Most of the interviews had two perspectives on the respective issue. The group of interviewees who had a positive approach to the use of photogrammetry believed that it was possible to highlight safety risky areas at construction sites when watching photographs and videos, but the other group of interviewees supported a neutral attitude. Responses included 'I believe that the identification of potential safety hazards in high-rise buildings can be made possible through photogrammetry and drone technology' and 'I believe that the identification of potential safety hazards in high-rise buildings cannot be made possible through photogrammetry because it is headache and time consuming to monitor and assess every area of building construction'.

#### 4.6. BIM Integration with GPS and RFID

GPS (global positioning system) and RFID (radio-frequency identification) are both used to find the actual location of the construction workers [109]. The interviewers asked, 'Often a safety sign is missing in construction of high-rise buildings such as no on-site monitoring system of workers, no safety sign location plan, according to your experiences, what do you think BIM technology helps to minimize this issue?' All the interviewees strongly agreed that with BIM integration-GPS-RFID, the location of the construction workers can easily be tracked. Responses included 'Yes sure with the integration of BIM with digital technologies, for example RFID, GPS can monitor the movements of construction workers in high-rise buildings' and 'I think yes, it can be done with the incorporation of BIM with RFID'.

In RFID, electromagnetic fields are the most useful and productive techniques for the role of construction workers. It is also possible that the BIM-RFID platform can support the visibility and traceability of construction workers in real time. The statements of the interviewees are also well backed by the literature studies. Cai et al. [110] suggested an

integrated RFID and GPS system for construction sites and revealed that the accuracy indicator helps to estimate the accuracy of RFID-based position and tracking systems in construction. Moreover, Su et al. [111] concluded that RFID technology has shown its ability to locate and track construction resources. Using BIM integration with GPS-RFID and other techniques, such as cloud computing, internet of things (IoT) etc., can be used in the tracking of construction objects, and these objects must be converted into smart objects that can be tracked in real time over the internet or in the cloud. Real-time internet or cloud-based monitoring enables better coordination between remote project stakeholders.

#### *4.7. BIM Integration with Virtual Environment*

Augmented reality (AR) and virtual reality (VR) are two essential components that will boost the construction industry and have the ability to introduce innovative productivity in the construction industry [112]. AR is comprised of real-world experience, whereas VR is comprised of a completely immersive experience that completely isolates the user from the physical world. The interviewers asked, 'In high-rise buildings, construction workers are working on dangerous scaffolding and scaffolding failures, how does the virtual environment help to identify construction workers during construction?' Interviewees believed that BIM integration with a virtual environment, such as AR and VR, enables the development of fully computer-generated environments that give the user the feeling of being truly immersed in a virtual environment. In addition, AR technology allows the overlay of digital information in real time and in the correct spatial location to increase or improve the real environment. VR can also be used to display portions of buildings that are superimposed on a real-world view. Responses included 'I think it will be possible to create a virtual environment', 'I think a BIM-based framework will be needed to monitor the situation', and 'I think BIM has the potential to integrate with AR and VR to improve safety monitoring in high-rise buildings'. Moreover, BIM integration with a virtual environment can be used to make construction safer, including the simulation of different accident scenarios in order to prevent the occurrence of an accident due to a safety hazard in building projects. The simulation of common unsafe acts and conditions are supplemented with accident reports, regulations, and precautions as well as virtual experiments of innovative construction technologies, systems, and processes, and the modelling of a dynamic construction site environment to enable dynamic construction site management.

#### *4.8. BIM Integration with Laser Scanning and Sensors*

The interviewer asked, 'In high-rise building projects, scaffolding and ladder failure (scaffolds are not fastened/tightened properly) due to negligence of construction workers while tightening the screws and bolts of scaffoldings, what is your opinion how with the laser scanning techniques integrating with BIM to detect the scaffolds which are not fastened/tightened in order to avoid accidents, in addition if there is (no warning signs), (no erection of signs as required) are present?'

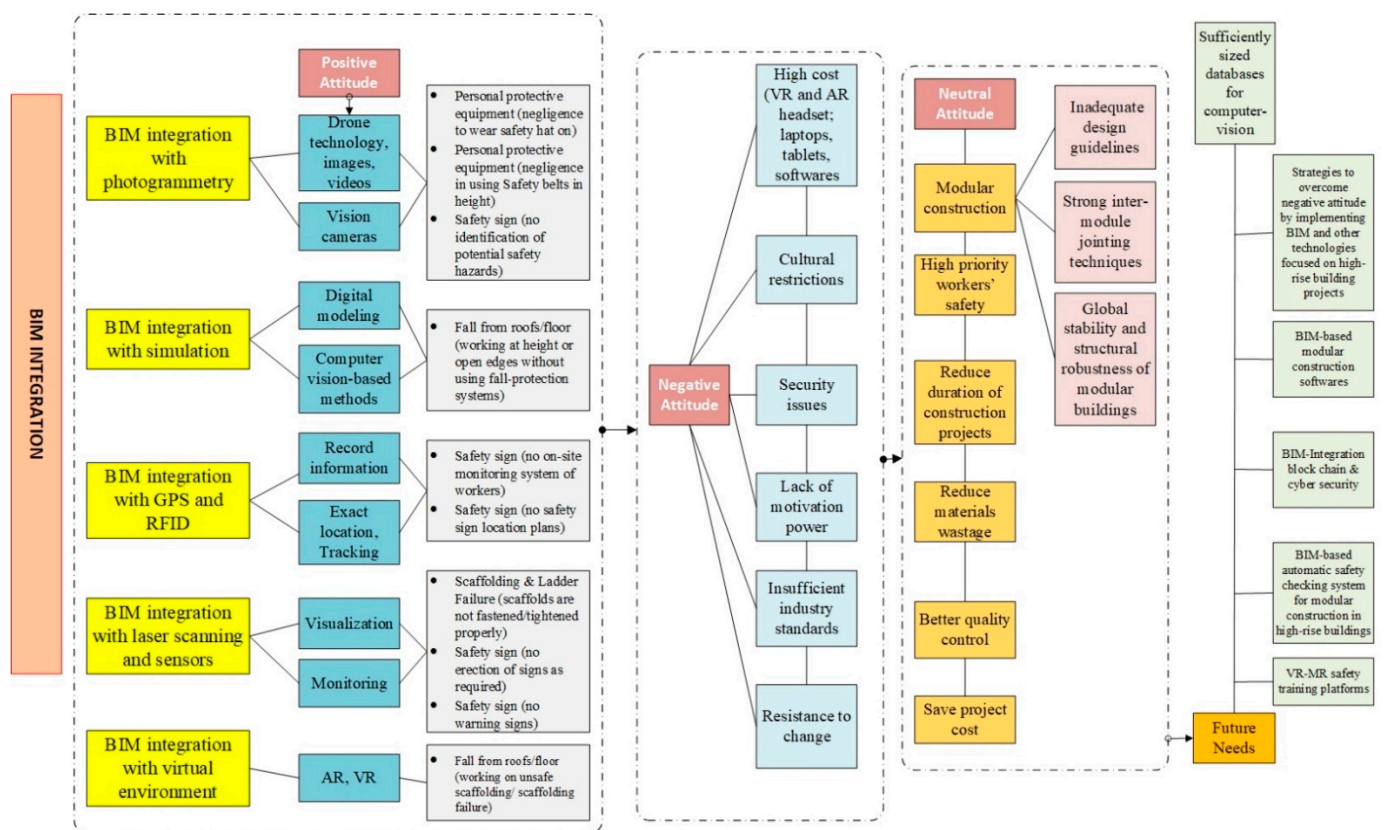
In this case, two types of opinions were gathered from interviewees. One group was in favor and showed a positive attitude towards integrating BIM with a laser scanning approach, but the other group was opposed and showed a negative attitude towards integrating BIM with a laser scanning approach. They assumed that the use of low-quality tools and materials (scaffolding and ladder) for any form of construction could lead to serious misfortunes, thus avoiding any mishap. Responses included 'According to my experience yes, it can be done with the help of sensors' and 'I do not think it is possible'. When the interviewer asked 'Why cannot it be possible?', responses included 'I think to use and place sensors in entire scaffolding areas is costly and need more worker force, therefore should be avoided', 'I think it would raise the cost of project, not feasible', and 'I do not think it is a good idea to use sensors'.

They believed that in the pre-construction phase, it was important to place the sensors in the scaffolding and ladder area, so that in the situation that the screws or bolts of the scaffolding and ladder would become shaky and loose, the sensors would automatically

detect the area and in this way the warning alarm would be sent to the construction manager for early intervention in order to prevent an accident. In addition, the laser scanning technique will reliably capture point clouds of damaged bolts and screws. To acquire point cloud data for the target area, scanning is conducted at various points and as a result, point cloud data acquired from each scan point are inserted into a file. This will allow the construction manager to quickly imagine the faulty area in order to prevent accidents. While the other group of interviewees who had a negative attitude towards using BIM with a laser scanning approach assumed that installing sensors in every location where there is scaffolding or a ladder would be time consuming and expensive, this should be avoided. As a result, for the purpose of thoroughly inspecting the scaffolding and ladder materials in high-rise buildings, laser scanning technology refers to a group of technologies capable of acquiring and altering point clouds, such as light detection and ranging (LiDAR). With great precision and resolution, laser scanning collects data on building projects in a direct manner in order to boost effective and safer construction.

### 5. Discussions and Research Framework

The summary of findings is elaborated in the form of a research framework in order to better understand the picture of the study. Figure 3 illustrates the framework incorporating BIM with other emerging digital technologies to mitigate safety accident factors in high-rise building projects for safety performance improvement and to make construction safer.



**Figure 3.** A research framework for the integrated BIM and emerging digital technologies in mitigating construction accidents in high-rise buildings.

Based on the information provided by the interviewees and Figure 3 it can be seen that one group showed a positive attitude towards integrating BIM with emerging digital technologies while the second group showed a negative attitude and the third group showed a neutral attitude towards using BIM with emerging digital technologies.

### 5.1. Positive Attitude towards BIM Integration with Emerging Digital Technologies

BIM integration with emerging digital technologies, such as photogrammetry, AR, VR, scanning approach, simulation, GPS, and RFID, has promising results for construction safety in high-rise buildings, for instance, computer vision-based methods, monitoring, tracking, drone technology, cameras, images, videos, and digital modeling. In addition, they believed that computer vision methods can be used in engineering management of construction projects to transform processes and to allow the collection and analysis of digital images and extraction of high-dimensional data from the real world to generate knowledge to enhance management decision-making. The literature study also supports their viewpoint that computer-vision methods have the potential to investigate the special issues during construction, such as progress monitoring [113], efficiency enhancement and analysis [114], and health and safety monitoring [115]. Normally, the inspection and assessment of infrastructure (bridges, tunnels, underground pipe, and asphalt pavements) is manually checked by structural engineers. It has been found that by using a 3-D digital image correlation technique and closed circuit television (CCTV) imaging, the structural integrity of tunnels, crack detection, and structural condition of bridges can be assessed and monitored [116]. Hence, there is a path for future researchers to integrate the computer-vision techniques for assessment, monitoring, and inspection of high-rise building projects during construction and in pre-construction phases. In addition, there is a lack of sufficiently large databases in literature studies to ensure the accuracy of the computer vision. The constraint of sufficiently large datasets, therefore, prevents the development of computer vision in construction.

### 5.2. Negative Attitude towards BIM Integration with Emerging Digital Technologies

Despite the positive attitude associated with the use of technologies, several negative attitudes were displayed during the interview session. The second group of interviewees believed that BIM integration with other emerging technologies is not easy and seamless for organizations to adopt this technique. They supported their claim by presenting evidence, such as high prices, cultural limitations, insufficient BIM skills and training sessions, government policies, security concerns, inadequate industry standards, lack of incentives to incorporate BIM in construction projects, and resistance to change. However, the literature study also supports their viewpoint that various restrictions and limitations prevent the implementation of BIM in construction projects [117]. For example, the purchase cost of VR and AR headsets with complete features for use in construction projects could be as low as \$500 [42] while the cost of hardware components, such as laptops, tablets, and motion trackers, and the cost of support systems could easily rise to \$5000. In addition, a developer must be hired to create an immersive test environment for the efficient use of on-site technology and this requirement entails significant costs [42]. In addition, the security risks of construction projects are also a big challenge for developers to integrate BIM with block chain and cyber-security technologies for security enhancement. There is no question that several studies have been carried out to address obstacles and limitations to the implementation of BIM and other emerging digital technologies, but further work needs to be done in the future to enhance the safety performance of construction and thus to embrace and incorporate revolutionary technologies.

### 5.3. Neutral Attitude towards BIM Integration with Emerging Digital Technologies

Modular construction or off-site construction is safer and more affordable due to its advantages over conventional on-site construction methods. In modular construction, one or more structural units are assembled in manufacturing plants outside the construction site. The third group of interviewees favored modular construction rather than on-site construction and use of BIM with other emerging technologies. They backed their arguments by providing evidence that more construction workers were expected to work at construction sites and that there is sufficient risk of accidents and injuries, but the safety of employees is the top priority of the construction organization. Moreover, they believed that modular

construction has many advantages, such as reduced duration of construction, reduced wastage of materials, and better quality control and resulting cost savings for high-rise buildings. In addition, modular construction is preferred in multi-unit buildings, such as homes, classrooms, offices, dormitories, hotels, and hospitals. The trend towards the adoption of modular construction in Australia, the United Kingdom, Singapore, and the United States is increasing where labor costs and housing shortages are of major concern [118]. Over the last three decades, however, modular construction has usually been extended to low-rise buildings, but its implementation is still limited to high-rise construction projects (less than 1%) [119]. This is due to a lack of (i) design guidelines, (ii) strong inter-module jointing techniques, and (iii) sufficient understanding of the structural behavior, global stability, and structural robustness of modular buildings [120]. The recent study conducted by Shan et al. [121] confirmed that the feasibility of extending modular construction for high-rise building construction may be possible if the above-mentioned technical barriers are resolved. The trend of future research should therefore be moved towards overcoming these technological obstacles in order to make modular construction feasible for high-rise building projects.

## 6. Conclusions, Limitations, and Future Directions

It is concluded that possible steps have been taken in high-rise building projects to prevent accidents via the integration of BIM with emerging digital technologies, such as photogrammetry, simulation, computer-vision methods, AR, VR, drone technology, GPS, RFID, and laser scanning techniques. However, in this study, more focus was placed on the use of photogrammetry and drone technology in high-rise building projects for safer construction. The first theoretical contribution of this study lies in the research framework, which includes positive, negative, and neutral attitudes towards using BIM with emerging digital technologies and provides construction stakeholders with assistance and improvement in construction safety performance. In addition, this approach exposed new knowledge gaps and the realistic needs of this study for construction safety management. From a technology perspective, the theoretical contribution of this study is that the research framework extends the role of BIM with emerging digital technologies in construction safety management. In addition, the current research also contributes to enhancing the safety performance in high-rise building projects by offering a BIM-based framework for emerging technologies. As far as safety is concerned, the implementation of the proposed research framework was practically implicit in the actual case studies and ongoing projects for monitoring and inspection purposes.

Although the aim and objective of this research were accomplished, this study also has some limitations that are worth mentioning. Firstly, this study was conducted in Malaysia and due to culture differences, the results of this study may not be valid in other regions. One suggestion is to further conduct this study in other areas and compare the findings in this study for validation purposes. Furthermore, in the future, empirical studies with questionnaire survey methods may be performed to overcome the limitations. In addition, future studies will focus more on introducing a web-based AR-VR-MR platform to address accidental safety factors by integrating BIM with the Internet of Things (IoT), block chain, and cyber security technologies, and make effective strategies to reduce the negative attitude of BIM with emerging digital technologies. It is necessary to integrate BIM with the block chain and cyber security to protect computer systems and networks from cyber attacks and to ensure that project information is only accessible to those who are authorized to do so. In addition, there is also a need to use BIM to improve modular integrated safety building projects. One recommendation is to examine and incorporate how BIM can be used with emerging technologies to track the safety of workers during the construction of heavy/bulk modules. More revolutionary BIM-integrated approaches can be used to quantitatively evaluate the safety performance of buildings, which is one of the future directions.



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## Appendix A. Interview Guide

1. Construction workers are working in heights in high-rise building projects, how with the help of BIM can make the impact of accidents minimal “Fall from roofs/floor (Working at height or open edges without using fall-protection systems)”?
  - 1.1 During Design Stage.
  - 1.2 During Construction Phase.
2. Personal protective equipment make the construction effective, however, some construction workers do not use “Personal protective equipment (Negligence to wear safety hat on, negligence in using safety belts in height)”, how with the help of BIM can monitor and track the construction workers? Is it possible? If yes, what are the effective techniques used to overcome the accidents by using BIM?
3. Sometimes, accidents are happening due to scaffolding and ladder failure (scaffolds are not fastened/tightened properly)”, how with the help of BIM to make the construction effective by mitigating the accidents?
4. Is it possible for the construction managers that with the help of BIM or other effective techniques to minimize the impact of accidents if there is “no warning signs” and “no safety site location plan” in construction area?
5. What are your views related to BIM in construction of high-rise building projects to overcome the impact of accidents in order to make the construction safer?
6. What do you think how with the usage of BIM the construction can become more effective and easier?
7. What are the other useful construction techniques incorporated with BIM be utilized in order to make construction projects safer?

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