buildings

MDPI

Article

Near-Miss Detection Metrics: An Approach to Enable Sensing Technologies for Proactive Construction Safety Management

Filzah Hashmi [1], Muhammad Usman Hassan [1,*], Muhammad Umer Zubair [2], Khursheed Ahmed [1], Taha Aziz [1] and Rafiq M. Choudhry [3]

[1] School of Civil and Environmental Engineering (SCEE), National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan; filzah.cem19@student.nust.edu.pk (F.H.); khursheed@nice.nust.edu.pk (K.A.); taziz.bece19nice@student.nust.edu.pk (T.A.)

[2] School of Civil & Environmental Engineering, College of Engineering, King Faisal University, Al Hofuf 31982, Saudi Arabia; mzubair@kfu.edu.sa

[3] College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11432, Saudi Arabia; rchoudhry@imamu.edu.sa

* Correspondence: usman.hassan@nice.nust.edu.pk

Abstract: One in every five occupational deaths occurs in the construction sector. A proactive approach for improving on-site safety is identifying and analyzing accident precursors, such as near-misses, that provide early warnings of accidents. Despite the importance of near-misses, they are frequently left unreported and unrecorded in the construction sector. The adoption of modern technologies can prevent accidents by automated data collection and analysis. This study aims to develop near-miss detection metrics to facilitate the automated detection of near-misses through sensors. The study adopted a mixed method approach including both qualitative and quantitative approaches. First, a quantifiable definition of near-misses was developed from the literature. Hazards, accidents, and the causes of accidents were identified. Through empirical and statistical analyses of accidents from the OSHA repository, combinations of unsafe acts and conditions responsible for a near-miss were identified. The identified factors were analyzed using a frequency analysis, correlation, and a lambda analysis. The results revealed twelve significant near-misses, such as A1—approach to restricted areas and C2—unguarded floor/roof openings, A5—equipment and tool inspection was incomplete and C8—unsafely positioned ladders and scaffolds, A2—no or improper use of PPE and C2—unguarded floor or roof openings, etc. Lastly, measurable data required by sensors for autonomous detection of near-misses were determined. The developed metric set the basis for automating near-miss reporting and documentation using modern sensing technology to improve construction safety. This study contributes to improving construction safety by addressing the underreporting of near-miss events. Overall, the developed metrics lay the groundwork for enhancing construction safety through automated near-miss reporting and documentation. Furthermore, it helps for the establishment of safety management schemes in the construction industry, specifically in identifying near-misses. This research offers valuable insight into developing guidelines for safety managers to improve near-miss reporting and detection on construction sites. In sum, the findings can be valuable for other industries also looking to establish or assess their own safety management systems.

Keywords: near-miss; sensing technology; proactive safety management; accident prevention; early warnings

Citation: Hashmi, F.; Hassan, M.U.; Zubair, M.U.; Ahmed, K.; Aziz, T.; Choudhry, R.M. Near-Miss Detection Metrics: An Approach to Enable Sensing Technologies for Proactive Construction Safety Management. *Buildings* **2024**, *14*, 1005. https://doi.org/10.3390/buildings14041005

Academic Editors: Marek Sawicki and Mariusz Szóstak

Received: 24 February 2024
Revised: 27 March 2024
Accepted: 2 April 2024
Published: 4 April 2024

1. Introduction

The construction industry has the highest fatality rate due to its temporary, dynamic, decentralized, and complex nature [1]. The construction site's ever-changing environment may result in unlimited hazards—for example, poor layouts, confined spaces, work in restricted areas, and many others [2]. Due to the high accident rate, researchers and professionals constantly seek ways to improve construction safety. One way to enhance construction safety is to collect and analyze safety indicators or precursors. These indicators are used by safety personnel to assess if they are taking suitable precautions and controlling risks in the workplace [3]. Lagging and leading indicators are the most common types of safety indicators [4]. Lagging indicators commonly used in the construction industry are after-the-damage safety measures, e.g., injury, fatality, or illness [3]. The disadvantage of using lagging indicators is that it takes an accident to discover and address an unsafe act or condition [5]. To address this shortcoming, attention has recently shifted to leading indicators linked with proactive measures that do not require lagging indicators to predict future results [6]. Several researchers have proposed programs for gathering, monitoring, and controlling leading indicators [7–9].

Previous research has highlighted the necessity of investigating accidents to reveal leading signs or precursors because their numbers are typically higher than the accidents [10]. One of the important leading indicators nearest to the accident's final state is near-misses [11]. Near-misses are defined as an unexpected event that did not cause an accident but may have done so under certain conditions [12]. According to the literature, increasing the reporting of near-misses significantly reduces the number of accidents; it helps managers to analyze the data, identify risk factors, and take action to reduce risks, preventing severe accidents [13,14]. For instance, 75% of lost-time injuries were avoided by implementing near-miss reporting programs [15]. These reports can help organizations spot new risks, gain insight into system safety, and spark learning opportunities [16]. Therefore, a near-miss must be detected, recorded, and reviewed to decide the best course of action for preventing accidents [17].

Various initiatives have been undertaken in the construction sector to increase near-miss reporting due to the evident importance of near-misses. For example, Cambraia et al. [18] performed a case study to identify, analyze, and disseminate near-miss information in the construction industry. Construction industry institute (CII) members created and implemented near-miss reporting programs based on workers' feedback [13]. Other strategies include safety audits and governmental initiatives [19,20]. Despite these efforts, the construction industry still lacks the efficient use of near-miss information because near-misses are often left unreported and undocumented on construction sites [21]. Since most of the reporting systems are mainly reliant on manual reports [22], the reporting of near-misses directly depends on workers' feedback [23]. The construction workers may fail to report near-misses due to a lack of awareness regarding near-misses [24], the reporting process, or how organizations use near-misses [25]. Even if near-misses are collected, the existing reporting mechanism fails to assure that the data are accurate and reliable or that they offer valid event information [26] due to their dependence on workers, which brings subjectivity into the reporting process. Despite technological advancements, very few organizations presently use systematized near-miss management systems [27]. More specifically, the conditions in developing countries are the worst in term of recognizing and reporting near-misses in the construction industry [28]. However, a few studies have shown improvements in safety in some sectors such as manufacturing, services, and chemical ones, following the implementation of incident learning systems [29]. These improvements include increased engagement in safety improvement, heightened awareness of safety issues, reduced fear of corrective measures, and greater confidence that reported incidents are utilized to enhance the system.

Real-time methods that can consistently and reliably collect and monitor near-misses from construction sites are needed. Some of the technologies present in the literature are promising but have limitations in terms of advancement and applicability; for example, Shen and Marks [30] contributed to the visualization of near-misses by developing a BIM-based near-miss visualization tool. The limitation of the developed tool was its dependence on manual reporting. Automated monitoring systems can collect, process, and deliver meaningful data to users in real-time. However, progress in the automated detection and real-time monitoring of near-misses has not been fully explored [21]. Despite the growing attention to incident reporting, there is limited understanding of its effectiveness in enhancing construction safety within the construction industry. Although there are numerous reports in the near-miss incident construction literature, it has been challenging to quantify its impact on automatic detection. Therefore, this research study put forward a mechanism to develop a near-miss detection metric that could serve as a foundation for deploying sensors to predict future accidents by real-time monitoring of near-misses.

The rest of the paper is organized as follows: First, an overview of the near-miss definitions found in the literature is presented, followed by the research approach used in this study. Then, according to the technique, a near-miss detection metric is established. The Discussion and Conclusion are presented at the end based on the developed metric.

2. An Overview of Near-Misses

2.1. Near-Miss Definition: Worldwide Perspective

The idea of near-misses is vastly expanding from numerous industries, including aviation, medical, retail, chemical, construction, and manufacturing industries. This widespread belief underscores the importance of reporting near-misses for enhancing safety. According to the WHO, near-misses are defined as a severe mistake with the potential to inflict harm but not due to luck or interception [31]. The OSHA defines a near-miss as an incident which could have led to severe injury or sickness but did not [32]. Another study defines a near-miss as "an unintended incident which, under different circumstances, could have become an accident" [33]. Jones et al. [33] suggested two concepts for near-misses based on the incident's consequences: major near-miss and near-miss. The first concept defines near-misses as incidents that might lead to a significant accident with long-term implications. In the second concept, near-misses are risky situations that lead to accidents. According to Phimister et al. [27], a near-miss is an occurrence that indicates a system flaw that, if not addressed, could have severe effects in the future [27]. From the chemical and hospital sector perspective, Vanderschaaf [34] and Caspi et al. [23] described a near-miss as a safety effect that does not result in accidents, but there is a risk of injury. In the railway industry, Ritwik [35] defined a near-miss as an unsafe condition with the potential for damage. All these worldwide definitions combined reveal that a near-miss results in a successful outcome, where no harmful result takes place. Accidents are widely acknowledged to be the tip of the iceberg. An estimate shows that 300 near-miss incidents exist before a workplace accident [36].

2.2. Near-Miss Incidents in the Construction Sector

Researchers in the construction sector have used near-misses, close calls, near hits, and other terms to describe near-misses relevant to their fields. These definitions center on the observer's perceptions, risk tolerance, experiences, and how organizations see near-miss incidents. For ease of comprehension, some have defined a near-miss as an unsafe act or condition with the potential for injury or property damage [37], and others have defined it as an unsafe act linked to some action (e.g., the release of energy) [18]. Near-misses are often considered accident precursors [38], warnings of prospective accidents when out of luck [39], or close signals of accidents [11]. Cambraia et al. [18] defined a near-miss as an unanticipated event that requires a rapid burst of energy and may end in an accident. Williamsen [40] stated that near-misses occur when there are no injuries, property damage, or other proof that they had taken place.

There is no standardized definition of a "near-miss". The existing definitions focus on using near-miss information to improve safety management rather than reporting near-misses. Previous definitions have viewed a near-miss as merely an event-driven occurrence requiring an energy burst, with identification relying on subjective judgment. In these definitions, there is much reliance on the observer's perspective. Workers on the construction sites are the primary source of discovery of near-misses, but some factors may prevent workers from reporting near-misses: (a) an apprehension of administrative action; (b) risk acceptance; (c) a lack of knowledge about how data reports are used, and (d) data collecting is complex and time-consuming [25]. Since the management efficiency of near-misses depends on the accurate identification of near-misses, a complete and easy-to-understand definition of near-misses is required.

2.3. Measures for Detecting Near-Miss Incidents in the Construction Industry

Prominent indicators serve as a proactive approach to safety metrics, focusing on evaluating the processes, events, and conditions that are indicative of safety performance and have the potential to forecast future outcomes [3]. A prime example of such an indicator is the reporting of near-misses. A significant benefit of tracking near-misses lies in the ability to collect and scrutinize data that can inform safety improvements without the occurrence of actual injuries [33,36]. Understanding the causation of accidents may facilitate quantifying near-miss definitions, as near-misses and accidents have the same causation model [41–44]. Based on this recognition, analyzing the underlying causes of accidents can assist in identifying previous near-misses, reducing uncertainty regarding the possibility of an accident. For example, falls are the predominant cause of worker deaths in the construction industry [45]. The detection of near-misses is vital for halting and averting the events that lead to falls. However, traditional methods for recognizing near-miss events rely on the self-reporting of workers, which can lead to inconsistent data. The adoption of modern technologies can prevent accidents by automated data collection and analysis. Therefore, this study aimed to develop near-miss detection metrics to facilitate the automated detection of near-misses through sensors.

3. Research Approach

This research intended to establish a technique for automating near-miss data collection from construction sites by implementing sensing technologies. Figure 1 depicts the layout of the research methodology adopted in this study.

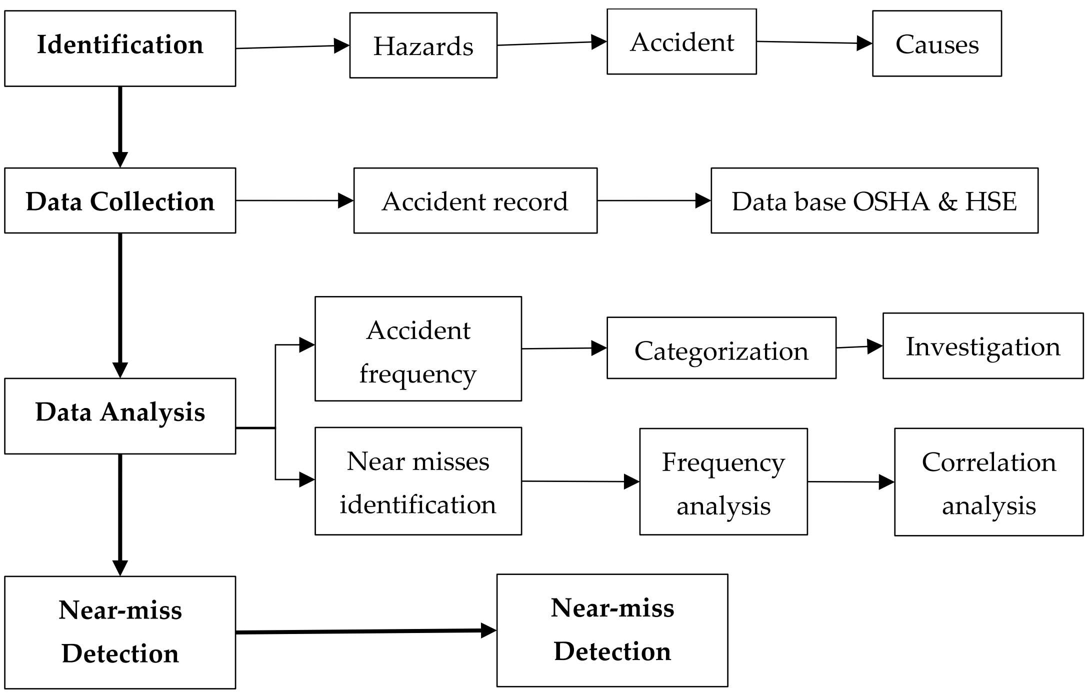

Figure 1. Layout of research methodology.

The research methodology included four major stages, including identification (i.e., hazards, accidents, and causes), data collection (accident and hazard records from the OSHA and HSE), data analysis (frequency analysis and correlation), and near-miss detection (establishing a near-miss metric). In the identification process, first, the authors identified significant hazards and accidents associated with these hazards. Then, they investigated the summary of the accidents to identify the underlying causes and performed a correlation analysis to find the significant causes responsible for these accidents. The authors subsequently created a well-designed near-miss data repository in terms of underlying causes identified from the summary of historical accidents. Lastly, they developed near-miss detection metrics consisting of quantifiable data required to autonomously detect near-misses. The detection metrics offered a strategic approach for selecting and deploying relevant sensors to collect and evaluate near-miss data. In the end, the key findings of this study are presented in the Discussion, and a conclusion is derived. The data required for near-miss identification were acquired based on the specified definition, and the near-miss detection metrics were established.

3.1. Developing Near-Miss Detection Metrics

Near-Miss Definition

Sensor-based safety management systems can be established more efficiently if each accident precursor is well investigated and quantitative metrics are defined [21]. Therefore, a quantifiable definition of near-miss is required to select and employ sensing technologies for autonomous near-miss data collection. Understanding the causation of accidents may facilitate quantifying near-miss definitions, as near-misses and accidents have the same causation model [33,36,43,44]. Near-misses share common causes with accidents, but unlike the latter, the effects of a near-miss are negligible because the opportunity factor is absent (Equation (1)) [37]. Ritwik [35] defined an opportunity factor as an uncertainty factor beyond control that decides the event's consequences. Based on the above recognition, analyzing the underlying causes of accidents can assist in identifying their previous near-misses, reducing the uncertainty regarding the possibility of an accident.

$$\text{Nearmiss} = \text{Accident} - \text{Uncertainty factor} \tag{1}$$

Heinrich [36] found that workers' unsafe activities combined with unsafe conditions were responsible for 88% of construction accidents. A recent systematic study of accidents also stated that the causes frequently responsible for accidents consist of combinations of unsafe behaviors and risky situations [43]. An unsafe working space (unsafe conditions) and weakness in safety practices result in an inadequate safety performance (unsafe act) [46]. For example, risky behavior such as not wearing personal protective equipment (PPE) in an unsafe situation, like working near unprotected machinery, may increase the risk of being struck by sharp objects.

Since near-misses have the same causation model as accidents, the preceding facts conclude that, similar to accidents, the frequency of near-misses caused by an unsafe act and conditions is much higher than near-misses caused by either an unsafe act or unsafe conditions. Defining near-misses through a full breakdown of each accident will facilitate identifying quantitative metrics for developing sensor-based near-miss monitoring systems. A near-miss can be defined as an occurrence that lacks an opportunity factor and mainly consists of unsafe acts and unsafe conditions that did not result in an injury. Therefore, identifying and tracking the interaction between unsafe acts and conditions aids in near-miss autonomous detection.

3.2. Data Collection

As mentioned above, near-misses mainly consist of unsafe behaviors and unsafe working conditions. To identify significant near-misses that occur on construction sites, the underlying causes of these near-misses need to be identified and collected in a database. Three types of data, including hazards, accidents, and their causes, were collected and analyzed. Figure 2 illustrates the overall flow of data collection.

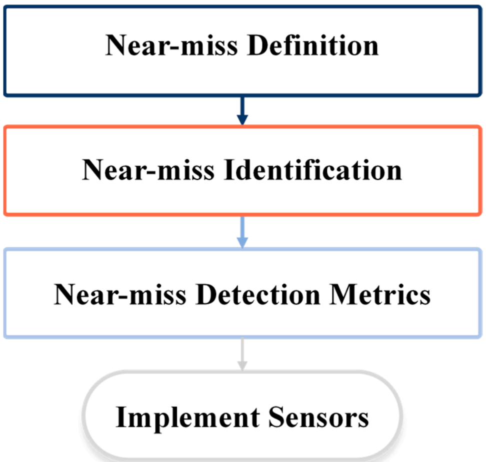

Figure 2. Overall flow of data collection.

3.2.1. Hazards

As the primary source of accidents, hazards are considered the basis for collecting relevant data. Organizations such as the Occupational Safety and Health Administration (OSHA) and the Health and Safety Executive (HSE) preserve accident data and analyze them to find their sources. According to the OSHA, the following hazards frequently contribute to fatal accidents: fall, electrocution, struck-by or -against, and caught-in or -between. In 2014, there were 782 fatal incidents reported in Europe. Among these accidents, falls (26%), breakage/fall/collapse (20%), and loss of control (19%) were the most common sources [44]. Falls and struck-by were two significant hazards responsible for 45% of fatal injuries in the United Kingdom in the last five years [47]. According to a survey, the most frequent causes of fatalities among construction workers in North Carolina between 1988 and 1994 were vehicles (21%), followed by falls (20%), machines (15%), electrocution (14%), and falling objects (14%) [48]. Another study on construction accidents discovered that substantial accidents occurred due to falls and contact with a fixed machine's moving parts [49]. Swuste et al. [45] stated that the most prevalent hazards were falls, struck-by, electric shock, and caught-in or -between. Naveen Kumar et al. [50] carried out a study in Bangalore stating that between 2014 and 2016, 41.1% of fall fatalities were related to construction activities. There were 1102 construction worker deaths in the United States in 2019, including 401 deaths from falls, 170 deaths from struck-by, 79 deaths from electrocution, 59 deaths from caught-in, and 393 deaths from other hazards [51]. Considering the available records and literature analysis, the leading hazards this study addressed were fall, struck-by, electrocution, and caught-in or -between.

3.2.2. Accidents

An accident demonstrates the effects of hazards or how a hazard will affect a worker's safety. The leading hazards identified in the preceding step were responsible for significant construction accidents. Accidents like falling from height [52], being hit by falling objects [53], slip and trip [54], machine-related accidents [55], exposure to electricity [56], and others may frequently occur on construction sites. Much research and various reports have identified construction accidents. Ale et al. [49] conducted a study to determine accidents. The findings revealed that non-fatal accidents involved tools and machinery, working at height, and being struck by flying objects, while fatal accidents were due to enormous falling objects, explosions, and heavy vehicles.

Fall is the leading cause of fatality on construction sites [57]. An increasingly common fall-related accident is falling from the roof, structures, and other falls [57]. The leading fall-related accident in the Indonesian construction industry is falling from height [58]. Other fall-related accidents include falls from openings, trenches, service pits, and falling at the same level. In the construction industry, struck-by accidents are the second most common cause of fatalities [59]. Accidents due to struck-by-equipment are 58% and falling objects are 42% of all accidents [59]. Wang et al. [60] stated that working with heavy machines (17.1%), working under elevated weights (15.6%), working on foot (13.5%), and moving equipment (13.5%) are risky elements that play a role in struck-by accidents. Haslam et al. [61] stated that 17% of construction accidents are caused by being struck by a falling or moving object. Caught-in or -between has been the leading cause of permanent injuries [62]. Most of the caught-in or -between accidents occur in activities that involve machinery, vehicles, cranes, and elevators [62]. Following falling from heights, vehicle accidents, and being struck-by, contact with electricity is fourth among the top ten accident scenarios that lead to construction fatalities [63]. The five electrocution accident patterns are worker or equipment contact with a power line, vehicle collision with an electrical power line, and incorrectly installed equipment [64].

Studies have identified a variety of accidents but have not grouped them into broad categories for simple recognition and comprehension. Correct and massive amounts of accident data are required to accurately identify near-misses. Accident data from various industries, including construction, are collected and stored by the OSHA. This study utilized an OSHA-provided data pool of historical accidents to identify major accidents on construction sites. The authors collected 8598 accidents over the past ten years between 2010 and 2020. The accident data were only related to the construction of residential buildings by screening the standard industrial classification (SIC) provided by the OSHA.

The final data set comprised 6663 accidents, among which 4532 were fatal and 2131 were non-fatal. The accidents included 4489 (67.4%) fall-related accidents, 933 (14.1%) struck-by-related accidents, 574 (8.61%) electrocution-related accidents, and 667 (10.2%) caught-in- or -between-related accidents. Figure 3 summarizes the statistical results of the OSHA accident records [65]. According to the occupational codes provided by the OSHA, the victims involved in these accidents were masons, carpenters, electricians, painters, plasterers, plumbers, roofers, duct installers, welders, cutters, and machines operators, and other workers.

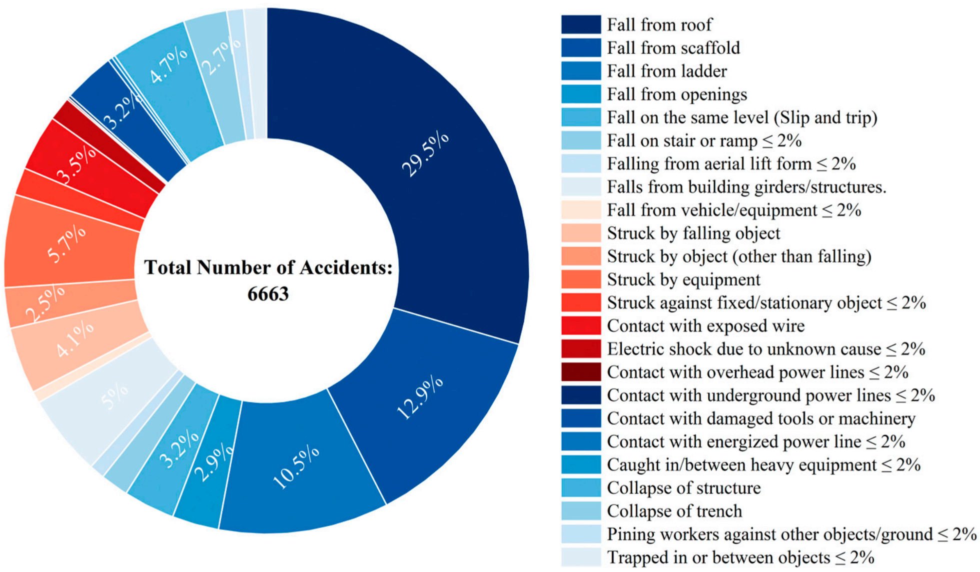

Figure 3. Categories of accidents.

From the detailed investigation, accidents with high occurrence rates were identified. The investigation was called off when no new accident was discovered. Accidents were categorized into the following four sources: (1) fall, (2) struck-by, (3) caught-in or -between, and (4) electrocution (see Table 1).

Table 1. Frequent accidents on construction sites.

S. No	Fall	Struck-by or -against	Electrocution	Caught-in or -between
1	From roof	By equipment	Contact with exposed wires	Collapse of structure
2	From scaffold	By falling or flying object	Contact with a damaged tool or machinery	Collapse of a trench (cave in)
3	From ladder	By object (other than falling, e.g., moving)	Electric shock by unknown cause	Trapped in or between objects
4	From building girders or other structures	Against a fixed or stationary object	Contact with overhead power lines	Pinned workers against other objects or the ground
5	On the same level (slip and trip)		Contact with underground, buried power lines	Contact of hand tools with an electrified wire
6	From openings (e.g., trench)			By heavy equipment

3.2.3. Unsafe Acts and Conditions

Identifying near-misses and implementing preventative actions before they become a problem requires determining their underlying cause. Primary causes were divided into workers' unsafe behavior and exposure to unsafe conditions. Some of the workers' unsafe acts found in previous research included non-compliance with work and safety procedures [66], inadequate or no use of PPE [67], unauthorized use of equipment [68], deliberately risking one's life [66], inadequate knowledge of hazardous situations [67], unsafe working posture [69], failure to use equipment safely [67], and a lack of experience [66]. Similarly, the primary unsafe conditions included poor site layout [70], excessive and loud noise [71], unsafe working procedures [72], defective PPE or equipment, insufficient supports or guards, poor warning systems, clothing hazards [72,73], task complexity [74], and poor lighting and weather [75]. The OSHA's original accident summaries and investigation reports [76] were reviewed to accurately view the unsafe acts and conditions responsible for the previously identified accidents. Summaries provided by the OSHA were entered into a spreadsheet along with accidents, inspection IDs, date, and occupation code, and the probable cause was determined by personally examining the summaries. Table 2 illustrates the methodology used to identify unsafe acts and conditions from the OSHA's accident summary.

Table 2. Investigation of accidents.

ID	Date	Occupation	Accident
316268895	**15 February 2013**	**Construction Laborers**	**Fall from Scaffold**
	Summary		**Causes**
The employee was working on a two-story scaffold. The scaffold was not fully planked. The employee was not wearing any fall protection. The employee fell from the scaffold.			Working at height/Not wearing PPE/Unsafely positioned scaffold

The accidents where the causes were ambiguous were neglected. Out of 6663 accidents, 5725 accidents were carefully analyzed. Twelve (12) unsafe acts and twelve (12) unsafe conditions were identified. Table 3 summarizes the unsafe acts and conditions identified.

Table 3. Summary of identified unsafe acts and conditions.

Unsafe Acts	Unsafe Conditions
A1—Approach to restricted areas	C1—Poor site layout
A2—No or improper use of PPE	C2—Unguarded floor or roof opening
A3—Inappropriate equipment usage	C3—Defective PPE
A4—Unsafe posture and position	C4—Unprotected excavations and trenches
A5—Equipment and tool inspection was incomplete or non-existent	C5—Unsuitable weather conditions
A6—Operating at an unusually high altitude	C6—Missing or defective warning sign
A7—Operating close to moving vehicles and equipment	C7—Places under unfixed materials/tools towards the edges
A8—Ignoring alarms and warning signages	C8—Unsafely positioned ladders and scaffolds
A9—Working close to overhead power lines	C9—Lack of training and poor experience
A10—Running heavy equipment near edges	C10—Lack of machine guards
A11—Worker carrying a heavy load	C11—Defective or damaged equipment
A12—Unauthorized use of equipment	C12—Unsuitable working conditions

4. Results and Discussion

4.1. Near-Miss Identification

Accident causation studies have concluded that risky behavior, combined with unsafe conditions, is the primary cause of accidents and near-misses. This study intended to find the relationships between unsafe acts and conditions that contribute to construction near-miss incidents through statistical analyses. Figure 4 illustrates the near-miss identification process. The process aimed to use a correlation analysis to identify the influential unsafe act and condition combinations responsible for significant near-misses on construction sites.

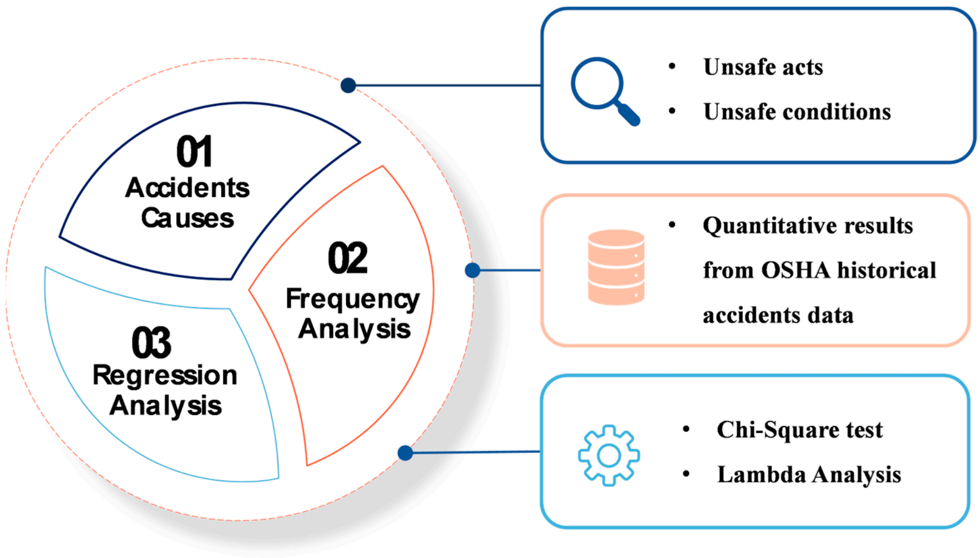

Figure 4. Near-miss identification process.

Because most accidents occur when an unsafe act and condition are combined, the authors performed a frequency analysis to identify the number of unsafe acts and conditions responsible for construction accidents among the unsafe acts and conditions previously identified. The 5725 construction accident cases were analyzed. Figure 5 shows the frequency of accidents caused by a particular combination.

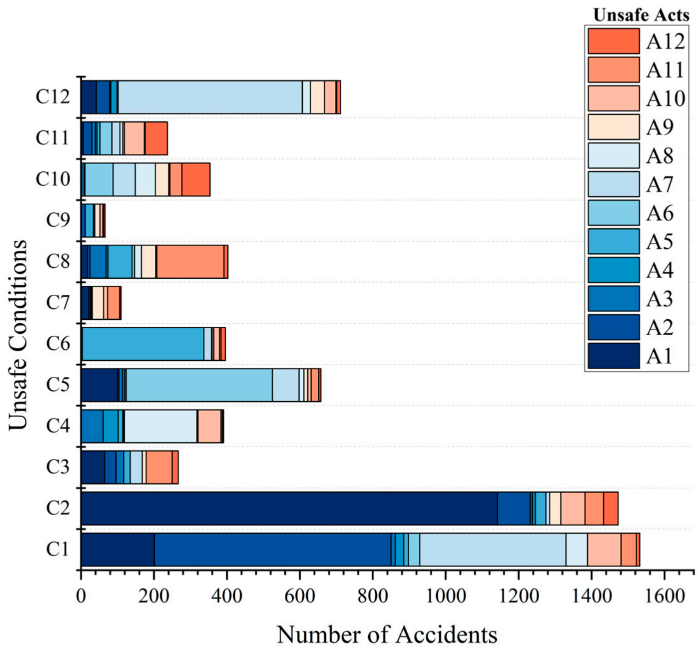

Figure 5. Results of the frequency analysis.

When determining major near-misses, dealing with highly correlated combinations would be more efficient than relying on frequencies, as combinations can have high frequencies and weak correlations. A correlation analysis was performed to identify the most effective combination that causes near-misses. The correlation analysis included the chi-square test and a lambda analysis. The chi-square analysis was used to determine whether there was a relationship between unsafe acts and conditions. On the other hand, a lambda analysis was used to determine how strong of a relationship existed between unsafe acts and conditions.

The SPSS 29 (IBM, Armonk, NY, USA) analysis software was used to perform this statistical analysis. No cell had an expected frequency of zero, and only 20% of the cells had an expected frequency of less than five. As a result, the data were eligible for the chi-square test. The chi-square test was performed at a significance level (p-value) of 0.01 (1%). The null hypothesis that "there is no association between the unsafe act (A) and unsafe condition (C) under test" was rejected when the estimated p-value was less than the accepted significance level, implying a strong correlation between the two variables. Only combinations that passed the chi-square test were considered for the lambda test. Figure 6 summarizes the results of the correlation analysis.

A lambda analysis was performed on the 24 combinations that passed the chi-square significance level of 0.01. The value of lambda is usually between 0 and 1, and the closer it is to 1, the more cohesive the variables are thought to be. The criteria to consider a combination as an effective combination is that the lambda value must be greater than 0.20. After deduction, twelve (12) significant near-misses were identified (see Table 4).

Table 4. Major near-misses on construction sites.

S. No	Near-Misses
1	A1—Approach to restricted areas and C2—Unguarded floor or roof openings
2	A5—Equipment and tools inspection was incomplete or non-existent and C8-Unsafely positioned ladders and scaffolds
3	A2—No or improper use of PPE and C2—Unguarded floor or roof openings
4	A2—No or improper use of PPE and C11—Inappropriately installed or defective tools and equipment
5	A6—Operating at an unusually high altitude and C11—Inappropriately installed or defective tools and equipment

Table 4. *Cont.*

S. No	Near-Misses
6	A7—Operating close to moving vehicles and equipment and C1—Poor site layout (congestion and overcrowding)
7	A8—Ignoring alarms and warning signages and C12—Unsuitable working conditions (e.g., limited visibility and excessive noise)
8	A7—Operating close to moving vehicles and equipment and C12—Unsuitable working conditions (e.g., limited visibility)
9	A12—Unauthorized use of equipment and C10—Lack of machine guards
10	A9—Working close to overhead power lines and C1—Poor site layout (congestion and overcrowding)
11	A9—Working close to overhead power lines and C5—Unsuitable weather conditions (heavy rain, poor lightning, high temperature, etc.)
12	A10—Running heavy equipment near edges and C4—Unprotected excavations and trenches

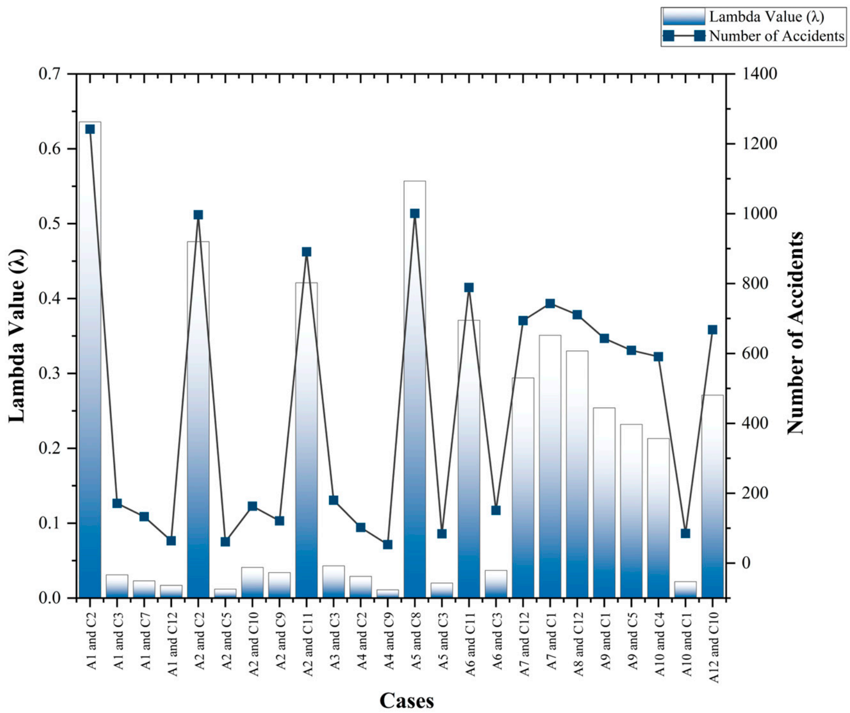

Figure 6. Correlation between unsafe acts and conditions.

4.2. Near-Miss Detection Metrics

The development of efficient real-time monitoring systems relies on a detailed understanding of specific accident precursors and quantitative measures for evaluating risky behaviors or situations [77]. The construction site risks, accidents, and causes discussed in the previous section were used to identify quantitative parameters that sensing technologies can collect and analyze to measure and monitor near-misses. Analyzing each near-miss in Table 4, the data required for autonomous near-miss detection were determined (see Table 5).

While analyzing the near-miss cases, an early warning system for employees operating in unsafe conditions can be constructed if the real-time location is estimated. As a result, worker position was required in N1, N5, and N3; relative positions of workers and equipment were required in N6 and N8; relative positions of workers and fixed powerlines were required in N10 and N11; and real-time location of equipment and vehicles was required in N12. Along with the location, these near-misses also required hazardous locations to spot workers' interactions for near-miss detection. N1 and N3 required the location of unsecured edges, N6 and N10 required updated site layouts, including equipment placement, and N12 required the location of unprotected excavation and trenches; these conditions were pre-programmed into the system. Similarly, N7 and N8 required environment information that included lightning, noise, visibility, etc. Real-time PPE information that included PPE status and a brief description of how to utilize PPE correctly was required in N3 and N4. N9 required real-time worker information that included the workers' experience, operators' working certificates, workers' training details, and others. Weather information was required by N11. Real-time information on equipment or tools included a summary of the most recent inspection reports, other information regarding their placement, and a correct procedure guide was required in near-misses N2, N4, N5, and N9.

Table 5. Data required for near-miss detection.

S. No	Near-Misses	Data Required
N1	A1—Approach to restricted areas and C2—Unguarded floor or roof openings	Real-time worker location and location of the mentioned unsafe condition
N2	A5—Equipment and tool inspection was incomplete or non-existent and C8—Unsafely positioned ladders and scaffolds	Real-time information on equipment/tools
N3	A2—No or improper use of PPE and C2—Unguarded floor or roof openings	Real-time worker location, real-time information on PPE status, and location of the mentioned unsafe condition
N4	A2—No or improper use of PPE and C11—Inappropriately installed or defective tools and equipment	Real-time information on PPE status and real-time information on equipment/tools
N5	A6—Operating at an unusually high altitude and A5—Equipment and tool inspection was incomplete or non-existent.	Real-time worker location and real-time information on equipment/tool inspections
N6	A7—Operating close to moving vehicles and equipment and C1—Poor site layout (congestion and overcrowding)	Real-time worker and vehicle location and construction site layout
N7	A8—Ignoring alarms and warning signages and C12—Unsuitable working conditions	Real-time environment information
N8	A7—Operating close to moving vehicles and equipment and C12—Unsuitable working conditions	Real-time worker and vehicle location and real-time environment information
N9	A12—Unauthorized use of equipment and C10—Lack of machine guards	Real-time information on equipment/tools and real-time information on workers
N10	A9—Working close to overhead power lines and C1—Poor site layout (congestion and overcrowding)	Real-time worker location, location of the mentioned unsafe condition, and construction site layout
N11	A9—Working close to overhead power lines and C5—Unsuitable weather conditions	Real-time worker location and location of the mentioned unsafe condition and real-time information about weather
N12	A10—Running heavy equipment/vehicles near edges and C4—Unprotected excavations and trenches	Real-time location of equipment/vehicles and location of the mentioned unsafe condition

The data required in Table 5 revealed four divisions of near-miss detection metrics: location (i.e., worker, vehicle, or equipment location), environment (e.g., temperature, noise level, light intensity, rain, and wind), real-time identity information (e.g., workers' information), and proximity (e.g., for locating the interaction to unsafe conditions, e.g., unguarded edges) (See Table 6). These detection metrics quantized all the previously reviewed unsafe acts and conditions required for near-miss detection. These measurable metrics provided a foundation for the proper deployment of sensing technologies (i.e., GPS, IMU, light sensors, anemometers, proximity sensors, RFID, etc.) to collect and monitor these metrics for real-time monitoring of near-misses.

Table 6. Near-miss detection metrics.

Detection	Metrics	Parameters	Device/Sensor	Remarks
Location	Worker, vehicle, or equipment location	Geometric coordinates	GPS, IMU	Sensor-based system for monitoring environmental conditions in confined workspaces
Environment	Temperature	Celsius	Temperature sensor	Sensor-based system for monitoring environmental conditions in confined workspaces
	Noise level	Decibel	Sound meter	
	Light intensity	Lumens	Light sensor	
	Rain	Mm	Rain gauge	
	Wind	Windspeed	Anemometer	
Proximity	Distance from unsafe conditions such as from unguarded edge	Distance	Proximity sensor, distance sensor, cameras	Near-miss/proximity analysis; proximity monitoring for struck-by hazard identification
Identity	Worker information	Name, gender, age, experience, trade	RFID cards, database	Assessing workers' perceived risk through monitoring workers' physiological and emotional response; awkward posture recognition, work-related musculoskeletal disorders (WMSDs), ergonomics

5. Practical Implications and Future Research

Effective accident prevention necessitates a proactive approach to monitoring hazards by focusing on leading indicators [4]. This study focused on near-misses, an important leading indicator often left unreported and undocumented. Regularly collecting and processing leading indicators can help improve safety decision-making [78]. Similarly, if the near-miss data are rapidly collected and updated, in that case, it will allow safety personnel to make quick decisions. This can be done by adopting modern sensing technologies that continuously collect and analyze data. This study developed a technique for facilitating the deployment of sensors for the autonomous monitoring of near-misses. This study's main findings included the near-miss detection metrics. The near-miss detection metrics consisted of measurable parameters that could be sensed and analyzed by sensing technology.

This research study was only the beginning of future research into using sensors for autonomous collection and analysis of near-misses and other precursors in preventing future accidents by providing early warnings. Although advanced sensing technologies have the potential to reveal construction safety improvement opportunities [79], compared to other industries, the use of sensors is limited in the construction industry. The advancement of promising digital technologies, such as cloud computing, RFID, wireless sensor networks (WSNs), and the Internet of Things (IoT), has sparked interest in researching their use in construction. Simultaneously, significant attempts have begun to automate the construction safety management process through sensors. Sensor technology offers safety managers measurements of the subjects' status on construction sites, allowing them to make more informed decisions on the efficacy of ongoing treatments and, if necessary, to make quick changes to the approach. A few applications of sensors include proximity detection and generating alerts when workers are present in unsafe zones [60,80,81]. Despite various research studies, the construction sector has been extremely slow to adopt sensors; there is much room for sensing technology for tailored construction safety management.

The developed detection metrics provided the data required by sensors for near-miss identification and data collection without relying on workers' feedback. Once the data were collected, they could be analyzed, processed, and used to predict accidents and provide other on-demand services. There are numerous commercially available sensor systems, each with their strengths and weaknesses, that can be effectively managed by combining two or more sensing devices to generate complimentary benefits. The findings of this study will enable future researchers to select suitable sensors as well as integrate several sensors and systems per the required metrics to detect near-misses on construction sites. Further, this research suggested that technology developers should concentrate their efforts on obtaining valuable data from many sensors merged into a single device that is simple to deploy and can measure all the required metrics.

In addition, sensor-based technologies hold the promise of continuously tracking exposures to safety risks, which can be used as a proactive indicator for near-misses. To ensure that these proposed systems are embraced by industry professionals, they must be seamlessly integrated into current practices, requiring minimal expertise and maintenance. Moreover, such systems should be merged with Building Information Modeling (BIM) to create comprehensive solutions. Presently, the focus of many studies has been on creating monitoring systems that gather and analyze specific types of data from different sources on construction sites, such as workers' movements, health statuses, activities, environmental conditions, and more. An integrated framework that consolidates this diverse information would be a valuable addition. Future studies should determine the most effective ways to convert this collected data into practical, actionable insights. Further research could also look into the development of data-driven platforms that support safety decisions for site managers, which could significantly encourage the industry to adopt sensor-based safety management practices.

6. Conclusions

Near-misses in the construction sector have long been seen as a great way to improve safety performance. Existing near-miss data collection practices are manual and face significant accuracy, interpretation, and efficiency challenges. Modern sensor technologies offer a non-intrusive solution for gathering and delivering real-time data that can be used to make proactive and efficient decisions. It is time for construction stakeholders and experts to fully embrace these rapidly evolving technological advancements in order to considerably improve safety performance.

The study proposed a quantifiable near-miss definition that defined a near-miss as an interaction of unsafe behaviors and conditions. Twelve significant near-misses were identified in terms of unsafe acts and conditions responsible for severe construction accidents through a correlation analysis. These near-misses were investigated to develop a detection metric that consisted of quantitative parameters for automatic detection and the documentation of near-misses. The detection metric was further divided into location, proximity, environment, and identity information. Based on the metric requirements, the best suitable sensors from a wide range of sensors could be chosen to collect the metrics by going over each division in detail. This research intended to shift the interest of researchers towards deploying advanced sensors to predict future accidents and generate early warnings by the real-time monitoring of near-misses.

This study contributes to improving construction safety by addressing the under-reporting of near-miss events. It developed near-miss detection metrics for automated detection using sensors. The study established a quantifiable definition of near-misses and identified combinations of unsafe acts and conditions leading to near-misses through an empirical analysis. Additionally, it determined the measurable data needed for autonomous near-miss detection. Overall, the developed metrics lay the groundwork for enhancing construction safety through automated near-miss reporting and documentation. Furthermore, it helped for the establishment of safety management schemes in the construction industry, specifically identifying near-misses. This research offers valuable insight into developing safety guidelines for managers to improve near-miss reporting and detection on construction sites.

Author Contributions: Conceptualization, F.H., M.U.H., T.A. and R.M.C.; methodology, F.H., M.U.H., R.M.C., M.U.Z. and K.A.; software, F.H., T.A. and M.U.H.; validation, M.U.Z., F.H., R.M.C. and K.A.; formal analysis, F.H., T.A. and M.U.H.; investigation, M.U.Z., F.H. and K.A.; resources, M.U.H., M.U.Z. and R.M.C.; data curation, F.H., T.A. and M.U.H.; writing—original draft preparation, F.H., M.U.H. and R.M.C.; writing—review and editing, M.U.Z., T.A. and K.A.; visualization, M.U.Z., F.H., M.U.H. and R.M.C.; supervision, M.U.H. and R.M.C.; project administration, M.U.H., M.U.Z., R.M.C. and K.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data that support the findings of this study are openly available in Data and Statistic, Fatality and Catastrophe Summaries at https://www.osha.gov/data, https://www.osha.gov/pls/imis/accidentsearch.html, reference number [65,76].

Conflicts of Interest: The authors declare that they have no conflicts of interest.

References

1. Lozano-Díez, R.V.; López-Zaldívar, O.; del Cura, S.H.; Verdú-Vázquez, A. Analysis of the impact of health and safety coordinator on construction site accidents: The case of Spain. *J. Saf. Res.* **2019**, *68*, 149–156. [CrossRef]
2. Sarasanty, D. Safety hazards identification of construction site layout based on geographic information system (GIS). *Int. J. Adv. Sci. Eng. Inf. Technol.* **2020**, *10*, 2021–2027. [CrossRef]
3. Hallowell, M.R.; Bhandari, S.; Alruqi, W. Methods of safety prediction: Analysis and integration of risk assessment, leading indicators, precursor analysis, and safety climate. *Constr. Manag. Econ.* **2020**, *38*, 308–321. [CrossRef]
4. Versteeg, K.; Bigelow, P.; Dale, A.M.; Chaurasia, A. Utilizing construction safety leading and lagging indicators to measure project safety performance: A case study. *Saf. Sci.* **2019**, *120*, 411–421. [CrossRef]
5. Hinze, J.; Thurman, S.; Wehle, A. Leading indicators of construction safety performance. *Saf. Sci.* **2013**, *51*, 23–28. [CrossRef]
6. Lingard, H.; Hallowell, M.; Salas, R.; Pirzadeh, P. Leading or lagging? Temporal analysis of safety indicators on a large infrastructure construction project. *Saf. Sci.* **2017**, *91*, 206–220. [CrossRef]
7. Choudhry, R.M.; Fang, D. Why operatives engage in unsafe work behavior: Investigating factors on construction sites. *Saf. Sci.* **2008**, *46*, 566–584. [CrossRef]
8. Hallowell, M.R.; Hinze, J.W.; Baud, K.C.; Wehle, A. Proactive construction safety control: Measuring, monitoring, and responding to safety leading indicators. *J. Constr. Eng. Manag.* **2013**, *139*, 04013010. [CrossRef]
9. Costin, A.; Wehle, A.; Adibfar, A. Leading indicators—A conceptual IoT-based framework to produce active leading indicators for construction safety. *Safety* **2019**, *5*, 86. [CrossRef]
10. Andriulo, S.; Gnoni, M.G. Measuring the effectiveness of a near-miss management system: An application in an automotive firm supplier. *Reliab. Eng. Syst. Saf.* **2014**, *132*, 154–162. [CrossRef]
11. Saleh, J.H.; Saltmarsh, E.A.; Favarò, F.M.; Brevault, L. Accident precursors, near misses, and warning signs: Critical review and formal definitions within the framework of Discrete Event Systems. *Reliab. Eng. Syst. Saf.* **2013**, *114*, 148–154. [CrossRef]
12. Ritwik, U. Risk-based approach to near miss. *Hydrocarb. Process.* **2002**, *81*, 93–96.
13. Marks, E.; Teizer, J.; Hinze, J. Near-miss reporting program to enhance construction worker safety performance. In Proceedings of the Construction Research Congress, Atlanta, GA, USA, 19–21 May 2014; pp. 2315–2324. [CrossRef]
14. Nyflot, M.J.; Zeng, J.; Kusano, A.S.; Novak, A.; Mullen, T.D.; Gao, W.; Jordan, L.; Sponseller, P.A.; Carlson, J.C.; Kane, G.; et al. Metrics of success: Measuring impact of a departmental near-miss incident learning system. *Pract. Radiat. Oncol.* **2015**, *5*, e409–e416. [CrossRef]
15. Macrae, C. The problem with incident reporting. *BMJ Qual. Saf.* **2016**, *25*, 71–75. [CrossRef] [PubMed]
16. Gnoni, M.G.; Saleh, J.H. Near-miss management systems and observability-in-depth: Handling safety incidents and accident precursors in light of safety principles. *Saf. Sci.* **2017**, *91*, 154–167. [CrossRef]
17. Cambraia, F.B.; Saurin, T.A.; Formoso, C.T. Identification, analysis and dissemination of information on near misses: A case study in the construction industry. *Saf. Sci.* **2010**, *48*, 91–99. [CrossRef]
18. HSE. Types of Reportable Incidents. Available online: https://www.hse.gov.uk/riddor/reportable-incidents.htm (accessed on 12 October 2021).
19. OSHA. Near-Miss Reporting Policy. Available online: https://www.osha.gov/sites/default/files/2021-07/Template%20for%20Near%20Miss%20Reporting%20Policy.pdf (accessed on 28 December 2021).
20. Asadzadeh, A.; Arashpour, M.; Li, H.; Ngo, T.; Bab-Hadiashar, A.; Rashidi, A. Sensor-based safety management. *Autom. Constr.* **2020**, *113*, 103128. [CrossRef]
21. Hislop, R.D. *Construction Site Safety*; Taylor & Francis Ltd.: London, UK, 1999; pp. 203–210. [CrossRef]
22. Caspi, H.; Perlman, Y.; Westreich, S. Managing near-miss reporting in hospitals: The dynamics between staff members' willingness to report and management's handling of near-miss events. *Saf. Sci.* **2023**, *164*, 106147. [CrossRef]
23. Bugalia, N.; Maemura, Y.; Ozawa, K. A system dynamics model for near-miss reporting in complex systems. *Saf. Sci.* **2021**, *142*, 105368. [CrossRef]

24. Winkler, M.; Perlman, Y.; Westreich, S. Reporting near-miss safety events: Impacts and decision-making analysis. *Saf. Sci.* **2019**, *117*, 365–374. [CrossRef]
25. Thoroman, B.; Salmon, P.; Goode, N. Evaluation of construct and criterion-referenced validity of a systems-thinking based near miss reporting form. *Ergonomics* **2020**, *63*, 210–224. [CrossRef]
26. Shen, X.; Marks, E. Near-miss information visualization tool in BIM for construction safety. *J. Constr. Eng. Manag.* **2016**, *142*, 04015100. [CrossRef]
27. Gnoni, M.; Tornese, F.; Guglielmi, A.; Pellicci, M.; Campo, G.; De Merich, D. Near miss management systems in the industrial sector: A literature review. *Saf. Sci.* **2022**, *150*, 105704. [CrossRef]
28. WHO. *WHO Draft Guidelines for Adverse Event Reporting and Learning Systems: From Information to Action*; WHO: Geneva, Switzerland, 2005.
29. OSHA. *Incident Investigations: A Guide for Employers*; Occupational Safety and Health Administration: Washington, DC, USA, 2015; p. 24.
30. Zhou, Z.; Li, C.; Mi, C.; Qian, L. Exploring the potential use of near-miss information to improve construction safety performance. *Sustainability* **2019**, *11*, 1264. [CrossRef]
31. Awolusi, I.; Marks, E.; Hainen, A.; Alzarrad, A. Incident Analysis and Prediction of Safety Performance on Construction Sites. *Civileng* **2022**, *3*, 669–686. [CrossRef]
32. Lee, S.; Koo, B.; Yang, S.; Kim, J.; Nam, Y.; Kim, Y. Fall-from-height detection using deep learning based on IMU sensor data for accident prevention at construction sites. *Sensors* **2022**, *22*, 6107. [CrossRef]
33. Williamsen, M. Near-miss reporting: A missing link in safety culture. *Prof. Saf.* **2013**, *58*, 46–50.
34. Jones, S.; Kirchsteiger, C.; Bjerke, W. The importance of near miss reporting to further improve safety performance. *J. Loss Prev. Process Ind.* **1999**, *12*, 59–67. [CrossRef]
35. Wright, L.; Vanderschaaf, T. Accident versus near miss causation: A critical review of the literature, an empirical test in the UK railway domain, and their implications for other sectors. *J. Hazard. Mater.* **2004**, *111*, 105–110. [CrossRef] [PubMed]
36. Chen, Q.; Wu, W.; Zhang, X. The differentiation and decision matrix risk assessment of accident precursors and near-misses on construction sites. *Int. J. Eng. Technol.* **2012**, *12*, 38–53.
37. Heinrich, H.W. *Industrial Accident Prevention: A Scientific Approach*, 2nd ed.; McGraw-Hill: New York, NY, USA; London, UK, 1941.
38. Hollnagel, E. *Barriers and Accident Prevention*; Routledge: London, UK, 2016.
39. Vanderschaaf, T.W. Near miss reporting in the chemical process industry: An overview. *Microelectron Reliab.* **1995**, *35*, 1233–1243. [CrossRef]
40. Cui, J.; Rosoff, H.; John, R.S. Public response to a near-miss nuclear accident scenario varying in causal attributions and outcome uncertainty. *Risk Anal.* **2018**, *38*, 947–961. [CrossRef] [PubMed]
41. Park, I.; Kim, J.; Han, S.; Hyun, C. Analysis of fatal accidents and their causes in the Korean construction industry. *Sustainability* **2020**, *12*, 3120. [CrossRef]
42. Eurostat. European Statistics on Accidents at Work (ESAW). 2014. Available online: https://ec.europa.eu/eurostat/web/health/health-safety-work/data/database (accessed on 22 December 2021).
43. HSE. Kinds of Accident Statistics in Great Britain. 2020. Available online: www.hse.gov.uk/statistics/causinj/kinds-of-accident.pdf (accessed on 12 December 2021).
44. Lipscomb, H.J.; Dement, J.M.; Rodriguez-Acosta, R. Deaths from external causes of injury among construction workers in North Carolina, 1988–1994. *Appl. Occup. Environ. Hyg.* **2000**, *15*, 569–580. [CrossRef] [PubMed]
45. Brown, S.; Harris, W.; Brooks, R.D.; Dong, X.S. Fatal injury trends in the construction industry. *CPWR Data Bull.* 2021, pp. 1–6. Available online: https://www.cpwr.com/wp-content/uploads/DataBulletin-February-2021.pdf (accessed on 1 April 2024).
46. Musasa, T.; Jerie, S. Challenges of near miss incidents reporting at a mine in the Midlands Province of Zimbabwe. *East. Afr. Soc. Sci. Res. Rev.* **2020**, *36*, 95–114. [CrossRef]
47. Ale, B.J.M.; Bellamy, L.J.; Baksteen, H.; Damen, M.; Goossens, L.H.J.; Hale, A.R.; Mud, M.; Oh, J.; Papazoglou, I.A.; Whiston, J.Y. Accidents in the construction industry in the Netherlands: An analysis of accident reports using story builder. *Reliab. Eng. Syst. Saf.* **2008**, *93*, 1523–1533. [CrossRef]
48. Swuste, P.; Frijters, A.; Guldenmund, F. Is it possible to influence safety in the building sector? A literature review extending from 1980 until the present. *Saf. Sci.* **2012**, *50*, 1333–1343. [CrossRef]
49. Naveen Kumar, T.; Jagannatha, S.R.; Venkatesha, V.T. Rise in deaths due to fall from height: A 3-year retrospective study. *Med. Leg. Update* **2019**, *19*, 113–116. [CrossRef]
50. Dogan, E.; Yurdusev, M.A.; Yildizel, S.A.; Calis, G. Investigation of scaffolding accident in a construction site: A case study analysis. *Eng. Fail. Anal.* **2021**, *120*, 105108. [CrossRef]
51. Wu, W.; Yang, H.; Li, Q.; Chew, D. An integrated information management model for proactive prevention of struck-by-falling-object accidents on construction sites. *Autom. Constr.* **2013**, *34*, 67–74. [CrossRef]
52. Lipscomb, H.J.; Glazner, J.E.; Bondy, J.; Guarini, K.; Lezotte, D. Injuries from slips and trips in construction. *Appl. Ergon.* **2006**, *37*, 267–274. [CrossRef] [PubMed]
53. Chinniah, Y. Analysis and prevention of serious and fatal accidents related to moving parts of machinery. *Saf. Sci.* **2015**, *75*, 163–173. [CrossRef]

54. Janicak, C.A. Occupational fatalities due to electrocutions in the construction industry. *J. Saf. Res.* **2008**, *39*, 617–621. [CrossRef] [PubMed]
55. Huang, X.; Hinze, J. Analysis of construction worker fall accidents. *J. Constr. Eng. Manag.* **2003**, *129*, 262–271. [CrossRef]
56. Latief, Y.; Suraji, A.; Nugroho, Y.S.; Arifuddin, R. The nature of fall accidents in construction projects: A case of Indonesia. *Int. J. Civ. Environ. Eng.* **2011**, *11*, 80–84.
57. Wu, W.; Yang, H.; Chew, D.A.; Yang, S.-H.; Gibb, A.G.; Li, Q. Towards an autonomous real-time tracking system of near-miss accidents on construction sites. *Autom. Constr.* **2010**, *19*, 134–141. [CrossRef]
58. Wang, X.; Love, P.E.D.; Davis, P.R. BIM + AR: A framework of bringing BIM to construction site. In Proceedings of the Construction Research Congress, Lafayette, Indiana, 21–23 May 2012; pp. 778–786. [CrossRef]
59. Haslam, R.; Hide, S.; Gibb, A.; Gyi, D.; Pavitt, T.; Atkinson, S.; Duff, A. Contributing factors in construction accidents. *Appl. Ergon.* **2005**, *36*, 401–415. [CrossRef] [PubMed]
60. Chi, C.F.; Lin, S.Z. Classification scheme and prevention measures for caught-in-between occupational fatalities. *Appl. Ergon.* **2018**, *68*, 338–348. [CrossRef] [PubMed]
61. Zhao, D.; Thabet, W.; McCoy, A.; Kleiner, B. Electrical deaths in the US construction: An analysis of fatality investigations. *Int. J. Inj. Control. Saf. Promot.* **2014**, *21*, 278–288. [CrossRef]
62. Chi, C.F.; Yang, C.C.; Chen, Z.L. In-depth accident analysis of electrical fatalities in the construction industry. *Int. J. Ind. Ergon.* **2009**, *39*, 635–644. [CrossRef]
63. OSHA. Accidents Data Statistics. 2010–2020. Available online: https://www.osha.gov/data (accessed on 12 January 2021).
64. Ling, F.Y.Y.; Liu, M.; Woo, Y.C. Construction fatalities in Singapore. *Int. J. Proj. Manag.* **2009**, *27*, 717–726. [CrossRef]
65. Cheng, C.W.; Lin, C.C.; Sen Leu, S. Use of association rules to explore cause-effect relationships in occupational accidents in the Taiwan construction industry. *Saf. Sci.* **2010**, *48*, 436–444. [CrossRef]
66. Ali, A.S.; Kamaruzzaman, S.N.; Sing, G.C. A study on causes of accident and prevention in Malaysian construction industry. *J. Des. Built.* **2010**, *3*, 95–113.
67. Abdelhamid, T.S.; Everett, J.G. Identifying root causes of construction accidents. *J. Constr. Eng. Manag.* **2000**, *126*, 52–60. [CrossRef]
68. Osama, J.M.; Hamad, A.A.-I. Effective industrial housekeeping: The supervisor's role. *Prof. Saf.* **1995**, *40*, 30–33.
69. Khankeh, H.R.; Hosseini, S.H.; Farrokhi, M.; Hosseini, M.A.; Amanat, N. Early warning system models and components in emergency and disaster: A systematic literature review protocol. *Syst. Rev.* **2019**, *8*, 315. [CrossRef] [PubMed]
70. Hamid, A.R.A.; Azmi, M.R.A.N.; Aminudin, E.; Jaya, R.P.; Zakaria, R.; Zawawi, A.M.M.; Yahya, K.; Haron, Z.; Yunus, R.; Saar, C.C. Causes of fatal construction accidents in Malaysia. *IOP Conf. Ser Earth Environ. Sci.* **2019**, *220*, 012044. [CrossRef]
71. Cheng, C.-W.; Leu, S.-S.; Lin, C.-C.; Fan, C. Characteristic analysis of occupational accidents at small construction enterprises. *Saf. Sci.* **2010**, *48*, 698–707. [CrossRef]
72. Hsiao, H.; Simeonov, P. Preventing falls from roofs: A critical review. *Ergonomics* **2001**, *44*, 537–561. [CrossRef]
73. Glazner, J.; Bondy, J.; Lezotte, D.C.; Lipscomb, H.; Guarini, K. Factors contributing to construction injury at Denver international airport. *Am. J. Ind. Med.* **2005**, *47*, 27–36. [CrossRef]
74. OSHA. Fatality and Catastrophe Investigation Summaries. 2010–2020. Available online: https://www.osha.gov/pls/imis/accidentsearch.html (accessed on 19 June 2021).
75. Seo, J.; Han, S.; Lee, S.; Kim, H. Computer vision techniques for construction safety and health monitoring. *Adv. Eng. Inform.* **2015**, *29*, 239–251. [CrossRef]
76. Pradhananga, N.; Teizer, J. Automatic spatio-temporal analysis of construction site equipment operations using GPS data. *Autom. Constr.* **2013**, *29*, 107–122. [CrossRef]
77. Zhang, M.; Cao, T.; Zhao, X. Applying sensor-based technology to improve construction safety management. *Sensors* **2017**, *17*, 1841. [CrossRef]
78. Fang, Y.; Cho, Y.K.; Zhang, S.; Perez, E. Case study of BIM and cloud–enabled real-time RFID indoor localization for construction management applications. *J. Constr. Eng. Manag.* **2016**, *142*, 05016003. [CrossRef]
79. Wang, J.; Razavi, S.N. Low false alarm rate model for unsafe-proximity detection in construction. *J. Comput. Civ. Eng.* **2016**, *30*, 04015005. [CrossRef]
80. Saqib, G.; Hassan, M.U.; Zubair, M.U.; Choudhry, R.M. Investigating the acceptance of an electronic incident reporting system in the construction industry: An application of the technology acceptance model. *J. Constr. Eng. Manag.* **2023**, *149*, 04023021. [CrossRef]
81. Choudhry, R.M.; Zahoor, H. Strengths and weaknesses of safety practices to improve safety performance in construction projects in Pakistan. *J. Prof. Issues Eng. Educ. Pract.* **2016**, *142*, 04016011. [CrossRef]