




Review

Occupational Accidents Related to Heavy Machinery: A Systematic Review

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Abstract: Surface and underground mining, due to its technical challenges, is considered a hazardous industry. The great majority of accidents and fatalities are frequently associated with ineffective or inappropriate training methods. Knowing that knowledge of occupational accident causes plays a significant role in safety management systems, it is important to systematise this kind of information. The primary objective of this systematic review was to find evidence of work-related accidents involving machinery and their causes and, thus, to provide relevant data available to improve the mining project (design). The Preferred Reporting of Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement methodology was used to conduct the review. This paper provides the main research results based on a systematic review protocol registered in the International Prospective Register of Systematic Reviews (PROSPERO), where the research strategy, information sources, and eligibility criteria are provided. From the 3071 articles identified, 16 were considered eligible and added to the study. Results are presented in a narrative-based form, with additional data provided in descriptive tables. The data analysed showed that the equipment often related to mining accidents are conveyor belts, haul trucks, and dumpers, especially during maintenance or repair activities. Attention should be paid to powered tools. Effective monitoring and machine operation control are some of the stated measures to minimise accidents. Particular attention should be paid to less experienced and senior workers, mainly through fatigue control, workload management, and appropriate training programs.

Keywords: accident; fatalities; injuries; machinery; mining



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1. Introduction

World economic growth has led to a global increase in demand for mineral raw materials. This pressure to increase supplies sometimes leads to adverse socio-environmental impacts [1–3] and high accident rates in the mining industry. According to Eurostat (https://ec.europa.eu/eurostat/statistics-explained/index.php/Accidents_at_work_statistics#Analysis_by_activity (accessed on 10 November 2020)), although between 2011 and 2017 the incidence rate of fatal occupational accidents in mining and quarrying was lowered from 15.1 to 6.8 per 100,000 workers, it remains the EU-28 sector in which this rate is the highest. Between 2010 and 2017, in this sector, 599 workers died, and 94,048 workers had nonfatal accidents with more than 4 days of absence. Although accident rates have been reduced over time, the exploitation of mineral (primary) raw materials has been and continues to be one of the industrial activities with the highest accident rates and even diseases worldwide [3–8] despite technological developments [1,9,10]. The investigation [11] and reconstruction [12] of accidents show that, due to the complexity of the industry, numerous factors can contribute in different ways to the accident rate [13,14]. Among them are unsafe behaviours by the workers themselves [8,15] and the increasingly larger equipment requiring more and better qualifications from its operators [16]. In recent years, the number of injuries associated with mining equipment has increased [17]. In terms of behaviour, it

seems that many workers can neither identify dangers nor perceive and identify risk situations [18,19]. However, it is recognised that adequate training can contribute to minimising the number and severity of accidents [12,20,21].

Consequently, training was placed at the centre of the measures to be implemented. In this context, new approaches have been tested and executed, such as virtual reality (VR) [22,23]. This technology makes it possible to simulate working conditions and train workers to respond adequately to complex and high-risk situations without compromising their safety during training [24,25]. Additionally, VR can be used to control systems for production and testing in mining, as well as in other fields [26].

Still, in the light of Industry 4.0, systems are evolving to include autonomous driving, especially in underground mining, where the working conditions are not always the most advantageous regarding workers' well-being. This evolution will ultimately protect the safety of both workers and equipment [27]. However, this is still far from reality in most countries and in most of the exploitations (mines/quarries). Concerning the use of giant equipment and the demands that operating it entails, the solution is not only simply to improve the manoeuvrability or adaptability of equipment [28]. In fact, it is necessary to rethink the mining project, especially in countries with fewer legal restrictions and/or less control capacity, which usually have higher accident rates within the sector. If the risk identification is made in an integrated manner at the design stage, as is already beginning to be done more and more systematically in the construction sector [29], reducing accident rates in mining faster and more easily all over the world might become a real possibility. Common causes of fatalities include falls; sliding of slopes, blocks, or rocks; loading and transport operations; and electrical problems. Additionally, equipment with engines has a significant impact on accident rates [30–32], especially due to the growing need for more complex and sophisticated machines that require an increasingly higher level of skills for their operation [16]. This problem is particularly sensitive when it comes to acquiring new equipment to replace existing ones or designing a new project.

It is known that, in the mining context, increased equipment speeds (combined with larger sizes of machinery) have increased the chance of striking on-foot workers [33]. The risks associated with heavy machinery are influenced by the working environment, machine specification, mine design, and human factor [34].

Thus, this research aimed to find evidence of occupational accidents involving machinery and better understand their root causes to improve mining design in various ways, namely, in the design of benches, roads, and ramps. However, the question arises, how to obtain and analyse these results? Accident models adopted throughout the years have described an accident as an event that shows the consequence of latent weaknesses (failures) combined with active weaknesses. These models have evolved to fit the required specificities regarding their contextual need and tried to determine the most appropriate variables when conducting an accident investigation (safety culture of the company, worker behaviour, the environment, among others). Despite the point of view from which they are applied, one thing they have in common is that what the investigator looks at (into) is usually what he or she is looking for, leading to a biased end [35].

2. Methodology

The Preferred Reporting of Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement [36] (<http://www.prisma-statement.org/> (accessed on 10 November 2020)) is the basis of a whole new vision for developing literature reviews since 2009. It was first used in the area of health. However, other areas of knowledge rapidly adopted this approach, because it brings to the literature review process the requirements associated with the scientific methodology, namely, the objectivity and reproducibility of the results. To give more strength to this component, the PRISMA Statement founders proposed in 2015 an important update on the methodological component of this approach, the Preferred Reporting of Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P) [37].

With this, the PRISMA Statement approach definitely brings the scientific methodology to the literature review process.

This systematic review methodology was based on the protocol registered in PROSPERO (International Prospective Register of Systematic Reviews at the University of York—<https://www.crd.york.ac.uk/prospero/> (accessed on 10 November 2020)) under the code CRD42018109858 by Duarte et al. [38], where the PRISMA-P guidelines were used [37].

The selected information sources were Scopus, Inspec, ScienceDirect, Academic Search Ultimate, Web of Science, Current Contents, IEEE Xplore, Taylor and Francis, Geological Survey of America, Cambridge Journals, Emerald, Ingenta, and Directory of Open Access Journals, which are the main journals and databases in the multidisciplinary and engineering fields. The set of keywords defined a priori were “accident” and “hazard,” combined with “mine,” “quarry,” “open pit,” and “open cast,” separated by the Boolean operator “AND.” After analysing the papers, the expression “accident analysis” was added, and another search was performed by combining it with the main keywords to address the late-defined research objective. In the screening stage, the following exclusion criteria were applied:

1. Date—only papers published between 2010 and 2018 were included in the first phase; 2010 was adopted as a result of a preliminary sensitivity analysis of the number of articles found from the selected keywords.
2. Document type—only research papers were considered.
3. Type of source—only peer-reviewed journals were screened.
4. Language—only papers written in English were considered.

The main objective of this process was to filter the best information (according to the established research standard) in a preliminary phase. However, in the second phase, all literature was considered, and the publication period extended, as suggested by the snowballing technique [39]. Each record was then put up against a set of inclusion criteria in the eligibility phase to determine its inclusion in the study: papers should report data for a well-defined period range, with accident quantitative analysis and equipment description. If any article failed these specifications, it would be excluded from the research.

The first analysis attempt was related to the controlled key terms found across studies provided by VOSviewer, which is a software that allows the construction of bibliometric charts, where a density map was built. The protocol regarding this systematic review suggested a table showing how the screening process was designed [38]. To help conduct the analysis, and as described in the proposal, a table was built to collect from each paper the most relevant information regarding the study aims. Elements such as authors’ identification (name), year of publication, study objectives, country in which the study took place, type of mine/quarry, exploited material, data source, period range, risk assessment (when applicable), standards (when applicable), population, sample and sample characteristics, questionnaire use, questionnaire validation, accident type, and equipment involved, as well as accident consequences, main results, main causes, prevention, and limitations, were collected. The same protocol mentioned that the inclusion criteria would be papers with a well-defined period range for data with quantitative accident analysis and equipment description. However, since one of the outcomes would be defining the accident causes, papers analysing such issues were also considered. From all the information gathered and after analysing the data extracted, a table describing the accident type and causes was constructed and is presented in the Results section. The equipment identified as directly related to the parameters mentioned above were bolting machine, dozer, dumper, excavator, forklift, haul truck, jackleg drill, load-haul-dump (LHD), and loader. The eligible papers were again analysed regarding the controlled terms used, and two graphics were created: one related to the number of accident type occurrences and one associated with the number of occurrences of accident cause (description).

As systematic reviews aim to systematise the studies found within a specific range of criteria, there is a need for determining whether (each research) design or analysis may influence the results and conclusions obtained (biases). Given the nature of the

selected papers, and considering that these studies fall out of the scope for which the methodology was first developed (clinical trials and other health-related studies), the risk of bias for each topic was assessed considering the “low-high-unclear” measurement, as proposed by Higgins et al. [40]. This analysis was carried out and adapted by the research team to analyse and better understand works with such different characteristics. The risk was classified as “low” when the assessed parameter did not affect the results, “unclear” whenever it was not possible to draw a relation between parameter and outcome, and “high” when the assessed parameter had a significant effect on the results, as proposed in the original methodology. However, this methodology was applied at the study level—in this context, data source, standards application, sample representativeness, data treatment, reporting quality, and references quality.

This systematic review was carried out following the PRISMA guidelines [36], and the research was updated in February 2020.

3. Results

In the identification phase, 3071 articles were tracked. After applying the exclusion criteria, 1554 papers were excluded by “date” (only articles between 2010 and 2018 were considered), 468 were excluded by “type of paper” (only peer-reviewed studies providing actual data were considered), 14 were rejected by “type of source” (only indexed journals were screened), and 136 texts were rejected due to “language” (only articles in English were considered). After removing by automatic procedures the articles mentioned above, the titles and abstracts of the remaining ones were read. From this last procedure, 802 more articles were removed because they did not comply with the aim of the systematic review. After this stage, articles that were not accessible in full text (after contacting the authors)—15 papers (classified as “Other” in Figure 1)—were removed from the research. Duplicated records (58 articles) were also removed before the eligibility phase began.

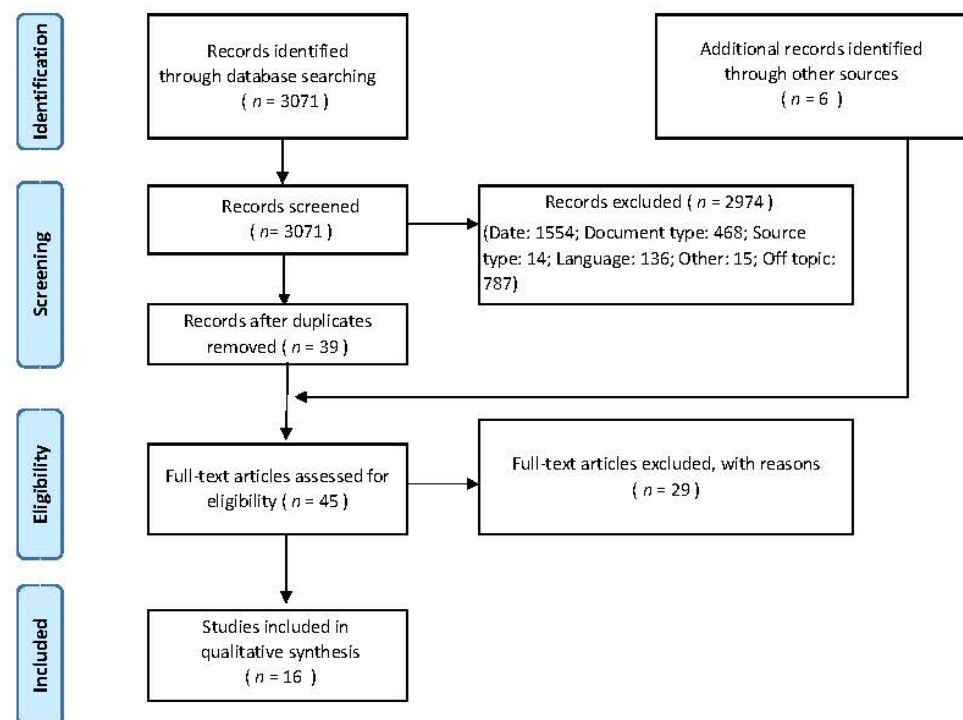


Figure 1. Flow diagram of the research, adapted from Moher et al. [36].

In the eligibility phase, 39 papers were considered, and the full text screened and analysed to design tables with evidence of mining equipment accidents. After applying the inclusion criteria described in the protocol mentioned above, only 10 articles were

included in the qualitative analysis. After analysing their references by title and abstract, and according to the snowballing technique procedures [39], 6 more papers were added to the study, which led to a final inclusion of 16 studies (Figure 1).

Figure 2 shows the density visualisation of some controlled terms automatically found across studies related to accidents, extracted with VOSviewer [41], where the expressions “human error” and “mobile equipment control” are mentioned among the studies, followed by “haul road design” and “accident pattern.” Nonetheless, this map does not represent the full extent of Table 1.

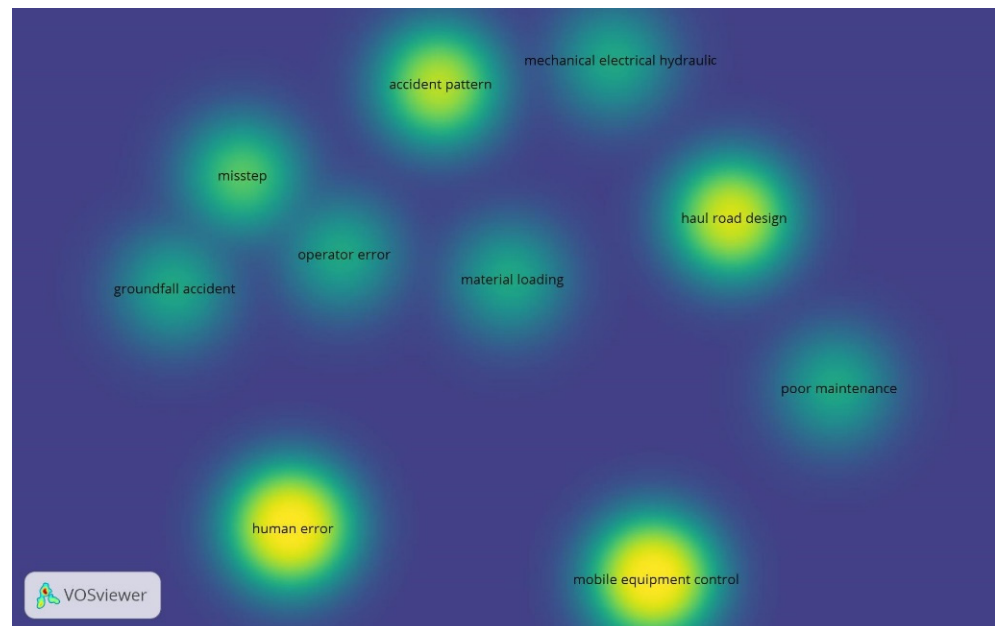


Figure 2. Density visualisation of controlled terms among the studies.

Appendices A and B contain the data extracted from each study. Throughout the analysis, it was possible to divide them into the following source data groups: nine studies used Mine Safety and Health Administration (MSHA) data [6,30,42–48], two used data from the Directorate General of Mines Safety (DGMS) [7,34], one was from the Directorate Technique and Environment of Mineral and Coal (DTEMC) [8], one was from the Shandong Coal Mine Safety Supervision Bureau (SCMSSB) [49], and the other three were case studies [50–52]. As most of the studies collected data from official sources, just one presented some information regarding sample [52]. None used any type of questionnaire or form to extract the data. Different types of equipment were identified across the studies analysed, including haulage truck, front-end loader, nonpowered hand tools, dumper, conveyor, continuous miners, forklift, longwall, dozer, LHD, jackleg drill, and shuttle car. Only nine had a complete link analysis related to both accident causes and type of accident.

Table 1 summarises the most commonly reported accidents occurring with some selected equipment (due to current utilisation in underground and open-pit mines): bolting machine, dozer, dumper, excavator, forklift, haul truck, jackleg drill, LHD, and loader. The causes of the accident can be found in the same table. Although some of the terms may seem related to or even the same as the reported issue, the research team decided to construct the table with the terms used in each study, without clustering them (for example, “collision with another worker” and “collision with pedestrian”).

Table 1. Type of accident and main causes per type of equipment.

| | | Type of Equipment | | | | | | | | |
|--------------------|---|---|---|---|---|--|--|--|---|---|
| | | Bolting Machine | Dozer | Dumper | Excavator | Forklift | Haul Truck | Jackleg Drill | LHD | Loader |
| Causes of accident | Type of accident | Caught between equipment [50]; slip/trip from the equipment [50]; struck by equipment [50]; | Not mentioned | Collision [7]; front run over [7]; reversal run over [7]; | Not mentioned | Not mentioned | Collision with another vehicle [42,45,47]; collision with another worker [45]; collision with pedestrian [42]; contact with public utility lines [42]; fall from vehicle [47]; rollovers [42,45] | fall of ground [46]; | Struck by equipment [50]; caught between [50]; got hit by equipment part [50]; slip/trip from the equipment [50]; | Collision with pedestrian [42]; contact with public utility lines [42]; fall from equipment [48]; replacement of the bucket [42]; rollovers [42]; slope failure [42]; |
| | | <i>Human error</i> -failure to control equipment [44,45]; -operator's fault [34]; -machine reversal [34]; -overloading [34]; -standing on track while operating equipment [43]; -pushing material above hopper while loading [43]; -failure to recognise adverse geological conditions [43]; | <i>Human error</i> -lost control of equipment [7]; -operator's fault [34]; -machine reversal [34]; -overloading [34]; | <i>Human error</i> failure to control equipment [44]; -operator's fault [44]; machine reversal [44]; | <i>Human error</i> failure to control equipment [44]; | <i>Human error</i> failure to control equipment [44]; excessive speed [45]; failure to recognise adverse geological conditions [42]; failure to respect the truck's working area [42,47]; failure to set the parking brake [42,45]; failure to wear seatbelt [45]; failure to regard safety regulations [47]; inadequate hazard training [42,45,47]; lack of and/or failure to obey warning signals [42,45]; operator's health condition [42,45] | <i>Human error</i> failure to control equipment [46]; not removing the loose material [46]; poor worksite preparation [46] | <i>Human error</i> -failure to control equipment [44]; -failure to recognise adverse geological conditions [42,43]; failure to adjust to poor weather conditions [42,43]; failure to respect the loader's working area [42,43]; failure to set parking brake before leaving [43]; failure to wear seatbelt [43]; foot slip [48]; inadequate provisions for secure travel [42]; | | |
| | | <i>Maintenance</i> inadequate maintenance procedures [50]; | <i>Maintenance</i> -inadequate maintenance procedures [34,43]; -failure of mechanical components [43]; | <i>Maintenance</i> inadequate maintenance procedures [34,45]; | <i>Maintenance</i> inadequate maintenance procedures [44]; | <i>Maintenance</i> inadequate maintenance procedures [47]; failure of mechanical components [42,45,47]; | <i>Maintenance</i> inadequate maintenance procedures [46]; | <i>Maintenance</i> inadequate maintenance procedures [50]; | <i>Maintenance</i> inadequate maintenance procedures [34,42,44]; failure of mechanical components [42,43]; | |
| | <i>Design</i> haul road design [34]; lack of visibility [34,44]; failure to provide adequate illumination [43]; failure to provide adequate sign/signal [43]; inappropriate task for equipment [43]; | <i>Design</i> haul road design [34]; lack of visibility [34]; | <i>Design</i> lack of visibility [44]; | <i>Design</i> lack of visibility [44]; | <i>Design</i> lack of visibility [44]; failure to maintain adequate berms [42,45,47]; | <i>Design</i> falling objects [46]; inadequate scaling [46]; | <i>Design</i> lack of visibility [44]; failure to maintain adequate berms [42,43]; failure to provide adequate illumination [43]; lack of warning signs [42]; | | | |

4. Discussion

The analysis given by VOSviewer [41] showed that the controlled terms related to accidents across studies were not very rich. They did not provide a network of concepts and only 10 different clusters were found, apparently with no relation between them. As previously mentioned, the terms “human error” and “mobile equipment control” were most frequent among the expressions found in the analysis, which is consistent with the line of investigation.

The different studies identified mining equipment as one the most significant contributors to accidents in the mining industry, with other causes related to working conditions: work pace, demand, and load, which affect operator behaviour in terms of attentiveness and awareness [16,48,51].

The total number of occurrences of accident by type (Figure 3) and cause (Figure 4) illustrates the scenario within this context: “collision” (between equipment or with pedestrians/workers), seen in Figure 3, is cited most often as an accident cause, followed by “falling from equipment” and “rollover.” Figure 4 shows that the most common reported cause is “inadequate maintenance procedures,” followed by “loss of control of the equipment”.

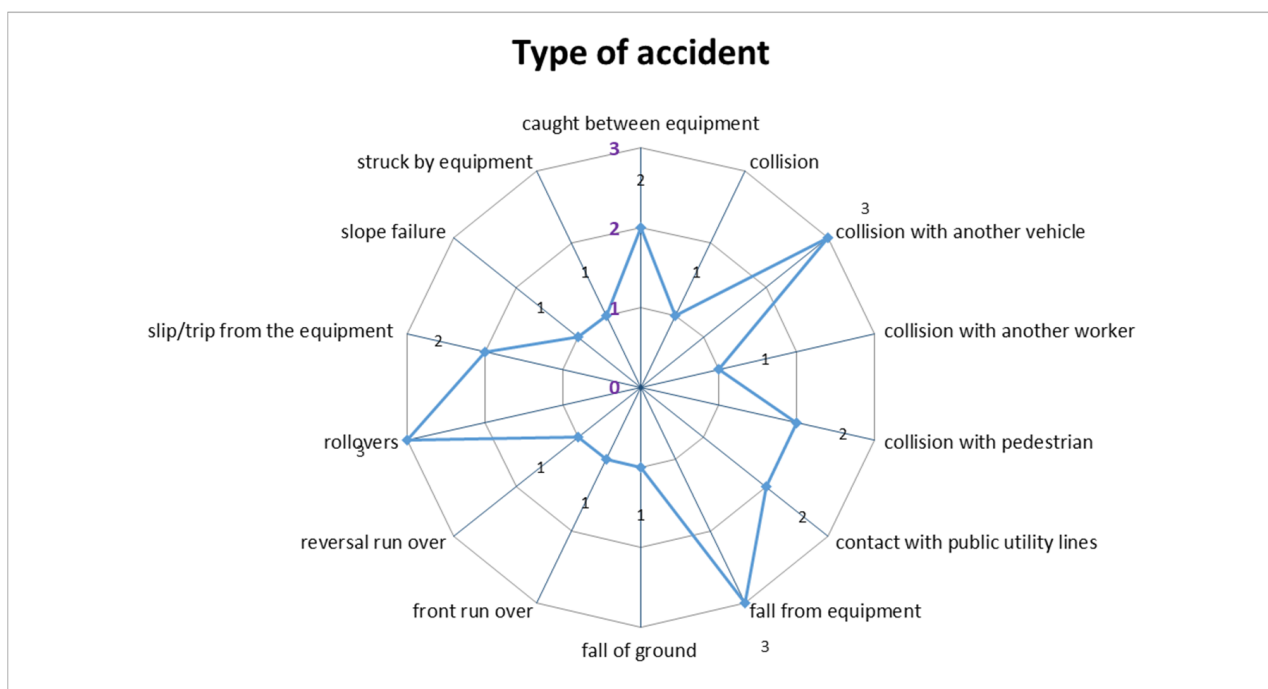


Figure 3. Number of occurrences of accident type in the articles analysed.

Some of the works analysed refer to inadequate engineering design, such as road and ramp design [6,47,49]. Safety education and training are among the critical factors, which suggests that, by improving both aspects, the job competencies would improve, avoiding severe consequences, such as accidents. Supervision and inspection should also be considered when improving safety in relation to human error in coal mine accidents [49].

Some of the causes associated with trucks and loaders were “unsafe and careless actions,” which were also expressed, for instance, as “operator’s fault” [8,47], “failure to recognise adverse geological conditions,” and “failure to respect the equipment working area” [42,43]. “Not maintaining adequate berms,” “lack of warning signs,” and “appropriate mine maps” are terms also found in the papers analysed. Worker behaviours included improper safety level prediction and adverse weather conditions [42,43] that were also stressed as accident root causes. As for surface mining, the leading source of equipment-related fatalities reported in one of the studies was losing control of the vehicle [44]. Mechanical failures, particularly in the brake system, were also pointed

out [42,43,47]. Bonsu et al. [51] identified as accident causes the modifications to equipment and equipment without handles to fit a specific purpose.

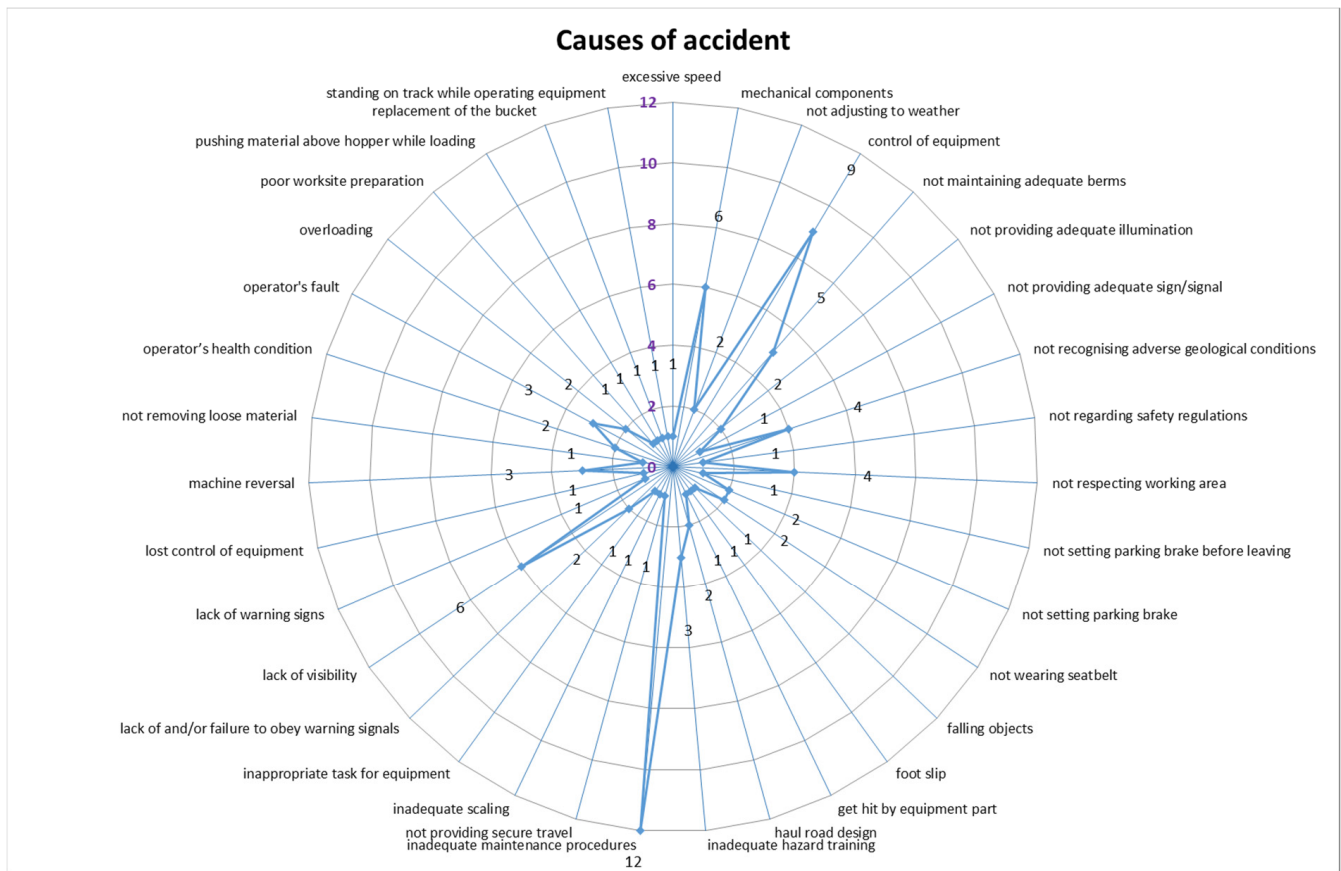


Figure 4. Number of occurrences of accident cause in the articles analysed.

One study reported other root causes of accidents, such as “collision with pedestrians or with another vehicle,” “rollovers,” “contact with public utility lines,” and “slope failure.” Lack of training (37%), failure to wear seat belts (31%), lack of efficient communications (19%), and inability to maintain the haul roads (13%) contributed the most to fatalities [42]. “Struck by” was also a prevalent reported cause [50].

Even though most of the reported accidents are related to transport heavy machinery, such as haul trucks [6,30,45] and dumpers [7,34], jackleg drills are also among the equipment with a higher rate of accidents [46]. Still, concerning mobile equipment (in general), the worker’s visibility is a common issue, regardless of exploitation type [41], which may be related to the equipment’s design and size.

Some studies went further in the accident analysis and concluded that maintenance is the occupational activity with the highest incidence of accidents [43,47,50,52]. Job experience plays a role: approximately 50% of the injured had less than 5 years of experience [30,47]. The estimated risk indexes also showed a higher risk for workers above 55 years old [30].

The most common root cause of the accidents was handling mining supplies (for example, the ones used in bolting tasks), and the consequence was the person, or a body part, getting trapped in the equipment [50]. This category accounts for 54% of the total accidents. The most frequently mentioned material agent for nonfatal damage was “nonpowered hand tools.” Among material agents, off-road and underground machinery were the most common causes leading to death [30].

From an analysis in Table 1, a simplified classification of the causes of accidents into three major groups was adopted: human error, maintenance, and design.

In general, the authors focus on human error, proposing the reinforcement of training to address the problem. In this matter, top management's commitment can play a significant role in identifying critical points that can be bottlenecks to any production increase. In the maintenance component, there are two fundamental problems: inadequate maintenance and mechanical component failure. The latter may be due to inadequate maintenance. Concerning accidents that can be solved by the engineering component, more specifically at the project level, and on which the attention of this work was focused, the articles focus attention on road design. In this context, parameters such as lack of visibility, adequate signage/signalling, and failure to maintain adequate berms are mentioned as causal factors. However, reference to factors such as road layout, width, slope, and conservation state is only circumstantial and without relevant data that can be considered directly for the traffic routes' design. Poor lighting and equipment suited to the tasks were also highlighted.

However, accidents occur as a result of defect(s) in a system, having manifold causalities. In the study of Lundberg et al. [35], the authors discussed the different accident models and scope known in the literature: simple linear system models and complex linear models, as well as complex interactions and performance variability. In simple linear system models, the analysis is considered a cause–effect system and only immediate surroundings are considered [53]. In complex linear system models, based on epidemiological models, there are three variables: a host, an agent, and the environment [54]. Additionally, in other complex systems, concepts include the inevitability of disasters, and in performance variability (resilience engineering), the concept is described as a necessity of the process and not a “threat” to the organisation [35]. Bearing this in mind and considering that, among the eligible papers, the course of action is not pointed out while analysing the results, it is hard to say which are the models used to draw such conclusions.

The risk of bias is provided in Table 2 based on Higgins et al. [40]. As most studies report information from official sources, this means that data collection and presentation had to follow specific standards. Therefore, this standardisation was found to be a “low risk” situation. The same applies to standards application (concerning methodology) and data treatment (concerning results) as the studies had to perform little or no action after data extraction. Sample representativeness was considered an issue in three papers: two did not provide information regarding the analysed equipment and the jackleg drill study. Additionally, reporting and reference quality were checked for potential biases affecting each study's results and conclusions.

Table 2. Study bias analysis.

| Study | Equipment | Methodology | | Results | | Others | |
|-------|---|-------------|-----------------------|---------------------------|----------------|-------------------|-------------------|
| | | Data Source | Standards Application | Sample Representativeness | Data Treatment | Reporting Quality | Reference Quality |
| [42] | Loader, truck | LR | NA | UR | UR | LR | UR |
| [30] | Haulage truck, front-end loader, nonpowered hand tools, conveyor, continuous miner | LR | NA | LR | UR | UR | UR |
| [6] | Haul truck, belt conveyor, front-end loaders, miscellaneous | LR | NA | LR | LR | UR | UR |
| [43] | Loader, dozer | LR | UR | UR | LR | LR | UR |
| [8] | Haul truck | LR | LR | LR | HR | UR | HR |
| [50] | Continuous miner, bolting machine, LHD, longwall, transport, shuttle car, handheld bolters, grader, stone dusting equipment, dolly car, road header, longwall move equipment, gas drainage drilling equipment | LR | NA | LR | UR | UR | LR |
| [44] | Conveyor, bolting machine, milling machine, LHD, front-end loader, continuous miner, crane, crusher, shuttle car, forklift, truck, shovel, hand tools | LR | NA | LR | UR | UR | LR |
| [52] | Not mentioned | LR | NA | LR | LR | LR | LR |
| [34] | Dumper, drilling machine, shovel, loader, dozer | LR | NA | LR | HR | UR | UR |
| [45] | Haul truck | LR | UR | UR | UR | LR | UR |
| [7] | Wheeled vehicles | LR | NA | LR | HR | HR | UR |
| [46] | Jackleg drill | LR | NA | HR | HR | HR | HR |
| [47] | Off-road truck | LR | NA | UR | LR | LR | LR |
| [49] | Not mentioned | LR | NA | HR | LR | LR | LR |
| [51] | Not mentioned | LR | NA | HR | HR | LR | HR |
| [48] | Front-end loader | LR | NA | UR | UR | LR | LR |

HR—high risk; LR—low risk; NA—not applicable; UR—unclear risk.

Study Limitations

Despite the results achieved, a relevant aspect of the study is that most of the records (13 in 16 studies) used data collected from official sources. From those 13, 9 analysed data were from the same source; the only differences relied on the period studied and the general research objective. This resulted in the overlapping of information to an extent that the authors cannot determine. Owing to the nature of the eligible papers, some equipment may be missing from the analysis conducted because this information was not sought (for instance).

The authors' aim was to do more than analysing statistical (general) information provided by official sources. This systematic review intended to collect information on the mining equipment most frequently associated with work accidents (both injuries and deaths) and mainly the root causes (or explanations) found.

Despite analysing (or at least reporting) the different accident root causes, none of the studies reported the accident models used, making interpretation of the results difficult. Additionally, it is known that the result of an accident investigation is often based on the concept "what you look for is what you find," which, ultimately, can lead to the concept "what you find is what you fix," which may be a bigger problem [35,55].

5. Conclusions

5.1. General Conclusions

The analysis indicated that the types of activities and equipment most frequently associated with accidents (both fatal and nonfatal) in mining were the same (for the period

in question) among the eligible articles. The most significant concern is powered haulage: haul trucks and dumpers, followed by conveyor belts. These accidents take place usually during repair and maintenance actions.

One of the approaches to be considered for accident prevention should be identifying and controlling mining hazards, combined with active monitoring, in both equipment operations and maintenance [56]. The operator must fully understand the equipment in advance, being the one to determine whether the vehicle is in proper order before its operation. Likewise, it is essential that the worker is both psychologically and physically fit and not under the influence of any substance (medication or alcohol) that may impair the worker's reaction time or senses [16,31]. All repair and maintenance personnel should be trained in standardised actions since training and education are fundamental in accident prevention [57,58]. Less experienced workers should receive particular attention as they seem to be more susceptible to machine-related accidents [3]. Training programs are proven to diminish the occupational accident rate in this specific group and the general workers' population [59].

Educational programs raising awareness of the use of personal protective equipment and disciplining workers on matters such as ergonomics (of hand-carrying equipment, for instance) show a great deal of promise [58]. As proposed in the literature, these programs should be divided into five steps. The first step is to identify and analyse the problem to be dealt with. Second, an adequate training programme has to be designed, and third, the accompanying materials created and developed. The fourth step is to implement the training, and because this activity is not definite, the programme has to be assessed, and the results have to be interpreted. A powerful tool, which results in significant safety training opportunities, is virtual reality, which can teach without putting the operator in any real danger [22,60]. The latest developments in this technology have created significant opportunities to improve safety amongst mineworkers, supervisors, and managers [12]. Machine learning algorithms would also help predict accidents [13] as studies point out that there are underlying patterns and trends in the accident event [61].

5.2. Practical Applications

The practical applications of such findings may lead to a better design of mining sites, which includes paths, berms, and platform dimensioning for equipment (and pedestrians), and other management considerations, such as traffic patterns to minimise the chance of operator error and operation sequence (related to mining cycles). Overall, this means safety planning beginning in the design phase. Other considerations found are planning operating velocities according to the road/path's conditions, operator's visibility, and when suitable, pedestrian traffic, although this last variable is not highly recommended [33].

Equipment general safety and protective devices should be improved and periodically revised by the manufacturer and, when possible, considered in the design phase to prevent incidents, especially those accidents with dreadful consequences [62]. Additionally, vehicles' obstacle detection sensors should be considered in a similar practice achieved in construction, which would serve as a warning sign for operators and a management level for operation control [63].

Most accidents can be avoided by careful job planning (including workload) and effective communication and information relating to tasks; this can be achieved by establishing a safety and health culture based on a prevention approach [3,57].

5.3. Current Trends and Future of Operation

Despite these results, it is important not to forget that the world is shifting to Industry 4.0, where human-machine interaction is becoming more and more prominent, bringing the system's complexity to a whole new level. In mining, this results in real-time visibility and control of operations, with an integrated system leading to a semismart mine [64]. Additionally, autonomous mining as a concept is slowly growing widely in applications,

such as autonomous LHD vehicles, real-time imaging from processes such as excavation, remote laser cutting (of rocks), among others [27].

This digitalisation leads to “new” jobs in safe and controlled room environments, providing space for workers’ creativity and full expertise, where new collaborative teams are surging [26]. In this context, these data’s visualisation must be easily comprehended and analysed using mixed reality technologies. For instance, virtual reality has been applied to cover mine safety issues, environmental impacts, and machine maintenance [64].

A digital twin (a digital representation of the real mine) may be the key answer to this, allowing the inclusion of the project’s different data layers and the interaction between the different role players [64]. Explicitly related to safety, one sees that the prevention course of action is preferred to protection. However, there is still a lot of ground to cover to implement these collaborative production systems in terms of efficiency, safety, and trustworthiness [26]. This prevention phase can and should be applied, beginning with the design phase of a mine, where all the variables should be analysed separately but considered as a whole.

In future research, it would be interesting to analyse how these technologies shape accident models in terms of new variables that come together with emerging risks and how they influence new operating systems.

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Appendix B

Table A2. Accident-related data extracted from the studies.

| Author, Year | Accident Type | Equipment | Accident Consequences | Main Results | Accident Cause | Prevention | Limitations |
|--------------------------------|----------------------------|---|-----------------------|---|--|--|---------------|
| Kecojevic & Radomsky 2004 [42] | Machine related | Loader, truck | Fatalities | Loader: personnel got hit, struck, or run over, representing 41% of the total fatalities. Truck: rollovers, collision with pedestrian/another vehicle, vehicle repair, or contact with utility lines. | Loader: (1) failure of mechanical components, (2) inadequate maintenance procedures, (3) failure to recognise adverse geological conditions, (4) failure to respect the loader working area, (5) failure to maintain adequate berms, (6) lack of warning signs or appropriate mine maps, (7) inadequate provisions for secure travel, (8) failure to adjust to poor weather conditions. Truck: (1) operator's health condition, (2) failure to obey warning signs, (3) mechanical failure, (4) inadequate procedures, (5) failure to respect working area, (6) failure to recognise adverse geological conditions, (7) failure to maintain adequate berms, (8) failure to set the parking brake, (9) inadequate training | Careful job planning, proper training | Not mentioned |
| Groves et al. 2007 [30] | Machine related and others | Haulage truck, front-end loader, nonpowered hand tools, conveyor, continuous miners | Fatalities, injuries | During the period analysed, a total of 190,940 accidents, injuries, and illnesses were recorded, of which 84% were fatalities. From those, 77% were related to machinery, where most fatalities were due to haulage trucks (16%) and front-end loaders (9%), continuous miners (8%), and conveyor (6%). The remaining events included roof falls (53%), repeated trauma injuries (16%), hoisting accidents (7%), and dust disease (6%). | Poor use of equipment (awkward position, for example) | Development of new interventions and control strategies, for example, vehicles using GPS and radar-based warning systems | Not mentioned |

Table A2. Cont.

| Author, Year | Accident Type | Equipment | Accident Consequences | Main Results | Accident Cause | Prevention | Limitations |
|---------------------------|--|--|-----------------------|---|---|--|---------------|
| Kecojevic et al. 2007 [6] | Machine related | Forklift, longwall, front-end loader, belt conveyor, dozer, LHD, haul truck, shuttle car, miner, drill | Fatalities | Haul trucks (22.3%), belt conveyors (9.3%), front-end loaders (8.5%), and miscellaneous equipment (36.6%). The proportional distribution of the remaining fatalities ranges from 6.2% for continuous miners to less than 1% for hoisting. Collision with pedestrians and rollovers are the most common accidents. | Failure of mechanical components, lack of and/or failure to obey warning signals, inadequate mechanical procedures, inadequate training, poor haulage road and dump design engineering, failure to wear a seat belt | Equipment safety training program (for both surface and underground mining operations), prevention methods | Not mentioned |
| Md-Nor et al. 2008 [43] | Machine related | Loader, dozer | Fatalities, injuries | Loader: there were a total of 43 fatalities for the period analysed. Dozer: there were a total of 30 fatalities for the period analysed. Two of the fatalities were caused by unknown hazards. Therefore, they were excluded from the analysis. | Failure to follow adequate maintenance procedure, failure of mechanical/electrical/hydraulic component, failure to identify adverse geological/site conditions, failure to respect equipment working area, failure to provide an adequate sign, failure to set the parking brake (before leaving equipment), failure to provide adequate illumination, failure to wear a seat belt, unfavourable weather conditions, failure to provide adequate berm, failure to control equipment, an inappropriate task for equipment, pushing material above hopper while loading | Risk control and implementation of control measures | Not mentioned |
| Permana 2010 [8] | Machine related, people transportation, fire, explosives | Not specified | Fatalities, injuries | The number of mine accidents increased during the period analysed. The higher-risk locations are mine pit and workshop, and "substandard tools" were considered the sources of mine accidents. | Not following the safe working procedure or standard operating procedure, workers' lack of awareness of working safely | Mine accident risk analysis, corrective action in the safety management system | Not mentioned |

Table A2. Cont.

| Author, Year | Accident Type | Equipment | Accident Consequences | Main Results | Accident Cause | Prevention | Limitations |
|----------------------------|-----------------|--|-----------------------|--|--|--|---------------|
| Burgess-Limerick 2011 [50] | Machine related | Continuous miner, bolting machine, LHD, longwall, transport car, shuttle, handheld bolter | Injuries | From the reports analysed, equipment-related accidents accounted for 46% (2149) of the total accidents (4633). Continuous miner (555 accidents), bolting machine (257 accidents), LHD (351 accidents), longwall (332 accidents), transport (194 accidents), shuttle car (152 accidents), handheld bolters (115 accidents), and the remaining accidents were due to miscellaneous equipment (graders, stone dusting equipment, dolly cars, road headers, longwall move equipment, and gas drainage drilling equipment). | Roadway abnormalities, striking part of the equipment, struck by falling objects, some part of the person caught between moving parts of the equipment, handling various objects (bolting supplies, for instance), maintenance actions, access to the operating platform | Proximity detection systems, redesign of platforms, improving roadway maintenance, improving vehicle maintenance | Not mentioned |
| Ruff et al. 2011 [44] | Machine related | Conveyor, roof bolting machine, haulage truck, milling machine, LHD, front-end loader, continuous miner, crane, crusher, shuttle car, forklift, truck (not haulage), dragline, bulldozer, hand tools, locomotive | Fatalities, injuries | A total of 562 accidents were reported: coal mining (242 accidents), stone (136 accidents), sand and gravel (83 accidents), nonmetal (53 accidents), and metal mining (48 accidents). From the 562 accidents, 259 occurred during the machine's operation, 139 occurred during maintenance or repair actions, and 34 accidents occurred while handling supplies or materials. At surface mining, the top 3 types of stationary equipment involved in accidents were conveyors, milling machines, and crushers, where the most common activities during the accident were maintenance and repair actions. As for moving equipment, trucks, loaders, scrapers, and dozers were the most mentioned equipment. | Equipment control loss, brake failure, operator error, operator visibility issues, collision with pedestrians, collision with other vehicles, maintenance and repair actions | Proximity warning systems, improved visibility, operator fatigue detector, detection of edges, improved training, emergency stop buttons | Not mentioned |

Table A2. Cont.

| Author, Year | Accident Type | Equipment | Accident Consequences | Main Results | Accident Cause | Prevention | Limitations |
|-------------------------|----------------------------|-------------------------------|-----------------------|---|---|--|---------------|
| Onder 2013 [52] | Machine related and others | Not specified | Fatalities, injuries | There was a reduction in the number of accidents over the period analysed; there was also a decrease in the number of workers. This study determined five categories of accident: mining machine (39.2%), machinery (25%), manual and mechanical handling (16.7%), hand tools (11.9%), and struck by/falling object (7.2%). | Hitting a moving object, hitting a nonmoving object, falling of an object, repair/maintenance actions, cutting with hand tool | Training, use of personal protective equipment | Not mentioned |
| Kumar & Ghosh 2014 [34] | Machine related and others | Dumper, shovel, loader, dozer | Fatalities, injuries | The distribution of accidents due to different equipment was as follows: dumper (59%), shovel/dragline (10%), tankers (10%), other heavy earthmoving machines (9%), loading machine (5%), drilling machine (2%), and other equipment (5%). | Machine reversal, haul road design, improper maintenance, human fault, operator fault, machine fault, visibility, overloading, dump design | Mine management | Not mentioned |
| Zhang et al. 2014 [45] | Machine related | Haul truck | Fatalities, injuries | Fault tree analysis was used in 12 truck reports, where the main root causes for the accident were sought. | Inadequate/improper preoperational check, poor maintenance, inadequate training, excessive speed, not following standards, brake control problems, inadequate proceeding, no seat belt provided | Training new operators, predictive maintenance | Not mentioned |
| Dash et al. 2015 [7] | Machine related | Dumper | Fatalities, injuries | Accidents related to wheeled trackless transportation system are still of concern despite all measures taken to improve the situation. | Reversal run over, front run over, lost control, collision | Not mentioned | Not mentioned |
| Clark et al. 2016 [46] | Machine related | Jackleg drill | Fatalities, injuries | Fifty-nine mines reported at least one jackleg drill incident during the analysed period: 54% were in metal mines, 31% in coal mines, and 15% in nonmetal mines. A total of 483 incidents involving this equipment were reported. | Fall of ground, failure to control equipment, falling objects, inadequate maintenance procedures, inadequate scaling, not removing the loose material, poor worksite preparation | Not mentioned | Not mentioned |

Table A2. Cont.

| Author, Year | Accident Type | Equipment | Accident Consequences | Main Results | Accident Cause | Prevention | Limitations |
|-----------------------------|----------------------------|------------------|-----------------------|--|---|--|---|
| Dindarloo et al. 2016 [47] | Machine related | Off-road truck | Fatalities, injuries | Off-road truck-related accidents reported 125 severe records, where 88 were fatalities and 52 led to permanent disabilities. | Losing control of the truck, berm/dump failure, truck/component, mechanical failure, maintenance/repair actions, failure to regard safety regulations, failure to block off/lock out the truck/bed, exiting the cab while operating the equipment | Not mentioned | Not mentioned |
| Zhang et al. 2016 [49] | Machine related and others | Not specified | Fatalities, injuries | Over the period analysed, the number of accidents decreased. Three influencing factors leading to accident were identified: lack of training and safety education, rules and regulations of safety production responsibility, and rules and regulations of supervision and inspection. | Unsafe operator behaviour, unsafe condition of equipment, unsafe condition of environment, unsafe condition of rules and regulations | Not mentioned | (1) The sample size was too small; (2) accidents were put into the same accident category, ignoring the type of accident. |
| Bonsu et al. 2017 [51] | Machine related and others | Not specified | Fatalities, injuries | The tasks more commonly associated with accident were drilling (25%), engineering tasks (24%), transportation of people (11%), and manual handling (11%). The accident causality analysis showed that “poor leadership” is the root cause of most of the violations identified. | Falls of ground, falling of material/rolling rock, slipping and falling, manual handling of material | Not mentioned | The authors could not determine the authenticity of the accident reports. |
| Nasarwanji et al. 2017 [48] | Machine related | Front-end loader | Injuries | The total number of incidents was 1457, of which, 924 occurred during front-end loader egress, 367 occurred during ingress, 70 occurred during maintenance actions, and 96 were “other tasks” or unknown tasks. | Contaminants on equipment, ground conditions | Inspecting ingress and egress systems; preventing uneven terrain, rocks, or slippery surfaces; providing adequate lighting | The numbers may not be representative, and the limited description occasionally leads to biased coding. |

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