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Research Article

Analysis and Prevention of Workplace Injuries Using a Situational Model of an Accident

Vadim Derevyansky*

Coal Dust Research Laboratory, State-financed Institution «Makeyevka Safety in Mines Research Institute», Makeyevka, Russian Federation

Abstract

Known accident models do not provide an explanation for why working in violation of safety regulations does not always result in injury. Theoretical research has been conducted, and a situational accident model has been developed that provides such an explanation. According to this model, the condition for an employee's injury is the presence in the production system of a specific combination of violations of regulatory safety requirements (causes of an accident) and a negative random factor. The combination of violations (causes) is called a "traumatic situation". Since the direction of the random factor can only be detected after the event has occurred, and it is impossible to predict or control it in advance, it is advisable to use an incomplete situational model of an accident that does not take into account the random factor to solve practical problems of injury prevention. An analysis of work-related injuries that occurred in coal mines due to various hazardous production factors (excluding cases of natural health deterioration and criminal incidents) using the obtained model revealed that the exclusion of at least one cause from the injury situation makes it impossible for a person to be injured; the number of violations (causes) can vary from one or more in different situations; and one injury situation can be repeated in different cases of injury. The results of theoretical research have allowed us to formulate a situational approach to managing the safety of an industrial system, which is based on the fact that "prevention of violations of regulatory safety requirements" and "prevention of accidents" are not identical concepts. Prevention of injuries is much simpler, as it does not require the prevention of all safety violations, but rather focuses on preventing the occurrence of at least one cause in a situation where an individual is injured. Within a single production system, injuries occur due to various hazardous production factors and a variety of situations. This variety includes more or fewer injury situations for different production systems, but it is always a finite set. At the same time, the same violations (causes) are repeated in different situations. By preventing one such violation (cause), it is possible to prevent injuries in several different situations. The possibility of preventing accidents by following just one safety requirement is demonstrated in the example of preventing injuries during the repair of belt conveyors in coal mines.

Keywords

Accident, Situational Model, Reason, Violation of Regulatory Requirements for Occupational Safety, Production System

*Correspondence: Vadim Derevyansky (maknii.niot@mail.ru)

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1. Introduction

The effectiveness of occupational injury prevention work largely depends on the available knowledge about this dangerous phenomenon and on how this knowledge is used in practice. The analysis of ways to further improve preventive work has shown that a promising area is the study of the laws (regularities) of accidents and the development of effective methods, ways, and means of ensuring safety based on these laws. The assumption that there are such laws (regularities) that are common to different cases of injury to people caused by different hazardous production factors (exposure to machines and mechanisms, electric shock and other types of energy, falls from a height, etc.) is based on the fact that each accident, regardless of the traumatic factor, is a specific manifestation of the same phenomenon called "injury".

Currently, there are many laws (regularities) of trauma, the authors of which present them in the form of models, theories, and concepts. This is stated in literary sources, in particular [1-12]. Some models (theories, concepts) describe the stages (phases) of an accident, others describe human behavior in hazardous conditions, still others reveal the cause-and-effect relationships of dangerous incidents, and still others are a methodological tool for studying events or generating injury statistics. All of them are designed to describe the mechanisms of accidents and solve research problems related to creating safe working conditions and preventing injuries among employees. Here are some examples:

1) The "Pure Chance" Theory (Greenwood and Woods), according to which accidents are a matter of fate and therefore cannot be prevented;
2) Domino Theory (Herbert W. Heinrich) is considered a "classic model of an accident" and is based on the "sequence of events concept," which states that an injury is the result of a series of events, each of which is a consequence of the previous event and a cause of the subsequent event;
3) The accident model, based on the "concept of multi-line event chains" (L. Benner), begins with a disruption in the human-machine interaction, which leads to a loss of balance between the demands of the work and the capabilities of the workers. This disruption changes the normal situation for the workers into a difficult one, increasing the risk of an accident;
4) The "Swiss Cheese" Model (James Reason) explains that an accident occurs when hidden dangerous conditions overlap at different levels of human decision-making and action;
5) Fault Tree Analysis (FTA) models of accidents have become widely used.

The analysis showed that the known models (theories, concepts) do not answer the question of why working with violations of regulatory requirements of occupational safety (hereinafter referred to as violations for short) does not always end in injury. Why in some cases, when working with violations, there was an accident, and in others (which are much more numerous!) – not? The answer to this question will allow to increase the efficiency of work to prevent occupational injuries. Therefore, it is necessary to conduct theoretical research and build a model of an accident, explaining why work with violations does not always end in injury.

2. Materials and Methods

The search for possible methodological approaches to solving the problem has shown that it is advisable to use classical logic. The logical conditions for an accident are formulated based on the following principles. Each case of occupational injury occurs within a specific production system, which can include a workplace, facility (section, workshop, etc.), or an entire enterprise. As practice shows, violations lead to the injury of an employee, which act as the causes of an accident. At the same time, work with violations does not always end in an injury. This indicates the existence of a condition of sufficiency of violations (causes) for the occurrence of an accident. Let us examine this pattern of the phenomenon of injury on the example of the act of investigation of a specific accident that occurred in a coal mine. Since the developed model is designed to prevent injuries from almost all hazardous production factors (with the exception of workers' unexplained disappearances during working hours, their natural deaths, and criminal incidents, which have their own specific nature of occurrence), the investigation act was selected randomly, "blindly".

3. Results

An accident investigation report was selected for an accident that occurred under the following circumstances and for the following reasons. The victim (a miner) left his workplace without permission before the end of his shift and headed towards the elevator shaft to exit the mine. On the way, he got into the rear cabin of a two-cabin electric locomotive that was carrying a batch of trolleys to the mine shaft. At a switch, the electric locomotive derailed, and the victim was crushed and severely injured by a falling battery. The causes of the accident were:

1) unauthorized early termination of work by the victim without the permission of an engineering and technical specialist;
2) unauthorized boarding of the victim into the rear cabin of an electric locomotive;
3) the electric locomotive driver allowed an unauthorized person to travel in the rear cabin of the electric locomotive;
4) unsatisfactory condition of the railway facilities;
5) the engineering and technical staff of the department

where the victim works failed to ensure compliance with production discipline in the shift they were in charge of;
6) insufficient level of control over production discipline by the engineering and technical staff of the mine transport section.

In order to simplify theoretical research, it is acceptable to exclude the lack of compliance with production discipline and the insufficient level of control over production discipline by engineering and technical personnel from further consideration, since in this case these violations have a causal relationship with violations of occupational safety requirements by the victim and the electric locomotive driver (i.e., they act as second-order causes – causes of causes); they cannot be considered as causes of the failure to eliminate violations in a timely manner before the employee was injured, since the victim and the electric locomotive driver did not have these engineering and technical personnel present at the time of the violations.

The condition of sufficiency of violations (causes) for an accident to occur is formulated using the principle of proof by contradiction, in terms of natural language, using logical implication, which is a conditional statement of the form "if..., then...":

1) "If the victim did not leave the workplace early, they were not in the cab when the electric locomotive derailed, and they were not injured by the moving battery box";
2) "If the victim left the workplace early but did not get into the cab of the electric locomotive, they were not in the cab when the locomotive derailed, and they were not injured by the moving battery box";
3) "If the victim left the workplace early and got into the cab of the electric locomotive, but the driver stopped the locomotive and let the victim out of the cab, the victim will not be injured by the battery box that moves when the locomotive goes off the track";
4) "If the victim left the workplace early, got into the cab of the electric locomotive, and the driver did not stop the locomotive and did not let the victim out of the cab, but the track meets the regulatory requirements, then the electric locomotive did not leave the track, and the victim was not injured by the moving battery box".

Thus, in order for this accident to occur, all four causes must be present. If any of the causes is excluded from the list, the miner's injury becomes impossible. This leads to the condition of sufficiency of violations (causes) for an accident to occur: not any combination of violations (causes) leads to an accident, but only a specific combination. This combination is referred to as the "injury situation" and is denoted by the symbol K. It is described by the elementary conjunction (logical product) of the violations (causes):

$$K=x_1 \wedge x_2 \wedge ,\ldots, \wedge\ x_r = \wedge^{r}_{i=1}\ x_i,$$

where $x_1, x_2, \ldots, x_r$ – violations (causes);

r – number of violations (causes) in the situation of injury (conjunction rank);

i – the sequence number of the violation (cause) in the situation;

$\wedge$ – logical multiplication (conjunction) symbol.

Along with the causes, in the accident under consideration, as in all cases of industrial injury, there is a factor of chance. In the book [13], David Bohm writes: "In order to more accurately express what is meant by chance, we can consider a typical random event, namely a car accident. It is now clear that the location, time, and nature of a car accident depend on a vast number of factors, and a small change in any of these factors could have a significant impact on the nature of the accident or even prevent it from happening at all. For example, in the case of a collision between two cars, if one of the drivers had left the road ten seconds earlier or later, or if he had stopped to buy cigarettes, or slowed down to avoid hitting a cat crossing the road, or for any of an unlimited number of similar reasons, the accident might not have happened at all. Additionally, even a slight change in the direction of the steering wheel could have prevented the accident or completely altered its outcome, either for better or for worse. We see that in relation to the circle of phenomena in which we, for example, consider the actions and precautions that can be taken by a particular driver, every accident has a random side". The author of the work [13] concludes: "We see that it is correct to speak of objectively valid laws of chance, which tell us about a side of nature that is not fully described by causal laws alone. In fact, the laws of chance are as necessary as the causal laws themselves." In other words, chance exists objectively.

Based on the work [13] and the available knowledge about occupational injuries, it can be concluded that there is a directional property of the randomness factor: negative directionality (symbolized by the letter "C" and the minus sign: C^-), when the randomness factor contributes to the occurrence of an accident, and positive directionality (symbolized by the plus sign: C^+), when the randomness factor allows the employee to avoid injury even in the presence of an injury-prone situation.

In the example of the miner's injury, the negative randomness factor manifested itself as follows:

1) the electric locomotive could have passed a little earlier or later than the time when the miner was walking in the mine, and the miner could have arrived a little earlier or later than the time when the electric locomotive passed (in both cases, the miner would not have encountered the electric locomotive or had the opportunity to board it);
2) not every derailment of an electric locomotive is accompanied by the battery box sliding.

Based on the above, a "situational accident model" is constructed:

$$(K \wedge C^-) \rightarrow A \qquad (1)$$

where $\rightarrow$ – implication sign ("if... then");

A – accident.

Model (1) is described by the following logical statement:

"if a situation of injury and a negative random factor occur in the production system, then an accident occurs".

Practice shows that the frequency of C^+ is much higher than C^-, but the direction of the randomness factor is detected only after the event has occurred and it is impossible to predict (and control) it in advance. Therefore, to solve the problems of injury prevention, the randomness factor should be excluded from model (1) and an incomplete situational accident model should be used:

$$K \rightarrow A \quad (2)$$

An analysis of occupational injuries in coal mines due to various hazardous production factors using an incomplete situational model (2) revealed the following patterns of accidents:

1) not any, but only a certain combination of violations (causes) leads to each injury – the situation of injury;
2) the exclusion of at least one cause from this situation makes it impossible for a person to be injured;
3) the number of violations (causes) in different situations can vary, from one or more;
4) one situation can be repeated in different cases of injury.

The results of theoretical studies of the patterns of injuries, which consist in the existence of a sufficient condition for violations (causes) to occur, have allowed us to formulate a situational approach to managing the safety of an industrial system. This approach suggests that "preventing violations of regulatory safety requirements" and "preventing accidents" are not identical concepts. Preventing injuries is much simpler, as it does not require preventing all violations of safety requirements. Instead, it focuses on preventing at least one cause in a situation where an injury occurs. As practice shows, within the same production system, injuries occur due to various hazardous production factors and a variety of situations. This set for different production systems includes more or fewer injury situations, but it is always a finite set. In this case, the same violations (causes) are repeated in different situations. By preventing one such violation (cause), it is possible to prevent injuries in several different injury situations. Therefore, in order to prevent injuries in the production system, it is sufficient to prevent only a limited number of violations (causes), which in most cases is less than the number of injury situations in this production system.

A set of injury situations in a production system is conventionally referred to as the system's hazard function. By analyzing the investigation reports of injuries caused by various hazards in a specific production system, it is possible to establish a comprehensive list of injury situations and use them to create a logical matrix $y(x_i)$ representation of the system's hazard function [14, 15].

Given the variety of causes of injury and the circumstances surrounding them, the task of accident prevention requires simplification, which can be achieved through a situational approach. The ultimate case of such simplification is the elimination of the possibility of an employee being injured, not just in a few situations at once, but in general, for the entire hazardous factor (the equipment being used, the type of work being performed by the victim, etc.), by complying with just one safety requirement. Since such a task is not assigned to equipment designers and developers of work technologies, it is extremely rare in practice, and most likely does not occur intentionally. Let us give such an example.

The analysis of fatal injuries on belt conveyors in coal mines showed that accidents occur during seven types of work: conveyor maintenance, crossing the conveyor, moving on a cargo and passenger conveyor, etc. It is possible to prevent injuries by following one safety requirement only during repair work (the results of the situational analysis are shown in Table 1).

Table 1. *Results of situational analysis of the causes of fatal injuries during the repair of belt conveyors in coal mines.*

Situation number (K_i)	An employee's injury situation	The cause of the accident (x_i)
1	Performing repairs with the drum guard removed and the conveyor running	Failure to shut down the conveyor before repairs are carried out (x_1).
		The victim is in the danger zone of the rotating (moving) conveyor elements (x_2).
		Removing the drum guard before carrying out repair work (x_3).
		A malfunction of the lock that prevents the conveyor from operating when the drum guard is removed (x_4).
2	Performing repair work while using non-factory drum guards and a running conveyor	Failure to shut down the conveyor before repairs are carried out (x_1).
		The victim is in the danger zone of the rotating (moving) conveyor elements (x_2).
		Use of non-factory-made fencing that does not completely cover the dangerous area of the rotating drums (x_5).
3	Repair work is	Removing the drum guard before carrying out repair work (x_3).

Situation number (K_i)	An employee's injury situation	The cause of the accident (x_i)
	carried out with the drum guard removed and the conveyor warning alarm malfunctioning	A malfunction of the lock that prevents the conveyor from operating when the drum guard is removed (x_4). Faulty conveyor activation warning system (x_6). Failure to take organizational and technical measures to prevent the conveyor from being turned on during repair work (the control equipment, cable-rope switch, starter, and "Do not turn on – people are working!" sign are not blocked) (x_7). Inconsistency in the actions of employees, which led to the conveyor being turned on during its repair (x_8).
4	Carrying out repair work with the drum guard removed and the conveyor warning alarm in good working order	Removing the drum guard before carrying out repair work (x_3). A malfunction of the lock that prevents the conveyor from operating when the drum guard is removed (x_4). Inconsistency in the actions of employees, which led to the conveyor being turned on during its repair (x_8). The victim did not leave the danger zone (became confused, did not have the opportunity, etc.) after the conveyor warning alarm was activated (x_9).
5	Performing repair work using non-factory drum guards and a malfunctioning conveyor activation warning system	Use of non-factory-made fencing that does not completely cover the dangerous area of the rotating drums (x_5). Faulty conveyor activation warning system (x_6). Failure to take organizational and technical measures to prevent the conveyor from being turned on during repair work (the control equipment, cable-rope switch, starter, and "Do not turn on – people are working!" sign are not blocked) (x_7). Inconsistency in the actions of employees, which led to the conveyor being turned on during its repair (x_8).
6	Performing repair work using non-factory drum guards and a working conveyor warning alarm	Use of non-factory-made fencing that does not completely cover the dangerous area of the rotating drums (x_5). Failure to take organizational and technical measures to prevent the conveyor from being turned on during repair work (the control equipment, cable-rope switch, starter, and "Do not turn on – people are working!" sign are not blocked) (x_7). Inconsistency in the actions of employees, which led to the conveyor being turned on during its repair (x_8). The victim did not leave the danger zone (became confused, did not have the opportunity, etc.) after the conveyor warning alarm was activated (x_9).

As in the previously cited case of an electric locomotive driver being injured in the cab, there are other reasons for the injuries listed in the table, such as the lack of supervision by the site's engineering and technical staff, the victim's intoxication, the assignment of repairs to a trainee electrician without the presence of an instructor, and so on. The injuries listed in Table 1 are typical, and the presence of other causes does not affect the results.

The data in Table 1 allowed us to create a hazard function for the production system during belt conveyor repair in the form of a logical matrix:

$$y(x_1, x_2, \dots, x_9) = \begin{vmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \end{vmatrix} = \begin{vmatrix} x_1x_2x_3x_4 \\ x_1x_2x_5 \\ x_3x_4x_6x_7x_8 \\ x_3x_4x_8x_9 \\ x_5x_6x_7x_8 \\ x_5x_7x_8x_9 \end{vmatrix} \tag{3}$$

From matrix (3), it is clear that in order to prevent injuries to workers during the repair of a belt conveyor, it is sufficient to prevent two causes: x_1 or x_2, as well as cause x_8. However, the solution to the problem of preventing such injuries can be further simplified. Since the conditions for an accident are the failure to turn off the conveyor before repairs are carried out and the turning it on during repairs due to uncoordinated actions, it is necessary to stop the conveyor and block the possibility of turning it on by any available technical means (device) located within direct line of sight from the repair site, so that no one can unlock and turn on the conveyor without the knowledge of the workers carrying out the repairs. There is a technical possibility to comply with this requirement: the conveyor can be stopped and its activation blocked using the conveyor control unit (remote control) located near the repair site. Cable-rope switches mounted along the conveyor bed have the same functions. Now, no matter what unforeseen events occur, it is impossible to injure the repair personnel, as there are no conditions for turning on the conveyor.

Applying a situational approach to the analysis and prevention of accidents will allow us to take a fresh look at the existing system of preventive measures to prevent occupational injuries. By conducting such an analysis by type of work, it is possible to redesign the technologies used to perform the work in such a way that the minimum set of safety requirements (ideally, just one requirement) will ensure that the worker is not injured, even if there are sudden malfunctions or unexpected disruptions in the production process.

The situational approach to injury prevention is based on the principle of simplicity and effectiveness.

To assess the impact of causes on injuries using quantitative indicators, a logical-probabilistic method can be used, which allows calculating the "weight" of causes based on the logical matrix (3) [14, 15].

4. Conclusions

Theoretical research has been conducted, and a situational model of an accident has been developed, according to which the condition for an employee's injury is the presence in the production system of a specific combination of violations of regulatory safety requirements (causes of an accident) and a negative random factor. The combination of violations (causes) is called a "traumatic situation." Since the direction of the random factor is only revealed after the event has occurred, it is advisable to use an incomplete situational model of an accident that does not take into account the random factor when solving problems of injury prevention. The results of theoretical research have allowed us to formulate a situational approach to managing the safety of an industrial system, which is based on the fact that "prevention of violations of regulatory safety requirements" and "prevention of accidents" are not identical concepts. Prevention of injuries is much simpler, as it does not require the prevention of all safety violations, but rather focuses on preventing the occurrence of at least one cause in a situation where an individual is injured. Within a single production system, injuries occur due to various hazardous production factors and a variety of situations. At the same time, the same violations (causes) are repeated in different situations. By preventing one such violation (cause), it is possible to prevent accidents in several different situations. For example, when repairing belt conveyors in coal mines, it is possible to prevent accidents by following only one safety requirement: it is necessary to stop the conveyor and block its activation by any available technical means (device) located within line of sight of the repair site, so that no one can unlock and activate the conveyor without the knowledge of the workers performing the repair.

Author Contributions

Vadim Derevyansky: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing

Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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