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Research paper

Association analysis of human error causes of electric shock construction accidents in China

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Abstract: Electric shock accident is one of the main causes of fatal construction accidents. In this study, 101 electric shock accidents are analyzed to mine the potential associations of human errors. The modified Human Factors Analysis and Classification System (HFACS) is used to classify human factors of accident causes. Characteristics and potential causes of the accidents are identified by employing frequency analysis. Chi-square test and Apriori algorithm are utilized to explore the associations among the causes. Some significant association between any of two factors are shared. According to association rules using three criteria: support (S), confidence (C) and lift (L), the two key paths are extracted based on the hierarchy of the HFACS. One is: organizational process loopholes → failed to correct problem → perceptual and decision errors ($S = 0.11$, $C = 0.423$, $L = 1.02$), and the other is: organizational process loopholes → poor skill level of workers → routine violation ($S = 0.149$, $C = 0.789$, $L = 1.945$). Managerial implications are proposed to prevent or reduce accidents based on interconnections of factors and key paths.

Keywords: construction, occupation safety, human error, electric shock accident, association analysis

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1. Introduction

Falls, electrocution, struck-by, and caught-in/ between are the four leading causes of death for construction workers. They are named the "fatal four". In China, about 80.72% of the total number of deaths were caused by "fatal four" from 2012 to 2017, and electrocution accounted for 3.1% of the fatal accidents [1]. In the United States, 47.1% of fatal electric shock were from the construction industry from 2004 to 2013 [2]; In the United Kingdom, about 6.0% of fatal accidents were caused by electrocution [3]. The proportion of electric shock accidents in the construction industry is heavy, and the risk of electric shock damage to workers is also high [2, 4, 5].

Human factors are widely known to be the main causes for the majority of accidents in different industries [6]. In order to prevent electric shock accidents and improve the safety of workplaces, it is important to understand the main causes of human error and their associations. This study includes three objectives: (1) to analyze the human factors resulting in electric shock accidents by adopting the modified HFACS, (2) to identify the key path of electric shock accidents caused by human error, (3) to prevent electric shock accidents by proposing interventions.

2. Literature review

2.1. Electrocution

Some scholars have analyzed the causes of electric shock accidents and proposed potential intervention measures. Taylor and Valent [7] conducted a statistical analysis of the 1992–1999 electric shock accidents and investigated the effects of gender, age, race, season, company size and industry. Suárez-Cebador et al. [8] provided a statistical description of the characteristics of workers who had experienced electric shock in the construction industry, such as age, occupation, and length of service. As a result, specific training program needs to be provided to protect workers. Chi et al. [9] conducted a classification analysis of 255 electric shock accidents in Taiwan based on individual factors, task factors, environmental factors, and management factors. They classified those accidents into five patterns, and accident causes and prevention measures were presented according to common scenarios of each pattern. Lucas et al. [10] proposed a safety training program of electrical safety using virtual environment simulation, which can cultivate workers' cognitive ability and safety awareness. Zhao et al. [11] evaluated 486 control measures of electrical hazards based on text analysis and data analysis. They identified that workers' behavior control was still the most effective measure to prevent electric shock. Chan et al. [12] utilized bayesian network to analyze the causes of electric shock and mechanical injury accidents in three categories: safety climate factors, personal factors and dependent variable. Findings revealed that increased safety attitude and safety procedures can effectively reduce accidents. Chi et al. [4] used Chi-Square Automatic Interaction Detector (CHAID) to classify and analyze the causes of electrocution accidents involving 250 deaths in Taiwan from 1996 to 2002 and formed a flow diagram to explain the mechanism of the accident.

2.2. Association analysis

Association analysis is an effective method for mining hidden relationships in large amounts of data. Some traditional statistical methods are utilized to analyze the connections among accident characteristics. Chi et al. [13] adopted Spearman's rank correlation, Cramer's and Phi coefficients to analyze 784 work-related single electrical fatalities in 1999 and 2000, and found the interrelationships among the causes such as age, gender, experience and so on. Cheng et al. [14] used the Chi-square test, Goodness-of-fit test, Independence test, and Homogeneity test to examine significance of factors in the Taiwan construction industry. Robert et al. [15] used the Chi-square test and the odds ratio to analyze occupational accidents with agricultural machinery, and identified the association of processes, causes, the type of injury and the affected body parts in Australia. Although the traditional statistical method can explain the association between the two factors, it can not find the potential path of the accident from a holistic perspective. Therefore, some scholars begin to conduct quantitative path analysis on three or more influencing factors. Verma et al. [16] excavated 35 meaningful association rules based on the analysis of 843 steel plant accident cases in form of injury, near miss, and property damage or in combination. Guo et al. [17] used a large number of photos reflecting unsafe behaviors on the construction site as data sources to study the association rules of unsafe acts in subway construction. Antonio Trillo Cabello et al. [18] conducted an association rule data mining of Spain's 1,525,865 construction accidents during 2003–2015 to explore the relationship among accident factors.

Although, there are several studies on association rule mining conducted in safety data analysis, but few studies pay attention to the relationships among direct and indirect causes for construction fatalities. Furthermore, no study focus on the associations for the electric shock accidents.

3. Methodology

3.1. Data

101 investigation reports of electric shock fatal accidents in construction industry that occurred between 2012 and 2017 in China are analyzed. These data are collected by the author from the Ministry of Housing and Urban-Rural Development (MHURD) and Safety Supervision Bureau of each province. In these accidents, the number of deaths is 115, the number of minor injuries is 7 and the number of serious injuries is only 1, 92% of accidents are only one fatal victim. These reports elaborate on the information of the project profile, the basic situation of victim, the accident process, direct and indirect reasons of the accident, the division of responsibility for the accident and the suggestions for punishment. The greatest value of data is that they are summarized and refined by the professionals of construction industry. Therefore, there is good reason to believe that data are reliable and valid.

3.2. The modified HFACS

The effective use of accident causation models can identify the sources of accidents and ultimately reduce or eliminate accidents [19]. Various models have different perception of the accident process. Especially, the HFACS is more detailed than other accident causation models, and it has the strong point of classifying the human factors of accident causes [20]. HFACS is based on the “Swiss-Cheese” model including four levels: 1) organizational influences, 2) unsafe supervision, 3) preconditions for unsafe acts and 4) unsafe acts, and each level contains several causes, which provides a comprehensive analytical framework for human error analysis [21, 22]. Reason [23] considered an accident occured when the holes in the different slices aligned to allow the hazard to passes through each slice of defense. Garrentt and Teizer described the accident mechanism (illustrated in Figure 1 [24]) based on the Reason’s model.

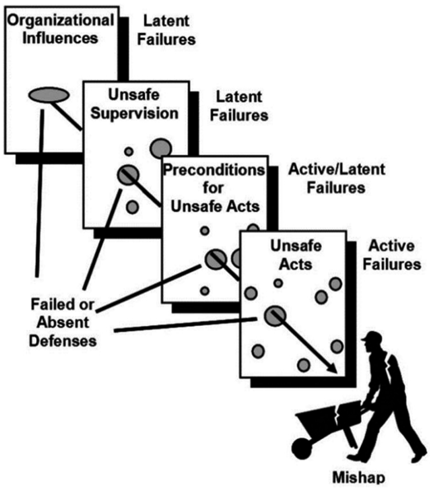

Fig. 1. Human error causation

The framework of HFACS was initially developed to analyze aviation accidents, and modified to be more applicable according to situations of different industries or different countries. In this study, some of factors were adjusted based on the version of HFACS developed by Wong et.al [20]. Patrick and Zhang [25] compared the Australian and Chinese construction safety production status and identified that the government’s actions including the safety-related laws and regulations, the unified safety supervision program, and the implementation of mandatory safety training for building participants can reduce construction safety incidents. Min and Hui [26] established a building safety supervision game model based on evolutionary game theory. The game targeted government supervision departments and construction units. Results showed that government safety supervision was helpful to reduce accident rate. So, at the level of organizational influences, government management is added. In the aviation industry, every step of the pilot’s operation has strict regulations, violations and mistakes can be identified. As a result, the pilot's mental state and physical/mental limitations can be checked. However, in construction industry, the workplace is more complex and varied. Each job has different operating procedures, so mental state and physical/mental limitations are seldom checked. Besides, the investigation reports of fatal accident rarely include analyzing the mental conditions of victims, so the modified HFACS don't contain these factors (mental states, physical/mental limitations and personal readiness). Finally, the modified HFACS and the codes of factors are illustrated in Figure 2.

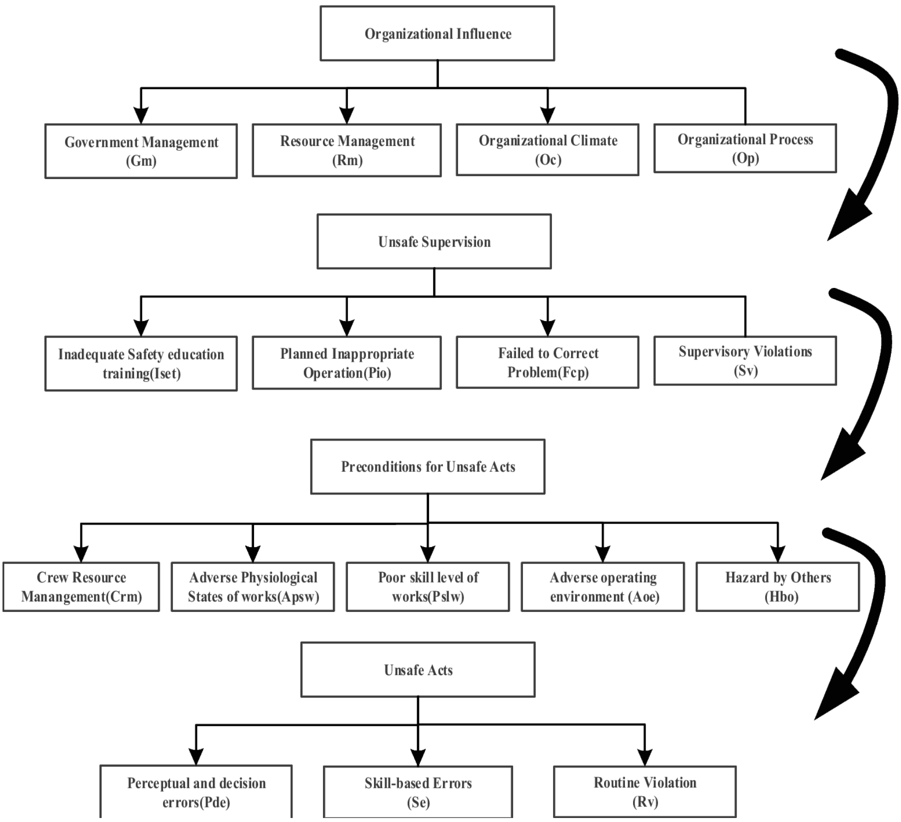

Fig. 2. The modified HFACS for electrical shock accident

3.3. Data analysis methods

The Chi-square test is usually utilized for statistical significance performed on categorical data [27]. It is applicable to the nominal and ordinal variables, which is widely used in the fields such as sociology and management. As all the factors based on the HFACS framework are categorical data in this study, Chi-square test is used to examine the significance between any of two causes. When the value is less than 0.05, there is a significant relationship between the pair of causes. Association rule mining aims at searching meaningful connections [28]. The core idea is the implication of $X \to Y$. Where X is called antecedent and Y is called consequent. Let $I = \{i_1, i_2, \cdots i_k\}$ defines the itemsets and each i_k is called an item. X and Y are two different itemsets of I, i.e., $X, Y \subseteq I$, and $X \cap Y = \emptyset$. One of the commonly used algorithms in association rules is the Apriori algorithm, which is proposed by Agrawal et al. [29], including three important parameters: support, confidence, and lift.

Support (S) is the measurement of the proportion occurrence of any itemset or combination of itemsets [16]. The calculation formula of support is expressed as follows:

$$\text{Support}(X \to Y) = \frac{P(X,Y)}{P(I)} = \frac{num(X \cup Y)}{num(I)} \tag{3.1}$$

Confidence (C) is used to determine how often Y appears in a transaction containing X. The calculation formula of confidence is expressed as follows:

$$\text{Confidence}(X \to Y) = P(Y/X) = \frac{P(X,Y)}{P(X)} \tag{3.2}$$

Lift (L) was proposed by Brin et al. [30] to improve the credibility of the rules. Lift is the measurement of correlation between X and Y. The calculation formula of lift is expressed as follows:

$$\text{Lift}(X \to Y) = \frac{P(Y/)}{P(Y)} \tag{3.3}$$

How to evaluate the most useful and interesting rules? They must satisfy minimum support and minimum confidence along with validated by lift verification ($\text{Lift}(X \to Y) > 1$) [17, 18]. Figure 3 shows the analysis process of association rule mining.

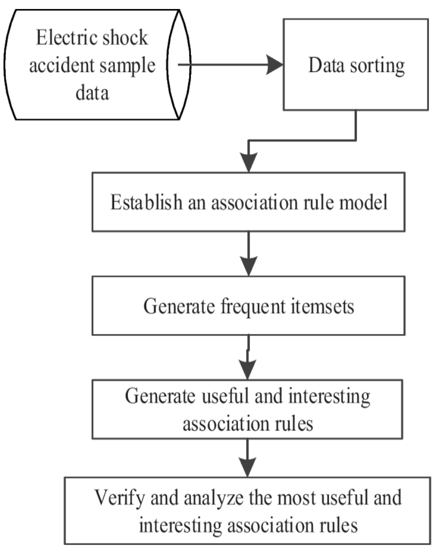

Fig. 3. The analysis process of association rule mining

3.4. Analytical framework

HFACS, frequency analysis, Chi-square test and association rule analysis are utilized to investigate accidents. Firstly, the HFACS model is adjusted to be suitable for the analysis of electric shock accidents. Secondly, the accident causes are identified based on modified HFACS, and the frequency analysis is adopted to describe the distribution of characteristics and causes in electric shock accidents. Thirdly, 2×2 contingency table, Chi-square test, are used to analyze whether there is significant correlation between any of two causes. Then, association rules are adopted to explore the accident paths from a holistic view of the HFACS. In this study, considering the unsafe acts as the direct cause of construction accident [31–33], the association rules and accident paths include human errors are analyzed. Finally, prevention interventions are proposed. The Figure 4 shows four-step research process of this study.

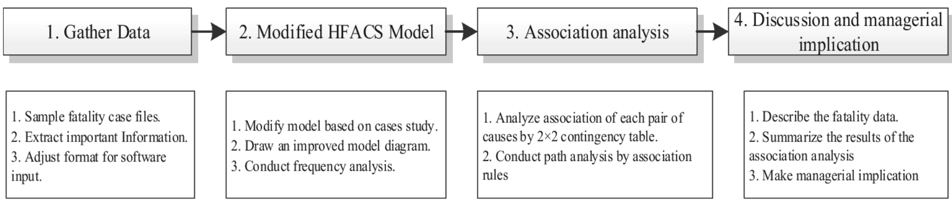

Fig. 4. Four-step research process

4. Result and discussion

4.1. Frequency analysis of electric shock accidents

101 electric shock accidents are statistically analyzed. The frequencies of incidents occurring by month and the time of day are showed in Figure 5 and Figure 6. Figure 5 reveals that fatal incidents occurred more frequently in August (19.8%). The finding is consistent with the research results by Zhao et al. [34]. And more accidents occur in summer during June to August than in other seasons. The higher temperature is, the less concentrated the workers are, especially when they conduct work in an outdoor environment. The lowest frequency appears in February (1%). The main reason may be the Chinese Spring Festival, which is a different date every year, usually between January 21 and February 20. Almost all construction projects are suspended during the festival. Figure 6 reveals that fatal incidents occur more frequently between 10:00–11:00 (10.9%), 15:00–16:00 (11.9%) and 17:00–18:00 (11.9%). The results are similar to the research by Wong et al. [20], which found that incidents occurred more frequently between 10:00–11:00, 13:00–15:00 and 17:00–18:00.

Figure 7 shows victims' age, ranging from 16 to 64 years old. The age group of 25 to 34 dominate the electric fatalities at 35.6%. Victims $\leq$ 45 years old account for over 68%. Figure 8 reveals the two occupations of the victims. Noelectrical workers account for 73.1%, indicating that noelectrical workers, who usually receive little or no electrical training, have much less perception of electric shock hazards than electrical workers.

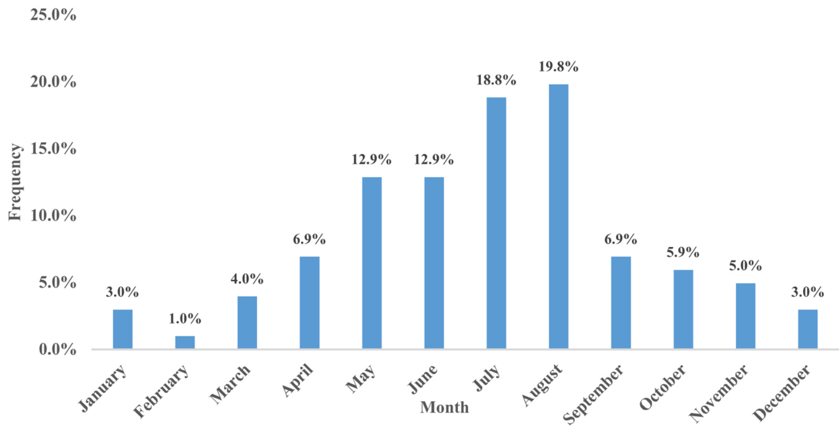

Fig. 5. Accident occurrence rate at different month

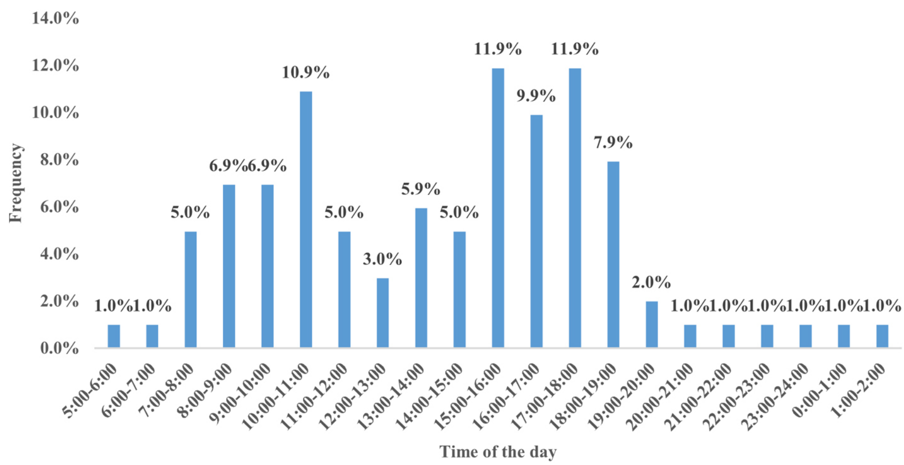

Fig. 6. Accident occurrence rate at different time

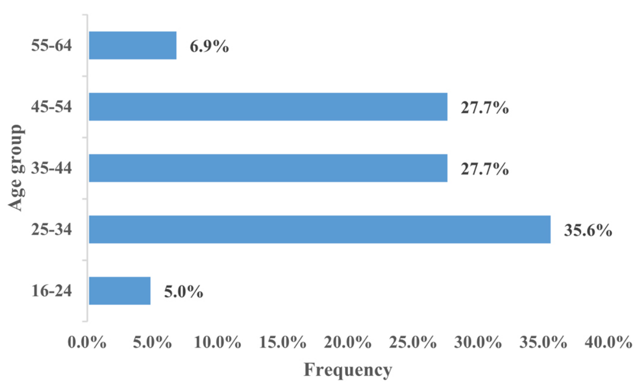

Fig. 7. Victims age of electric accidents

Fig. 8. Victims occupation of electric accidents

4.2. Frequency analysis of potential causes of the HFACS

The direct and indirect causal frequencies based on the modified HFACS are shown in Figure 9. At the level of organizational influences, statistics show that the loopholes in organizational process (Op) (75.3%) accounts for the largest proportion. This is mainly because in many cases, upstream analysis leads to safety management loopholes at the construction site. In one case, special safety plan wasn't developed for construction under the high-voltage power line, which caused scaffolding worker got an electric shock when he handled steel pipes. Wong et al. [20] indicated that the fatal cases either missed clear work procedures, or supervision, or both. At the level of unsafe supervision, the phenomenon of inadequate safety education training (Iset) (56.4%) is prominent, indicating that safety training has an important impact on accidents. Eteifa and El-Adaway [35] suggested that

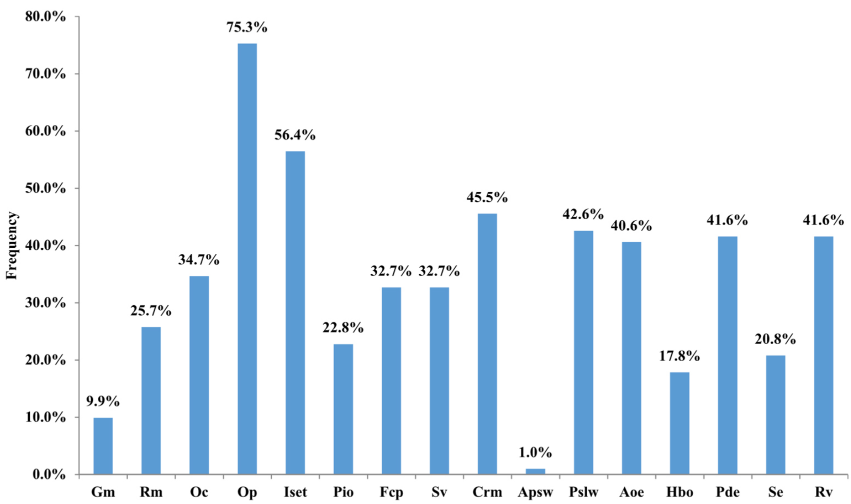

Fig. 9. Frequency diagram of the HFACS factors involved in the electric shock accidents

workers who didn't have sufficient training to perform jobs were usually much more prone to fatal hazards. At the level of preconditions for unsafe acts, the frequencies of inadequate crew resource management (Crm) (45.5%), poor skill level of works (Psle) (42.6%) and adverse operating environment (Aoe) (40.6%) have small difference. Perceptual and decision errors (Pde) (41.6%) and routine violations (Rv) (41.6%) are the two major unsafe acts leading to electric shock accidents. Other causes of accidents with relatively low frequencies may also have a significant impact on the accident.

4.3. Associations between any of two causes

Accidents are seen as emergence of complex systems. There are both causal and hierarchical relationships among causes based on the systematic accident causation models [36, 37]. It was meaningful to analyze the association between any two factors. The Chi-square test of the two causes in the framework is carried out by IBM SPSS V22.0. Results show in Table 1.

According to Table 1, there are 17 significant correlations. Among them, the weak of government management (Gm) is related to supervisory violation (Sv) ($p = 0.003^a$) and the poor crew resource management (Crm) ($p = 0.049^a$). In some accident investigation reports, under the circumstance of poor supervision by government agencies, a number of projects, especially small projects, were illegally contracted or subcontracted to enterprises that had no relevant qualifications and poor management, resulting in higher probability of accident. The results are similar to the study by Patrick and Zhang [25], which found that government played an important role in reducing accidents. Resource management (Rm) is significantly related to the adverse operating environment (Aoe) ($p = 0.010$). In one case, in process of wiring, a worker got electric shock, as the construction company didn't provide personal protective equipment (PPE) (e.g., insulated gloves). Garrentt and Teizer [24] emphasized that defined equipment management programs can promote safety awareness among employee and foster safety operation. Organizational climate (Oc) is related to inadequate safety education training (Iset) ($p = 0.001$), implying that the construction company with poor Oc more likely ignore to promote the safety awareness of workers. The electricians and non-electricians with no safety training will increase the risk of accidents. Therefore, the most key recommendation in investigations of Fatality Assessment and Control Evaluation (FACE) by the National Institute of Occupational Safety and Health's (NIOSH) is adequate safety training and regular specialized electrical safety training programs [34]. There is a significant connection between planned inappropriate operation (Pio) and hazard by others (Hbo) ($p = 0.006$). The Pio may cause the failure of on-site safety procedures, which increases the impact of hazard by others. In one case, in the process of pouring concrete of the ground beam, the concreter got electric shock, because the operator of boom violated the standard operating procedures leading to the top of the boom was too close to the high-voltage line. Poor skill level of works (Pslw) is related to perceptual and decision (Pde) ($p = 0.046$) and routine violation (Rv) ($p = 0.001$), implying that inexperienced workers are at high risk of making mistakes. Other significant associations are more logical and easier to understand.

Table 1. *P* of Chi-square test for each pair of causes

Factor 1	Factors 2															
	Gm	Rm	Oc	Op	Iset	Pio	Fcp	Sv	Crm	Apsw	Pslw	Aoe	Hbo	Pde	Se	Rv
Gm	–	1[a]	1[a]	0.429[a]	0.565[a]	0.537[a]	1[a]	**0.003**[a]	**0.049**[a]	1[a]	0.402[a]	1[a]	0.532[a]	0.262[a]	0.052[a]	0.704[a]
Rm	–	–	**0.017**	**0.016**	**0.001**	0.297	0.468	0.465	0.324	1[a]	0.158	**0.010**	0.937[a]	0.403	0.146	0.471
Oc	–	–	–	0.106	**0.001**	0.988	0.278	0.486	0.656	0.746[a]	0.083	0.172	0.499	**0.018**	0.886	**0.004**
Op	–	–	–	–	0.179	0.703	0.556	0.060	0.776	0.557[a]	0.868	0.139	0.979[a]	0.778	0.306	0.590
Iset	–	–	–	–	–	0.154	**0.048**	0.309	0.221	1[a]	0.914	0.091	0.544	0.488	0.674	0.242
Pio	–	–	–	–	–	–	0.203	0.203	0.098	1[a]	0.390	0.871	**0.006**[a]	0.451	0.453[a]	0.198
Fcp	–	–	–	–	–	–	–	0.051	0.086	0.710[a]	0.082	0.261	0.535	0.905	0.942	0.546
Sv	–	–	–	–	–	–	–	–	**0.011**	0.710[a]	**0.011**	0.864	0.947	0.905	0.552	0.794
Crm	–	–	–	–	–	–	–	–	–	1[a]	0.813	0.067	0.532	0.647	0.830	0.589
Apsw	–	–	–	–	–	–	–	–	–	–	1[a]	1[a]	1[a]	0.864[a]	1[a]	1[a]
Pslw	–	–	–	–	–	–	–	–	–	–	–	**0.025**	0.727	**0.046**	0.641	**0.001**
Aoe	–	–	–	–	–	–	–	–	–	–	–	–	0.080	0.696	0.461	0.055
Hbo	–	–	–	–	–	–	–	–	–	–	–	–	–	**0.018**	0.264	0.871
Pde	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.283	0.167
Se	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.072
Rv	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

Note: *a* = the corrected *p*.

4.4. Critical path analysis

R Programming Language V3.5.1 and Apriori algorithm are employed to analyze the association rules of construction electric shock accidents. There is no uniform standard for the threshold determination, and different thresholds for support and confidence values depend on the availably of data and the implementation of powerful rules [17, 18, 38]. Therefore, authors select the thresholds for support (Min – 0.11) and confidence (Min – conf = 0.40) in terms of document analysis and multiple iterations of data. Since the associations between any of two factors has been analyzed by Chi-square test. We only discuss three-item rules and four-item rules. According to the hierarchy of the HFACS, critical path analysis is conducted. 64 association rules with three-item and four-item rules are mined based on the defined thresholds and the rule of $Lift > 1$. Considering the factor at the level of unsafe act as the last item of the association rule, path diagram about the perceptual and decision errors (illustrated in Figure 10) and path diagrams about routine violation (illustrated in Figure 11) are mined. However, the useful and interesting association rule about skill-based errors (Se) is not found. A probable reason is that Se is the minimum factor of unsafe act account for accidents (show in Figure 9).

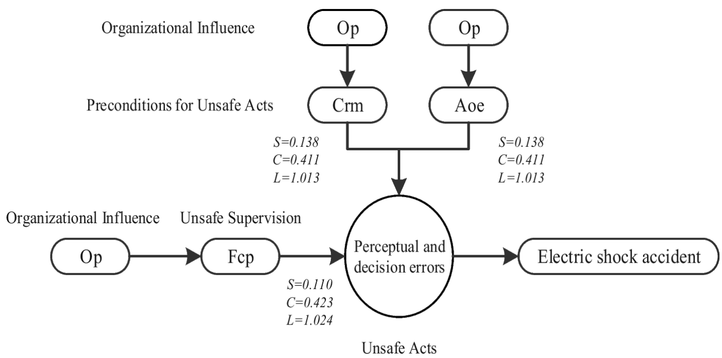

Fig. 10. The path diagram for accidents caused by perceptual and decision errors

In Figure 10, the key critical path of electric shock accidents is Op → Fcp → Pde: "organizational process loopholes → failed to correct problem → perceptual and decision errors" ($S = 0.11$, $C = 0.423$, $L = 1.02$), which signifies that the electrical accidents is most likely to have happened due to the poor of process safety management and negligence of known hazards. The result is similar to the research by Zarei et al. [6], which found that the poor operational process of organization, failure in correction of known problems and failure in workers' skill acquisition process played the key roles in accident occurrence. It is worth noting that lifts of the three paths are very close, and organizational process (Op) is the top factor inducing electric shock accidents. The results probably reflect the status quo of inadequate or improper formal process for safety management. With the failure of safety procedure or prevention (e.g., a checklist for certain electric risks), the workers are likely to misjudge the hazardous situation. And the Figure 10 shows that crew resource

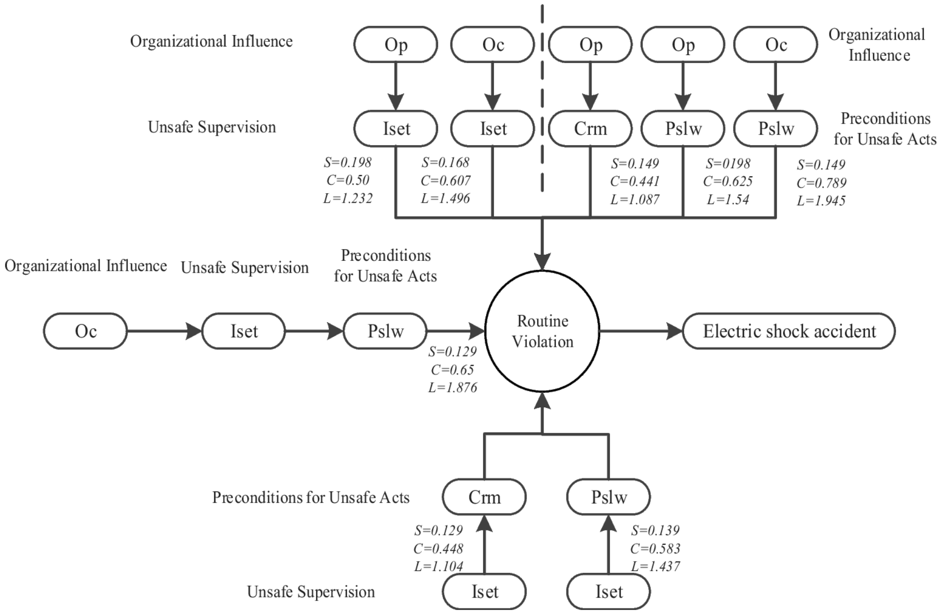

Fig. 11. The path diagram for accidents caused by routine violation

management (Crm) and adverse operating environment (Aoe) have important influences on workers' unsafe behavior.

In Figure 11, the key critical path of electric shock accidents is Op → Pslw → Rv: "organizational process loopholes → poor skill level of works → routine violation" (S = 0.149, C = 0.789, L = 1.945), which signifies that the electrical accidents is most likely to have happened due to the poor of process safety management and incapable staffing. This finding supports the influencing relationships of causes in study of Xia et al. [39], which found that poor management commitment, poor safety awareness and habitual violation affect the occurrence of accidents. Pslw reflected in some accident reports that the workers who have not obtained special operation certificate for electrician (SOCE) are still carrying out construction work. In one case, the worker without SOCE conducted electric welding operation and caused the welding rod to touch the steel platform to form a circuit, resulting in electric shock accident. In addition to Op, organizational climate (Oc) (e.g., safety culture) also has an important impact on the safety management of the entire construction cycle. Positive safety culture which influences safety acts in an organization can reduce incidents and accidents [40]. Inadequate safety education and training (Iset) appears frequently in Figure 11, the main reason may be the significant correlation between poor organizational climate (Oc) and Iset (shown in Table 1). The only accident chain with a path length of 4 is Oc → Iset → Aoe → Rv: "poor organizational climate → inadequate safety education training → adverse operating environment → routine violation (S = 0.129, C = 0.65, L = 1.876).This path signifies that the poor Oc are more likely to be the reason for electric shock accident while workers are not trained enough in an adverse operating environment.

4.5. Managerial implication

The results of Chi-square test and association rule analysis imply the different mechanisms of the accidents and further prove that accident is not caused by the one or two factors, but the combined effects of multiple factors. The control of key nodes can effectively prevent accidents. Combining the interconnections between the causes of electric shock accidents and the human error path diagram, the managerial implication for preventing electric shock accidents are proposed at every level of HFACS.

At the level of organizational influence, organizational process loopholes and poor organizational climate have great impacts on accidents. They connect with the factors of inadequate safety education training, perceptual and decision errors and skill-based errors. Therefore, the construction enterprises attach importance to safety culture construction, and strengthen internal management and improve supervision system, which will be of great significance for preventing electric shock accidents. At the level of unsafe supervision, inadequate safety education training and failed to correct problem occupy a significant proportion. It is important to implement safety education training and establish a management system of eliminating hidden dangers. At the level of preconditions for unsafe acts, poor skill level of works accounts for the most proportion, because it directly affects the unsafe behavior of workers. Organization need establish a special operation system to ensure workers qualified. The poor crew management and adverse operating environment shouldn't be ignored. At the level of unsafe act, the accidents are mainly caused by perceptual and decision errors and routine violation. The two causes can be reduced by reinforcing the management of the upstream level such as adequate safety equipment and safety training.

5. Conclusions

The main purpose of this paper is to identify the main causes and internal correlations of causes of electric shock accident. An analytical framework including some methods of HFACS, frequency analysis, Chi-square test and association rule for incident investigation is raised.

Authors revised the HFACS to be suitable for electric shock construction by analyzing 101 investigation reports. From frequency analysis of causes, it is identified that process management loopholes, inadequate safety education training and poor crew resource management are the top three causes of accidents. The association between any of two causes is discussion by 2×2 contingency table, and some significant relationships are shared. The key paths are extracted using association rule based on the hierarchy of the HFACS. The findings indicate that the most useful path of electric shock accidents caused by perceptual and decision errors is organizational process loopholes → failed to correct problem → perceptual and decision errors ($S = 0.11$, $C = 0.423$, $L = 1.02$), and organizational process loopholes → poor skill level of works → routine violation ($S = 0.149$, $C = 0.789$, $L = 1.945$) by routine violation. In addition, the only incident chain with a path length of

4 is identified, which is bad organizational climate → inadequate safety education training → adverse operating environment → routine errors ($S = 0.129$, $C = 0.65$, $L = 1.876$).

Those main causes and accident chains act as guidelines for the management to make policy of enhancing performance. Safety culture construction and safety education and training are emphasized to prevent accident in this study. This study has limitations. The accident reports have different formats, because they are prepared by different investigation teams in different provinces. However, this problem is overcome by taking expert suggestions and multi-person analysis.

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References

[1] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Bulletin of Production Safety Accidents in Housing and Municipal Engineering. [Online]. Available: https://www.mohurd.gov.cn. [Accessed: 2012-2017].

[2] D. Zhao, W. Thabet, A. McCoy, et al., "Sociotechnical systems of fatal electrical injuries in the construction industry", *Journal of Construction Engineering & Management*, 2016, vol. 142, no. 1, art. ID 04015056, DOI: 10.1061/(ASCE)CO.1943-7862.0001036.

[3] Health and Safety Executive Website. London (DC): HSE. [Online]. Available: http://www.hse.gov.uk/statistics/industry/construction.pdf. [Accessed: Nov. 2018].

[4] C.F. Chi, Y.Y. Lin, M. Ikhwan, "Flow diagram analysis of electrical fatalities in construction industry", *Safety Science*, 2012, vol. 50, no. 5, pp. 1205–1214, DOI: 10.1016/j.ssci.2011.12.012.

[5] M. Lombardi, M. Fargnoli, G. Parise, "Risk Profiling from the European Statistics on Accidents at Work (ESAW) Accidents' Databases: A Case Study in Construction Sites", *International Journal of Environmental Research and Public Health*, 2019, vol. 16, no. 23, DOI: 10.3390/ijerph16234748.

[6] E. Zarei, M. Yazdi, R. Abbassi, et al., "A hybrid model for human factor analysis in process accidents: FBN-HFACS", *Journal of Loss Prevention in the Process Industries*, 2019, vol. 57, pp. 142–155, DOI: 10.1016/j.jlp.2018.11.015.

[7] A.J. Taylor, G. McGwin, F. Valent, et al., "Fatal occupational electrocutions in the United States", *Injury Prevention*, 2003, vol. 8, no. 4, pp. 306–312, DOI: 10.1136/ip.8.4.306.

[8] M. Suárez-Cebador, et al., "Characterization of workers suffering serious electrical accidents in the construction industry", in *Occupational Safety and Hygiene*, P. Arezes, et al., Eds. CRC, 2013, pp. 107–110.

[9] C.F. Chi, C.C. Yang, Z.L. Chen, et al., "In-depth accident analysis of electrical fatalities in the construction industry", *International Journal of Industrial Ergonomics*, 2009, vol. 39, no. 4, pp. 635–644, DOI: 10.1016/j.ergon.2007.12.003.

[10] D. Zhao, J. Lucas, V. Tech, et al., "Using virtual environments to support electrical safety awareness in construction", in *Proceeding of the 2009 Winter Simulation Conference*, 13–16 Dec. 2009, Austin, USA. IEEE, 2009, DOI: 10.1109/WSC.2009.5429258.

[11] D. Zhao, A.P. Mccoy, B.M. Kleiner, et al., "Control measures of electrical hazards: An analysis of construction industry", *Safety Science*, 2015, vol. 77, pp. 143–151, DOI: 10.1016/j.ssci.2015.04.001.

[12] A.P.C. Chan, F.K.W. Wong, C.K.H. Hon, et al., "A Bayesian Network Model for Reducing Accident Rates of Electrical and Mechanical (E&M) Work", *International Journal of Environmental Research & Public Health*, 2018, vol. 15, no. 11, DOI: 10.3390/ijerph15112496.

[13] C.F. Chi, T.C. Chang, K.H. Hung, "Significant industry–source of injury–accident type for occupational fatalities in Taiwan", *International Journal of Industrial Ergonomics*, 2004, vol. 34, no. 2, pp. 77–91, DOI: 10.1016/j.ergon.2004.03.002.

[14] C.W. Cheng, C.C. Lin, S.S. Leu, "Use of association rules to explore cause–effect relationships in occupational accidents in the Taiwan construction industry", *Safety Science*, 2010, vol. 48, no. 4, pp. 436–444, DOI: 10.1016/j.ssci.2009.12.005.

[15] Robert K, Elisabeth Q, Josef B, "Analysis of occupational accidents with agricultural machinery in the period 2008–2010 in Austria", *Safety Science*, 2015, vol. 72, pp. 319–328, DOI: 10.1016/j.ssci.2014.10.004.

[16] A. Verma, S.D. Khan, J. Maiti, et al., "Identifying patterns of safety related incidents in a steel plant using association rule mining of incident investigation reports", *Safety Science*, 2014, vol. 70, pp. 89–98, DOI: 10.1016/j.ssci.2014.05.007.

[17] S.Y. Guo, H.B. Luo, Z. Teng, et al., "Research on association rules of unsafe behavior for metro construction workers", *Journal of Safety Science & Technology*, 2015, vol. 11, no. 10, pp. 185–190.

[18] A.T. Cabello, M. Martínez-Rojas, J.A. Carrillo-Castrillo, et al., "Occupational accident analysis according to professionals of different construction phases using association rules", *Safety Science*, 2021, vol. 144, art. ID 105457, DOI: 10.1016/j.ssci.2021.105457.

[19] C.A. Arboleda, D.M. Abraham, "Fatalities in Trenching Operations – Analysis Using Models of Accident Causation", *Journal of Construction Engineering & Management*, 2004, vol. 130, no. 2, pp. 273–280, DOI: 10.1061/(ASCE)0733-9364(2004)130:2(273).

[20] L. Wong, Y.H. Wang, T. Law, et al., "Association of Root Causes in Fatal Fall-from-Height Construction Accidents in Hong Kong", *Journal of Construction Engineering & Management*, 2016, vol. 142, no. 7, DOI: 10.1061/(ASCE)CO.1943-7862.0001098.

[21] S.A. Shappell, D.A. Wiegmann, "A Human Error Approach to Accident Investigation: The Taxonomy of Unsafe Operations", *The International Journal of Aviation Psychology*, 1997, vol. 7, no. 4, pp. 269–291, 1997, DOI: 10.1207/s15327108ijap0704_2.

[22] D.A. Wiegmann, S.A. Shappell, "Human error analysis of commercial aviation accidents: application of the Human Factors Analysis and Classification system (HFACS)", *Aviation Space & Environmental Medicine*, 2001, vol. 72, no. 11, pp. 1006–1016.

[23] J. Reason, *Human error.* West J Med, 1990, pp. 393–396.

[24] J.D. Garrett, J. Teizert, "Human factors analysis classification system relating to human error awareness taxonomy in construction safety", *Journal of Construction Engineering & Management*, 2009, vol. 135, no. 8, pp. 754–763, DOI: 10.1061/(ASCE)CO.1943-7862.0000034.

[25] X.W. Patrick, G.M. Zhang, "Comparative Study on the Perception of Construction Safety Risks in China and Australia", *Journal of Construction Engineering & Management*, 2009, vol. 135, no. 7, pp. 620–627, DOI: 10.1061/(ASCE)CO.1943-7862.0000019.

[26] C. Min, C. Hui, "Game analysis of construction safety supervision", in *International Conference on E-business & E-government (ICEE2011), 6-8 May 2011, Shanghai, China*. IEEE, 2011.

[27] K. Curtis, S.T. Youngquist, "Part 21: Categoric Analysis: Pearson Chi-Square Test", *Air Medical Journal*, 2013, vol. 32, no. 4, pp. 179–180, DOI: 10.1016/j.amj.2013.04.007.

[28] G.P. Lei, M.L. Dai, Z.F. Tan, et al., "The Research of CMMB Wireless Network Analysis Based on Data Mining Association Rule", in *International Conference on Wireless Communications*, 23–25 Sept. 2011, Nanjing, China. IEEE, 2011, DOI: 10.1109/wicom.2011.6040545.

[29] R. Agrawal, H. Road, S. Jose, "Mining Association Rules between Sets of Items in Large Databases", in *Proceeding of the ACM SIGMOD Conference on Management of Data, Washington, DC*. ACM Press, 1993.

[30] S. Brin, R. Motwani, J.D. Ullman, et al., "Dynamic itemset counting and implication rules for market basket data", *ACM SIGMOD Record*, vol. 26, no. 2. 1997, pp. 255–264, DOI: 10.1145/253260.253325.

[31] R.A. Haslam, S.A. Hide, A.G.F. Gibb, et al., "Contributing factors in construction accidents", *Applied Ergonomics*, 2005, vol. 36, no. 4, pp. 401–415, DOI: 10.1016/j.apergo.2004.12.002.

[32] D. Feldmann, K.H. Welge, "Understanding the Causation of Construction Workers' Unsafe Behaviors Based on System Dynamics Modeling", *Journal of Management in Engineering*, 2015, vol. 31, no. 6, DOI: 10.1061/(ASCE)ME.1943-5479.0000350.

[33] A. Suraji, A.R. Duff, S.J. Peckitt, "Development of Causal Model of Construction Accident Causation", *Journal of Construction Engineering & Management*, 2001, vol. 127, no. 4, pp. 337–344, DOI: 10.1061/(ASCE)0733-9364(2001)127:4(337).

[34] D. Zhao, W. Thabet, A. Mccoy, et al., "Electrical deaths in the US construction: an analysis of fatality investigations", *International Journal of Injury Control and Safety Promotion*, 2014, vol. 21, no. 3, pp. 278–288, DOI: 10.1080/17457300.2013.824002.

[35] S.O. Eteifa, I.H. El-Adaway, "Using Social Network Analysis to Model the Interaction between Root Causes of Fatalities in the Construction Industry", *Journal of Management in Engineering*, 2018, vol. 34, no. 1, DOI: 10.1061/(ASCE)ME.1943-5479.0000567.

[36] N. Leveson, *Engineering a Safer World: Systems Thinking Applied to Safety*. Cambridge (MA), MIT Press, 2011.

[37] P.M. Salmon, M. Cornelissen, M.J. Trotter, "Systems-based accident analysis methods: A comparison of Accimap, HFACS, and STAMP", *Safety Science*, 2012, vol. 50, no. 4, pp. 1158–1170, DOI: 10.1016/j.ssci.2011.11.009.

[38] A. Montella, "Identifying crash contributory factors at urban roundabouts and using association rules to explore their relationships to different crash types", *Accident Analysis and Prevention*, 2011, vol. 43, no. 4, pp. 1451–1463, DOI: 10.1016/j.aap.2011.02.023.

[39] N. Xia, P.X.W. Zou, X. Liu, et al., "A hybrid BN-HFACS model for predicting safety performance in construction projects", *Safety Science*, 2018, vol. 101, pp. 332–343, DOI: 10.1016/j.ssci.2017.09.025.

[40] J.I. Håvold, E. Nesset, "From safety culture to safety orientation: validation and simplification of a safety orientation scale using a sample of seafarers working for Norwegian ship owners", *Safety Science*, 2009, vol. 47, no. 3, pp. 305–326, DOI: 10.1016/j.ssci.2008.05.002.

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