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Flow diagram analysis of electrical fatalities in construction industry

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Abstract. The current study reanalyzed 250 electrical fatalities in the construction industry from 1996 to 2002 into seven patterns based on source of electricity (power line, energized equipment, improperly installed or damaged equipment), direct contact or indirect contact through some source of injury (boom vehicle, metal bar or pipe, and other conductive material). Each fatality was coded in terms of age, company size, experience, performing tasks, source of injury, accident cause and hazard pattern. The Chi-square Automatic Interaction Detector (CHAID) was applied to the coded data of the fatal electrocution to find a subset of predictors that might derive meaningful classifications or accidents scenarios. A series of Flow Diagrams was constructed based on CHAID result to illustrate the flow of electricity travelling from electrical source to human body. Each of the flow diagrams can be directly linked with feasible prevention strategies by cutting the flow of electricity.

Keywords: fatal electrocution, accident analysis, prevention measure, CHAID

1. Introduction

Electrical hazards are some of the most dangerous hazards present in construction industry. Many workers are unaware of the potential electrical hazards in their work environment, which increase their vulnerability to the danger of electrocution [1]. Electrical fatalities accounted for 14.6% of all fatal accidents and were the second leading cause of occupational fatality in Taiwan, following falling fatalities.

In our previous study [2], we developed a classification scheme to analyze 250 fatalities of occupational electrocution in construction industry in terms of age, company size, experience, performing, tasks, source of injury, and accident causes and described these fatalities based on Casini (1993)'s five hazard patterns. These five hazard patterns of Casini came from 3 types of electrical sources (i.e. power lines, energized equipment, and damaged or improperly installed equipment) and two major possible ways of electrocution (i.e. direct contact or through intermediary object) [1, 3]. Casini differentiated contact with energized power lines into direct contact and indirect contact and further divided indirect contact into indirect contact through boomed vehicle and indirect contact through conductive material. However, Casini had not differentiated electrocution with energized equipment and damaged equipment into direct and indirect contact as his classification for contact with power lines. Therefore, this current study added two new hazard patterns, indirect contact through energized equipment (Pattern 5) and indirect contact through damaged equipment (Pattern 7) to improve the analysis and prevention measures for these two types of accidents. Fig. 1 shows 7 hazard patterns used in this study.

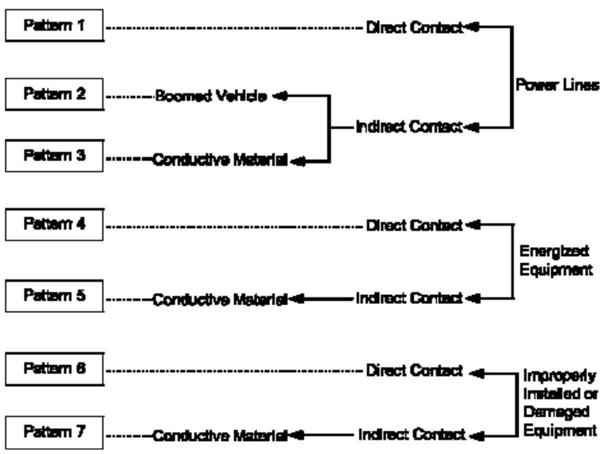

Figure 1. Taxonomy of 7 Hazard Patterns for electrocution

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When a person comes in contact with electrical agent or vehicle carrying electricity, the flow of electricity passes through the person's body so as to complete its path from the source to the ground, wherein, human body acts as a conductor of electricity [1]. Oleske, et al., defined the source of injury as the object, substances, exposure or bodily motion which directly produced or inflicted the injury [4]. In case of electrocution, the source of injury is either direct contact with the electricity source or indirect contact with intermediary object or equipment conducting electric current.

Pineault, et al., proposed a Flow Diagram (See Fig. 2) to show possible paths (direct contact or indirect contact through intermediary object) between the electrical source (*ES*) and the victim (*VI*) in terms of vectors (*VE1*, *VE2*, ... *VEn*) (See Fig. 2) [5]. The idea is to block the electricity flow from electricity source to the victim so as to prevent the electrocution. However, without real example, it was not clear what *VE1*, *VE2*, or *VEn* mean in this model or how this model can be applied for preventing electrical injury. Therefore, the current research proposed to adopt 250 electrocution fatalities cases as examples to study and modify the flow diagram by replacing vectors with source of injury (i.e. object that conducts electricity to victim from electrical source) because the victims were not always working with an electrical source or performing electrical task**.** The arrow direction was also changed from electrical source to source of injury or directly to victim. The flow diagram could then be used to propose effective barriers by cutting a trace between electrical sources and the victim [5].

Instead of drawing one flow diagram for each fatality case, these flow diagrams would become more useful, as each flow diagram can denote a significant number of similar fatality cases. But Casini (1993)'s hazard pattern characterized each scenario only by electrical source and type of contact. In order to draw flow diagrams, these accident patterns must also incorporate source of injury and perhaps other contributing factors. Therefore, CHAID (Chi Square Automatic Interaction Detection) Analysis was applied to classify 250 fatality cases into limited number of meaningful patterns [6] to reduce the number of diagrams that had to be drawn for implementing barriers. In other words, age, company size, experience, performing, tasks, source of injury, and accident causes were used as predictors for differentiating between 7 hazard patterns in order to divide all fatalities into several mutually exclusive patterns. In the end, Reliability Block Diagram (RBD) was adopted in order to incorporate accident causes into the flow diagram to reveal the best possible prevention measures directly.

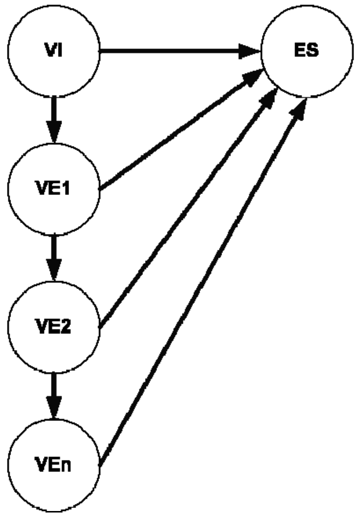


Figure 2 Model for Implementing Barriers [5]

2. Material and methods

The current study reanalyzed 250 fatal electrocution accidents from 1996 to 2002 [2] using CHAID and Flow Diagram. All accident reports were extracted from case reports that were published by the Council of Labor Affairs of Taiwan. Each accident report identified age, experience level of the victim, performing task, source of injury, and accident causes.

2.1. Chi-square automatic interaction detector (CHAID)

The CHAID analysis [7, 8] was applied to the coded data of 250 fatal electrocution accidents to search through the selected predictor variables (age, company size, experience, performing tasks, source of injury, and accident cause), in order to find a subset of predictors that might explain differences between 7 hazard patterns of electrocution.

In the current study of fatal electrocution, source of injury should be the most important predictor for differentiating 7 hazard patterns. Since the sequential order of selected predictor variables was not important, we decided to conduct CHAID analysis using automatic mode. After CHAID classified 250 electrocution fatalities into mutual exclusive patterns, the flow diagram illustrating potential pathways of electric current from electrical source to human body was drawn for each distinguishable pattern.

2.2. Flow diagram

Electricity travels in closed circuits, through conductor. As human body is an efficient conductor of electricity, when it comes in contact with electric flow, it becomes part of the electric [9]. When a person receives an electric shock, electricity flows between parts of the body or through the body to a ground or the earth [10]. In the current study, a flow diagram is drawn for each distinguishable pattern to illustrate the "electrical circuit with human as one of the conductors in it".

The current study adopted and modified the flow diagram proposed by Pineault et al, 1994 (See Fig. 2) to show possible paths of electricity travelling from electrical source (*ES*) to the victim (*VI*). Each path identified one source of injury (*SI*) (denoted by a circle) as an object or equipment delivers electric current from source to victim. The source of injury was the electrical source responsible for electrocution caused by either direct contact with electrical source or indirect contact through an intermediary object or equipment like metal bar and job ladder.

In order to incorporate the accident causes (denoted by rectangles) into the flow diagram [5], this study adopted the Reliability Block Diagram (RBD) to show the relationship among contributing causes based on 250 case reports. In the original RBD, each block stands for a working physical component and failure of this component was indicated by removal of the corresponding block [11].

In the current study each block has been placed between the electrical source and the victim, in the flow diagram to denote one respective cause of accident that has contributed to the accidental electrocution. In other words, each cause block created a potential path connecting the victim and the electrical source to make the electrocution happened. Thus, each cause block also corresponds to a feasible prevention measure. Using RBD format tends to be easier for an analyst to visualize the logic diagram such as fault tree [12]. Generally, there are two main types of connections, i.e. series and parallel connections to which link between two or more cause blocks. In case of parallel paths, being redundant i.e. many alternative paths connecting source and victim, at least one of the parallel path must fail for the failure of entire network. On the contrary, in case of series paths, it is necessary that all paths in the series must fail for the failure of network, i.e. for accident to take place [11].

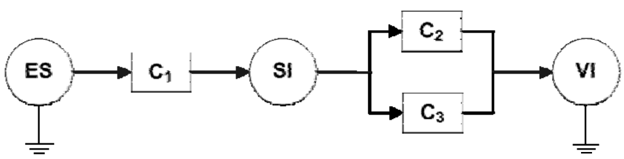
Most fatality cases had multiple causes [13] and there are 3 possible causes (C_1, C_2, and C_3) derived from all accident reports of a specific accident pattern combined in 3 potential formats (C_1C_2, $C_1C_2C_3$, and C_1C_3), for example. An accident will take place if any one of the three different combinations occurs (See Table 1). The three different combinations can be simplified based on Boolean logic expression $C_1C_2+C_1C_2C_3+C_1C_3 = C_1 (C_2+C_2C_3+C_3) = C_1 (C_2+C_3)$ [14]. The logic expression states that according to logic expression, C1 will be in series with parallel C_2 and C_3. Fig. 3 has shown an example of incorporating 'accident causes' in the Table 1, into the flow diagram for presenting electrocution scenarios derived from CHAID analysis in terms of flow diagram and RBD. The Arrow illustrates an electric current flowing from an electrical source (*ES*) through a source of injury (*SI*) and passing through the victim (*VI*). Electrical 'Ground' symbol below *VI* and *ES* represents the 'close-loop' leading to an electrocution.

The flow diagram in Fig. 3 illustrates the sequential position of cause blocks between the victim and source of injury. *C1* indicates an accident cause (i.e. error) contributed to the electricity flow through *SI* from an *ES*. Either C2 or C3 must be present to cause the victim to be electrocuted through a *SI*. Overall, there are two possible combinations of cause (C_1-C_2 and C_1-C_3).

Table 1 An example of coding database for accident causes

Case No.	1st Cause	2nd Cause	3rd Cause
1 C	1	C_2	
2 C	1	C_2	C_3
3 C	1	C_3	

Figure 3 An example of Flow Diagram with one source of injury



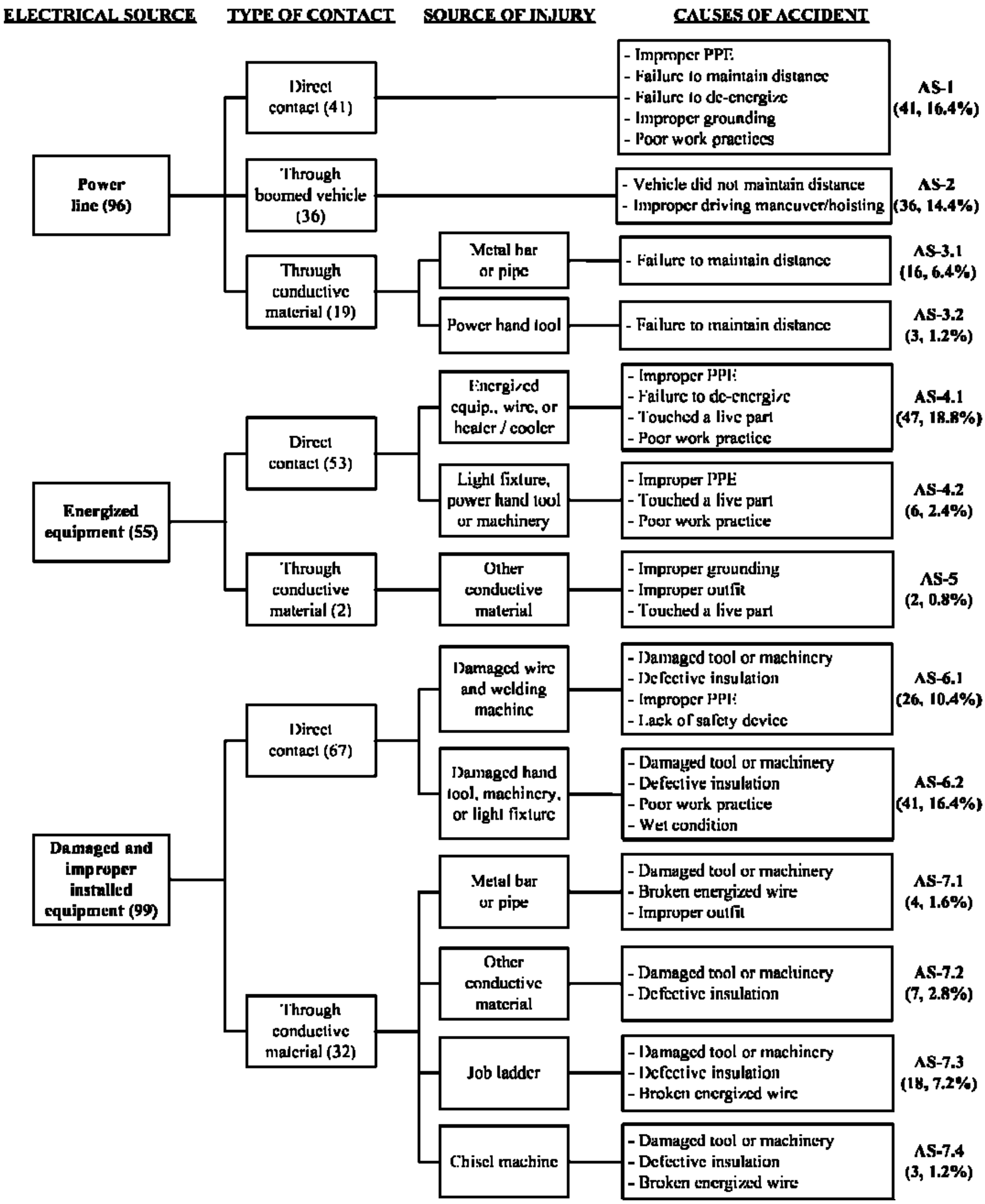


Figure 4. CHAID result for fatal electrocution in Taiwan’s construction industry

3. CHAID result: the accident scenarios

CHAID divided total population into two or more distinct groups, based on categories of the "best" predictor of a dependent variable (i.e. the 7 Hazard Pattern), and split each of these groups into smaller subgroups based on other predictor variables, e.g. accident causes. The result of CHAID showed that age, company size, job experience, and performing were not found to be significant predictor variables of electrocution. Sources of injury being identified as the "best" or most critical predictor ($p<0.001$) which divided total population in the format of hazard pattern into nine different groups (nodes). Causes were found to be the second critical predictor and it was nested under the levels of the most critical factor, source of injury. The causes for electrocution indicated various possibilities a victim can be electrocuted through the source of injury. Since the resulting accident scenario from CHAID is mainly used for the flow diagram, different accident scenarios can be merged if they share similar source of injury or accident causes.

As shown in Fig. 4, 13 distinct accident scenarios were generated based on predicting 7 hazard patterns using significant predictors, source of injury, and cause of accident. Electrical source and type of contact were added to link the 7 hazard patterns so that each accident scenario can be understood as accident pattern or sub pattern for each accident pattern. For example, hazard pattern 1 and 2 were analyzed into accident scenario AS-1 and AS-2, respectively. Hazard pattern 3 (i.e. indirect contact with power line through conductive material) was divided into two distinct accident scenarios, AS-3.1 for indirect contact with power line through metal bar or pipe and AS-3.2 for indirect contact with power line through power hand tool, respectively.

Distinguishable groups of accident scenario were used as the basis for drawing flow diagrams. These accident scenarios are mutually exclusive and exhaustive; such that each scenario did not overlap, and each fatality case belonged to exactly one pattern. By illustrating each scenario in the form of flow diagrams, it would be very easy to determine the appropriate prevention measures to stop recurrence of accidents.

Since the CHAID result could be different depending on the coding scheme, each of the hazard scenarios was checked manually to see if any of these scenarios can be combined in terms of source of injury or accident cause, to reduce complexity. Regarding hazard pattern 3 i.e., indirect contact with power line, scenario AS-3.1 metal bar or pipe contact with power lines, and scenario AS-3.2 power hand tool contact with a power line can be combined because both metal bar or pipe and power hand tool share the same nature as source of injury. While, in pattern 4, scenario AS-4.1, i.e. direct contact with energized equipment, the direct contact with light wire and heater or cooler machine and scenario AS-4.2, i.e. direct contact with light fixture, power hand tool or machinery can be combined based on similarity of accident causes. Similarly, AS-7.2, AS-7.3 and AS-7.4 or AS-6.1 and AS-6.2 can be combined based on the same ground. A series of flow diagram analysis would be drawn as follows to show distinct accident scenarios after manual combination of similar sources of injury and accident causes.

4. Some examples of presenting accident scenarios using flow diagram

Two hundred and fifty cases were analyzed into seven accident patterns with each containing one to four scenarios. Each of the accident patterns was elaborated using flow diagram as follows. Notice that for each scenario, the number of cases for accident cause does not seem to add up because the inspectors only registered important causes.

4.1. AS-1: direct worker contact with an energized power line

In Accident Scenario 1 (AS-1), victims directly touched an energized power line, mostly while installing, moving or repairing utility pole or power lines (37 cases out of 41) [2]. Whereas, improper use of PPE (25 cases) and failure to de-energize electrical system (9 cases), improper grounding (8 cases), failure to maintain safe distance (8 cases) and poor work practices (8 cases) were the most common accident causes. Fig. 5 illustrated all possible cause combinations associated with worker directly touched power line without any immediate object.

Based on our database, the five cause blocks were arranged in two parallel series. The first parallel series showed that, proper use of PPE (e.g. helmet, safety gloves, and safety boots), de-energizing, and proper grounding of the power line should be done simultaneously before work in order, to ensure that, no electrical energy from the power line could endanger the worker. Proper grounding of the power line was also critical, because 5 victims were electrocuted by back feed voltage from household generators. However, only the power company personnel can de-energize the power line, and sometimes, it is not feasible to work out an agreement with the utility company [15]. Therefore, worker must put on PPE before performing task on or near utility pole. The second parallel series of cause blocks indicate that, poor work practice or not maintaining safe distance of body with the live part could electrocute the body parts are not currently covered by PPE.

4.2. AS-2: boomed vehicle contact with power lines

All cases in AS-2 had indirect electrocution, caused by operating boomed vehicles and failure to maintain safe distances (36 cases), then boom touched the power line. Four cases were associated with poor work practice, for e.g., improper driving maneuver. Fig. 6 illustrated boomed vehicle as the source of injury to conduct electricity from source (i.e. power line) to the victim. Failure to maintain distance and improper driving maneuver were the 2 cause blocks arranged in parallel to indicate either one can cause the fatality.

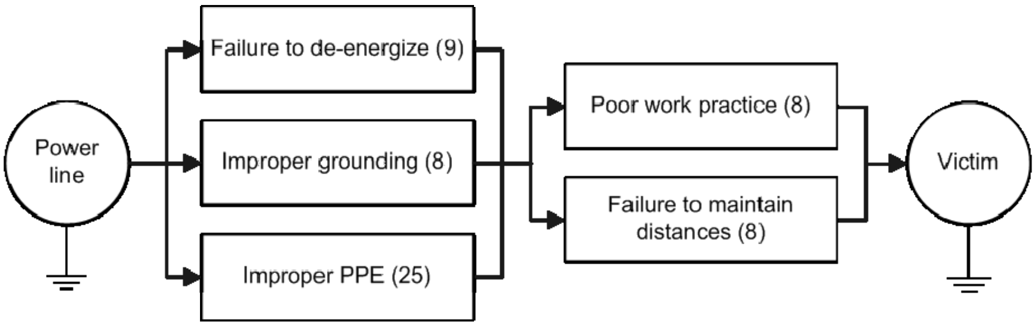


Figure 5 Flow Diagram for hazard pattern 1

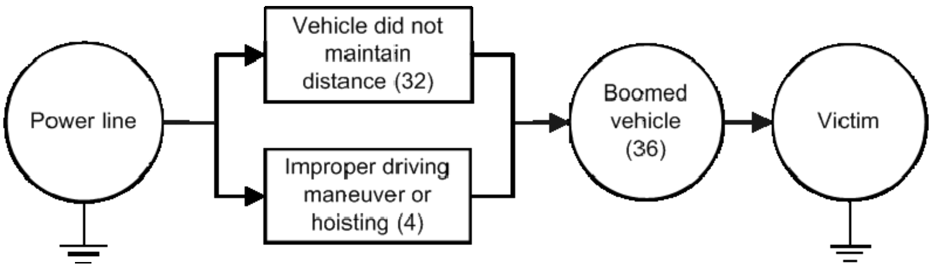


Figure 6 Flow Diagram for hazard pattern 2

4.3. Hazard pattern 4: direct worker contact with energized equipment

In case of hazard pattern 4, victim gets electrocuted due to his/her direct contact with energized equipment such as, distribution box circuit, switches, fuses, and transformer or energized wire or heater / cooler (AS-4.1), or with lighting fixture, hand tool, or machinery (AS-4.2). These two scenarios were combined because most fatalities shared common accident causes including improper PPE (29 cases), accidentally touched a live part of the electric equipment (21 cases), and poor work practice (13 cases). On the other hand, these two scenarios were distinguished by different source of electricity; and failure to de-energize was the only cause occurred in AS-4.1 because de-energizing procedure such as cleaning the distribution box or replacement of spare parts was not feasible for cases in AS-4.2 (see Fig. 7).

In hazard pattern 4, according to the case report, each accident cause could lead to an electrocution fatality by itself, thus all accident causes were arranged in parallel to indicate that all causes should be prevented simultaneously. The number of cases does not seem to add up, because inspectors could have registered only important causes. Besides, as explained in our previous study [2], when two accident causes tied together in a significant number of cases, if the primary cause implied a secondary cause, then only one primary cause was coded to cover the accidental situation. Thus only poor work practice was coded when the poor work practice automatically lead to touch a live part in 13 cases, so as to reduce redundant causes.

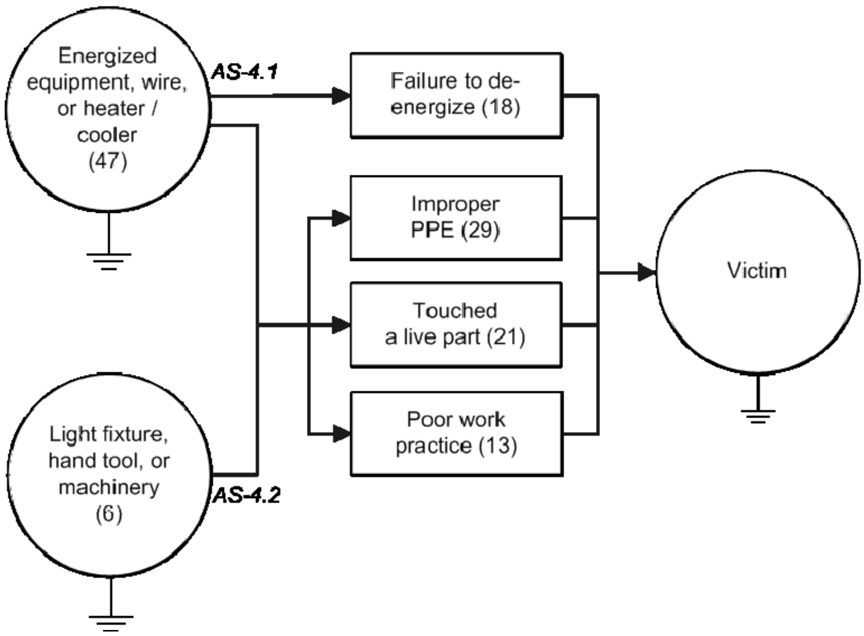


Figure 8 Flow Diagram for hazard pattern 5

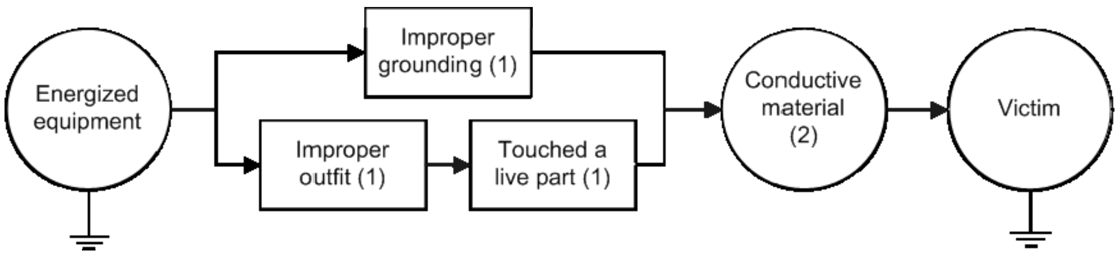


Figure 7 Flow Diagram for hazard pattern 4

4.4. Hazard pattern 5: indirect worker contact with energized equipment

As shown in Fig. 8, there are only two cases for hazard pattern 5, worker got indirect electrocution by energized equipment through intermediate conductive material. One accident was caused by worker's gold necklace contacting live transformer while working in a stooping position. Another electrocution took place because the victim touched an extinguisher pipe for which another co-worker performed welding on it without grounding properly, and the electricity conducted from the welder electrode to the victim worker through the pipe.

5. Conclusion

Construction workers face a much higher risk of electrocution because they interact with various kinds of machinery, power hand tool with temporary electricity suppl y cabl es, a nd extension c ords st rewn across all ove r the place on the work floors. All of the above situations present very high risk of electrocution accidents to all construction workers. The current study developed flow diagrams proposed by Pineault et al. (1994) bas ed on 250 fatal electroc ution accidents in the c onstruction i ndustry in Taiwa n. Each of the flow diagrams can be directly linked with feasible prevention strateg ies b y cu tting t he flow of electricity.

Notice that, the flow diagram in this research on ly illustrated th e electrical so urce, th e so urce of inj ury, and the acci dent cause iden tified in 250 fat ality reports. An in spector may identify on ly obvious or important accide nt causes a nd the inconsist ency be - tween in spectors cou ld b e the po tential limitatio n of this stu dy. Also, in consistency in th e repo rt cou ld have hap pened d ue to di fferences in investigation assumptions a dopted by i nspectors a bout causes o f accidents and respective pre vention measures [16]. As stated by S vedung & Rasmussen (2002), gra phic representation can b e very effective in creatin g an overview of co mplex o ccurrence and also it will b e useful for ef fective c ommunication of ass umptions and findings [17]. The flow diagram based on fatality cases, helps workers and general pu blic to reco gnize the danger of electricity co ming th rough metal p arts and other conducting agents.

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