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Early intervention mechanism for preventing electrocution in construction engineering

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Abstract: The aim of this study is to establish an effective early intervention mechanism for construction engineering to prevent electrocution while improving labor safety and reducing the casualty risk. This study used narrative text analysis and the Haddon Matrix for data collection, and analyzed the causes from the 113 electrocution deaths among in the construction industry, the exhaustive chi-square automatic interaction detector algorithm was employed the segmentation of the correlations. Based on the theory of inventive problem solving, through IDEF0 (ICAM DEFinition) for function modeling was designed the early intervention mechanism. This study revealed the operating features related to electric shock hazards. Early intervention was introduced to reduce the relevant risks and establish safety mechanisms. The first contribution of this study is the determination of hazard correlations between operating features and conductive media, and entry point for the prevention of electrocutions. The second contribution is the suggestion of the establishment of inspection stations for electric tools, thereby ensuring that the portable power tools are safe. The final contribution is the joint application of TRIZ (Teoriya Resheniya Izobreatatelskikh Zadatch) and IDEF0, which establishing the pre-entry testing, strengthening safety mechanisms.

Key words: Electrocution, Inspection stations for electric tools, Prevention through design, Early intervention mechanism, Portable electrical tools

Introduction

The US Census of Fatal Occupational Injuries revealed that the number of electrocution deaths in 2011–2017 was 1,049[1]. According to the BLS of the United States, 51.1% of all electrocution deaths in 2013 occurred on construction sites. The US Occupational Safety and Health Administration thereby listed electrocution as one of the four most common fatal hazards to building safety and human health[2, 3]. Electrocution was the third most common cause of death in the 2004–2016 statistics of occupational disasters in Taiwan's construction industry, totaling 162 victims[4, 5]. If factors related to electrocution risk can be eliminated, numerous lives can be saved each year. Therefore, monitoring and interventions tailored to high-risk occupations are required to reduce the frequency of severe injuries[6].

Dissimilar to the manufacturing industry, which utilizes mass production, the construction industry utilizes one-off production, most of which is not routine[3, 7]. A survey of labor safety in Italy from 2008 to 2013 showed that construction workers were exposed to extremely hot construction sites for a long time, with a higher probability of occupational injuries[8]. Occupational disaster data col-

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lected in the United States and European Union member countries clearly revealed that development of a healthy and safe working environment is crucial to enhancing labor productivity and corporate competitiveness[9)].

Electrical workers are exposed to various working environments for long periods, resulting in relatively high injury severity. Although safety training and safety culture development can reduce the number of accidents caused by human error, they cannot completely eliminate hazards[10)]. The existing problems that require urgent solutions are how the hazard factors causing electrocution deaths can be determined and how hazard factors in the workplace can be eliminated. Controlling occupational hazard risk is a fundamental and effective method of protecting workers. The Hierarchy of Controls (HOC)—which is composed of the following levels of control: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE)—strengthens the safety system and considerably lowers the risk of disease and injury. Moreover, the incorporation of prevention through design (PtD) can reduce the number of occupational injuries, illnesses, and fatal accidents[11, 12)].

To determine the possible correlations between variables and accident severity, data were categorized across the dimensions who, which, when, what, and where to construct the contingency table of the statistical χ^2 test, enabling analysis of the electrical accidents in one construction industry in Spain[13)]. Additionally, the tree classification method was employed in one study to identify job characteristics and the integrated definition for function modeling (ICAM DEFinition method, IDEF) by using decision chains[3)]. Based on case analyses of accidents, a flowchart of implementation difficulties was proposed for preventing indirect electric shocks[14)]. Learning from failures and using that knowledge to improve the current state is an effective path to success. Lethal risk assessment and controlled assessment of electrical deaths were previously employed to identify the operating features that lead to electrical deaths[15)]. Because construction workers have long been exposed to risks, need to be alert and attentive, therefore, wearable sensors have been used to monitor the perceived risks of construction workers[16)]. The US Center for Construction Research and Training reported that the mistake-proofing design established using TRIZ (Teoriya Resheniya Izobreatatelskikh Zadatch) for the construction process can improve performance in safety and health, particularly in the construction industry[17)]. With the goal of eliminating the electrocution hazards of construction projects, this study had the following specific objectives:

-To determine the hazard correlation between operating features and conductive media by analyzing the summary reports of 113 electrocution deaths in the construction industry.

-To eliminate hazard sources and establish inspection stations for electrical tools by using the concept of PtD.

-To establish an early intervention mechanism for pre-entry testing on construction sites through the joint application of TRIZ and IDEF0.

Methods

This study employed narrative text analysis (NTA) and the Haddon Matrix structure to determine the hazard factors involved in deaths caused by the electrocution of construction engineering for occupational disasters. Subsequently, the classification tree method was used to categorize the hazard correlations between operating features and conductive media. In order to the controlling occupational hazard risk, through the mistake-proofing framework established using HOC and TRIZ were employed, to illustrate the IDEF0 diagram for preconstruction process modeling, with the objective of applying an early intervention mechanism that can solve difficulties in preventing electrocution accidents. Steps in the research methodology as illustrated in Fig. 1.

Narrative Text Analysis, NTA

In the collected occupational health and safety data, the causes of accident hazards must be analyzed to develop effective measures, thereby reducing the incident rate or increasing the overall safety standards[18)]. Because the accident case data were in the form of narrative text, this study employed NTA to explore the hidden information in the text for coding.

To categorize the different variables, the Haddon Matrix was employed to collect data prior to, during, and after construction accidents as well as related factors such as conductive media and environment attributes, thereby obtaining the relative importance of different factors and design interventions[3, 19, 20)]. Therefore, this study used the Haddon Matrix architecture for intervention analysis.

For the electrical death study between 1997–2007 in the construction industry of Canada, through the Haddon matrix and through text analysis to identify relevant factors, including direct contact with power, low voltage sources and outdoor work, conductive media and environmental characteristics[21)]. The Haddon Matrix is used to explore the characteristics of events to respond to disasters.

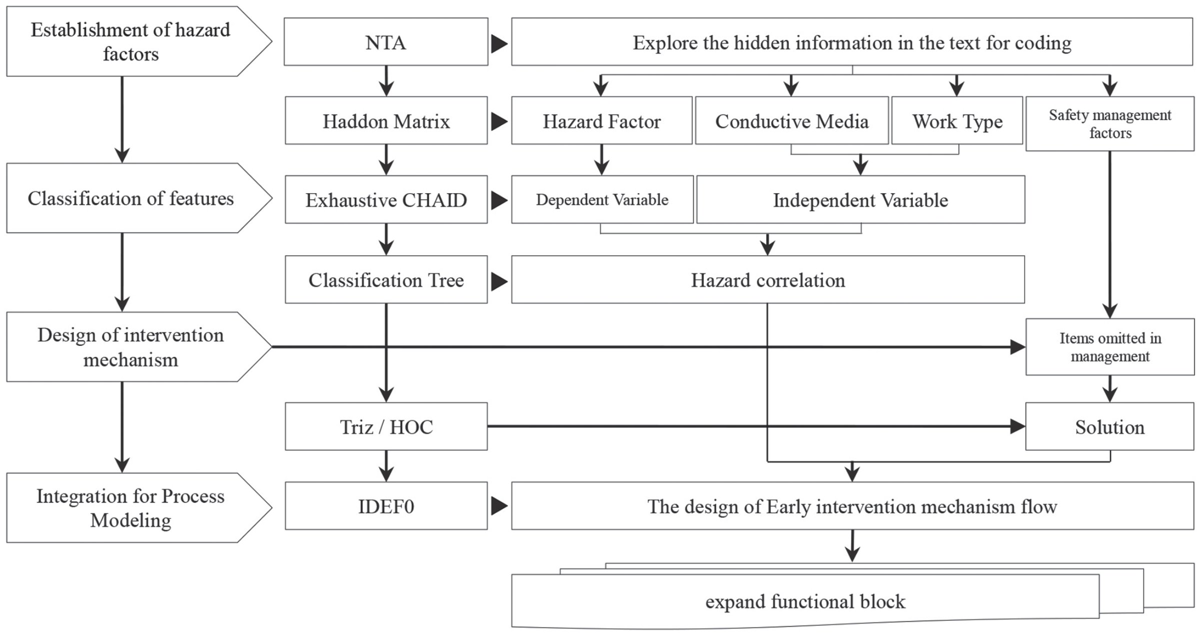

Fig. 1. Research methods and steps.

Classification tree method

The Chi-square Automatic Interaction Detector, CHAID[22] and Exhaustive CHAID[23] algorithms both allow multiple node-splits and consist of the steps merging, splitting, and stopping. Exhaustive CHAID determines the optimal segmentation derived from each step. According to chi-square values, classification is performed starting from the root node. An exhaustive search procedure is used for merging. A tree is grown by repeatedly using these three steps on each node until a single pair remains. Therefore, this study uses Exhaustive CHAID for multi-factor node segmentation to find the hierarchical correlations that influence variables.

TRIZ

When meeting the innovation needs of the construction industry and developing building technology, TRIZ can be employed to improve construction project management and the effect of value engineering[24]. Suitable for use in both problem solving and program evaluation, TRIZ has an engineering contradiction principle that overcomes fault sites and considerably improves performance[25]. Therefore, this study employed the TRIZ principle to design a mistake-proof structure of the construction process for eliminating hazard factors.

IDEF0 functional model

IDEF0 is a method of modeling the decisions, operations, and activities of organizations or systems[26, 27]. The main method components are the input of information required for decision making, the output of decisions, controls (internal and external control of the operating system), and modules composed of mechanisms of the resources required to support the workflow. The modules are then connected to form the system model.

Accident risks (e.g., risks of collision, impact, and fall), physical risks (e.g., risks of physical strain or consumption and being crushed), and environmental risks (e.g., risks of exposure to or contact with extreme temperatures, electric currents, and hazardous substances) are the three layers of the hierarchical structure of construction site safety[9]. To assess the need for information management, six items of the control category (i.e., occupational safety and health knowledge, policies, efficiency, productivity, collaboration, and funding) and five items of the mechanism category (i.e., professionalism, equipment, materials, time, and space) were used as components of functional modeling to summarize the decision-making mechanism regarding electrical safety on construction sites and the work characteristics related to electrical hazards[3, 28]. Therefore, this study uses IDEF0 as a communication tool for expressing the resources and functions of the system.

Table 1. Haddon matrix

Factor/Phase	Pre-event	Event	Post-event
Human factors	·PPE ·Identification of operational hazards	·Inappropriate insulation of protective tools/equipment	-
Physical factors	·Power supply ·Tools, equipment, and materials	·High/low voltage ·Conductive media ·Insulation failure	-
Environmental factors	·Labeling and monitoring ·Safety distance/barricades	·Work type	-
Safety management factors	·Operation of construction safety management	-	CPR

Results

Establishment of hazard factors

To gain deep understanding of electrocution hazards, this study performed NTA on 113 cases from the abstract of 2006–2015 electrocution accidents among major occupational disasters in the construction industry, which was compiled by the Occupational Safety and Health Administration (OSHA), Taiwan. The Haddon Matrix was used to collect and classify predictor variables. The matrix consists of the pre-event, event, and post-event phases as well as human, physical, environmental, and management factors. The hidden information in the text data of the 113 cases was identified, encoded, and classified accordingly (Table 1).

Subsequently, varied information was obtained from the summary reports of industry type, accident occurrence, accident cause analysis, accident prevention strategy for 113 electrocution deaths. On the basis of the human, physical, environmental, and safety management factors listed in Table 1, the obtained data were categorized into 11 hazard factors, eight types of conductive media, five work types, and six management factors, constituting 30 predictor variables in total, as detailed in Tables 2–5.

Classification of features

After establishing the variables, the exhaustive CHAID growing method was employed in SPSS to perform optimal segmentation for determining the correlations between the dependent variables (i.e., hazard factors) and independent variables (i.e., conductive media and work type). Due to this study is a data type of a small number of observations, the observation value of the upper node is set to 6, and the lower limit of the observation value of the lower node is set to 3, in order to produce more useful results. The results are presented in Fig. 2.

Node 0 provides a summary of the 113 records in the data set. In the data set, HF-5 (30.1%) and HF-2 (28.3%) have the highest percentages of Hazard Factor. First, it is segmentation by the CM layer (Conductive Media), and CM-6 is assigned to node 2. Obviously, this type of risk is the highest (35.4%), including HF-5 (70.0%), which has the highest risk in this node. The remaining items are assigned to other nodes. Continuing, according to the WT layer (Work Type), node 2 is branch into three subcategories (nodes 5, 6, 7), of which the risk of node 6 is the highest (25.7%).

In summary, as can be seen from the classification tree results, through the combination of conductive media and work type, the hazard factors were found to branch into seven leaf nodes (nodes 1–7) from a root node (node 0), which includes the three nodes branched by node 2 (nodes 5–7). Calculate and take the action that gives the smallest p-value, one for the set of categories formed by merging the missing category with its most similar category, namely Conductive Media ($p<0.001$), and the other is a collection of categories formed by adding missing categories as separate categories, namely Work Type ($p=0.001$). Found that the two are significantly correlated with the hazard factors. And take the top three hazard factors of each node, listed as the main hazard factor. The classification tree branches were summarized into six operating features (Table 6). Branched out from Node 2, the aforementioned characteristics 4–6 (Nodes 5–7) were electrocution incidents caused by the use of low-quality portable electrical tools. These occurrences include live line operations, sporadic repair operations, sporadic construction projects, and the operation of portable construction vehicles.

In addition to the above classification, there are: First, the incidence was categorized by voltage level in Taiwan: low voltage (below 750 V, example 110, 220, and 380 V) accounted for 87.61% of incidents, high voltage (more than 750 V and less than 33 kV, example 3,300, 5,700, 11,400, and 22,800 V) for 8.85%, and extra high voltage

Table 2. Hazard factors

Code	Hazard factor	Description
		Human factors
HF-1	Lack of hazard awareness	·Insufficient hazard awareness and identification
		·Lack of basic electrical safety knowledge
		·Incomplete coverage of the end of a wiring line with insulating tape
HF-2	No or improper use of insulating protective tools or equipment	·No or inappropriate use of PPE
		·No installation of insulating protective equipment
HF-3	No or inadequate on-site inspections	·No or failed on-site inspections
		·Power supply not properly cut off
		·Operational hazard identification not properly conducted
		·Moveable wires blocking the flow on the construction site
HF-4	Pressure-induced insulation deterioration in cables or wires	·Insulation deterioration caused by metal objects pressing and yanking the wire
		·Insulation deterioration caused by accidental pressing of wires when moving tools
		Physical factors
HF-5	Damaged or lack of required components in an electrical machine tool	·Damaged or lack of required components in an electrical machine tool
		·Alternating current welding machine with no or an ineffective automatic electric shock prevention device
HF-6	Insulation failure caused by grounding	·Direct contact with the ground/copper wire or the metal casing of the equipment
		·No removal of the short-circuiting device
HF-7	No grounding or use of a damaged or nonfunctional residual current circuit breaker	·No grounding
		·Use of a damaged or nonfunctional residual current circuit breaker
		·Use of a portable electric motor without installation or passing the residual current circuit breaker
		·Insulation deterioration in the outer casing or wire of a portable electric motor
HF-8	Insulation deterioration in wires	·Insulation deterioration in the outer casing of the extension cord
		·Defective insulation or insulation aging in the outer casing of the extension cord
		Environmental factors
HF-9	Defects in safety procedures	·No set-up of barricades
		·Safety measures not taken when removing operating wires or pipelines
		·No comprehensive construction method
HF-10	No safety labels or monitoring	·Switch box left unlocked
		·No warning labels placed on the switch box
		·Failure to protect workers through safety monitoring, supervision, and direction
HF-11	No safety distance	·Safety distance not maintained
		·Minimum approach distance from the charge body not maintained

Table 3. Conductive media

Code	Conductive media	Description
CM-1	Wires	Direct contact with the power supply / electrical cables or wires
CM-2	Support equipment	Stepladders, scaffolds, or other support equipment
CM-3	Conductive materials	Electricity and pipeline networks, utility poles, or other conductive structural materials
CM-4	Construction vehicles	Derrick cranes, bucket lifts, or other vehicles
CM-5	Metal objects	Metal objects such as iron wires, iron sheets, hoses, and tools
CM-6	Portable electrical tools	Portable electric motors or electrical hand tools
CM-7	Power controller	Electrical generation/substation equipment, switch boxes, or junction boxes
CM-8	Electrical equipment	Electrical equipment such as air blowers, crushers, iron rolling door boxes, and air conditioners

Table 4. Work type

Code	Work type	Description
WT-1	Building-related construction projects or operation of other nonelectrical building elements	Installation, inspection, wall painting and maintenance, windows, roofs, steel structure assembly, hoses, formwork, sealing, fences, cleaning, and operations regarding other nonelectrical building components
WT-2	Live line operation	Installation, testing, maintenance of electrical panels, elevators, fuses, alternating current, low current, lighting equipment, and other electrical components in building systems
WT-3	Welding, drilling, chiseling concrete, and demolition work	Sporadic work such as installation, removal, and cutting of roofs, canopies, and walls or floor chiseling
WT-4	Piping/hydropower engineering/waterproofing works	Firewater pipeline, hydropower pipeline, air-conditioning pipeline, waterproofing and leakage-blocking operations, and thermal engineering for chilled-water pipelines
WT-5	Operation of construction vehicles	Hoists, mobile cranes for hanging or moving building materials, ready-mixed concrete trucks, and pump trucks

(above 33 kV, example 34,500, 69,000, and 161,000 V) for 3.54%. Second was project type: new construction projects accounted for 48.67% of incidents, sporadic repair projects for 31.86%, other projects for 10.62%, and demolition projects for 8.85%. Third was industry type (top 3): site preparation, foundation, and structure construction accounted for 32.65% of incidents; mechanics, telecommunications, and electricity facilities installation for 22.12%; civil engineering contractors for 15.93% of incidents in total.

Design of intervention mechanism

According to Reinforcement of Inspection Notices in articles 26 and 27 of Taiwan Occupational Safety and Health Act indicates that business entities shall compile health and safety management responsibilities and inform the contractors of such responsibilities prior to delivering or contracting projects. Moreover, business entities shall urge contractors at all levels to create a workplace that complies with the health and safety conditions specified in this act, thereby reducing the occupational accident rate[29]. By analyzing cases, this study discovered that among the factors in construction safety management, relevant health and safety education and training is most frequently omitted (72.6%), followed by automatic inspections (61.9%), and health and safety rules for workers (61.1%; Table 7). Managers did not inform the workers and contractors of the health and safety rules for laborers, protocols of organization and affairs, or the measures required in response to hazard factors. Moreover, the managers neither conducted inspections automatically nor established a labor health and safety management staff member or supervisor.

Regarding automatic inspections, this study employed the TRIZ tool[30] to suggest a solution for improving automation, maintaining measurement accuracy, and simplifying the operation (Table 8).

Table 5. Safety management factors

	Items omitted from construction safety management
1	Relevant health and safety education and training
2	Automatic inspections
3	Health and safety rules for workers
4	Coordination of organization and affairs
5	Labor health and safety management staff or supervisor
6	Required measures in response to hazard factors

In accordance with the HOC principle, behavioral control was promoted to the technical control level of automatic prevention. The main objective is to eliminate hazard factors, thereby controlling and preventing hazardous events. In order to retain the functions of (EP28) Measurement accuracy and (EP33) Ease of Operation, and to improve the (EP38) Extent of automation program, therefore, the solutions suggested in Table 8 are optimized into the intervention mechanism was designed (Fig. 3). The automatic inspection procedure (EP33 & EP38) was placed in the pre-entry testing stage (TP10 preliminary action), with a multifunction detection machine employed for inspections (TP28 mechanics substitution, TP1 segmentation, and TP12 equipotentiality). The safety of portable electrical tools may thus be controlled in a timely manner (TP3 Local quality), and the inspection data will be included in the database. If the tool is approved, approval labels are printed (TP26 Copying) before the subsequent step. Tools that fail the inspection are removed from the site to be repaired or replaced (TP34 discarding and recovering) before reentering the construction site.

Integration for process modeling

According to the import/export characteristics of the IDEF0 system functional block, a mechanism for early

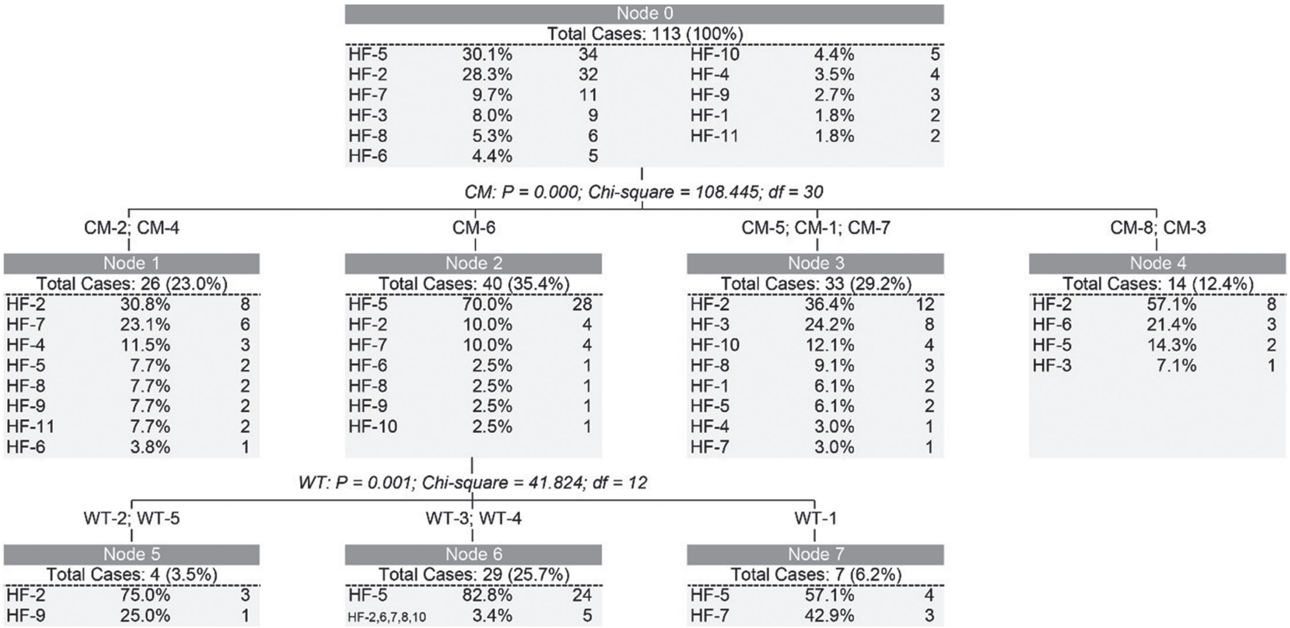

Fig. 2. Classification tree.

Table 6. Hazard correlation between operating features and conductive media

Node	Operating feature	Conductive media	Hazard factor (Top 3)
1	Regional power wiring	CM-2. Stepladders, scaffolds, or other support equipment CM-4. Derrick cranes, bucket lifts, or other vehicles.	HF-2. No or improper use of insulating protective tools or equipment HF-7. No grounding or use of a damaged or nonfunctional residual current circuit breaker HF-4. Pressure-induced insulation deterioration in cables or wires
3	Power line inspection and maintenance	CM-5. Metal objects and tools CM-1. Direct contact with the power supply / electrical cables or wires CM-7. Electrical generation / substation equipment, switch boxes, or junction boxes	HF-2. No or improper use of insulating protective tools or equipment HF-3. No or inadequate in-site inspections HF-10. No safety labels or monitoring
4	Power line installation and repair	CM-8. Electrical equipment CM-3. Electricity and pipeline networks, utility poles or other conductive structural materials	HF-2. No or improper use of insulating protective tools or equipment HF-6. Insulation failure caused by grounding HF-5. Damaged or lack of required components in an electrical machine tool
5	Live line operation and operation of construction vehicles	CM-6. Portable electric motors or electrical hand tools	HF-2. No or improper use of insulating protective tools or equipment HF-9. Defects in safety procedures or preventive design
6	Sporadic work (welding / drilling / chiseling / piping / hydropower engineering / waterproofing)	CM-6. Portable electric motors or electrical hand tools	HF-5. Damaged or lack of required components in an electrical machine tool HF-2. No or improper use of insulating protective tools or equipment HF-6. Insulation failure caused by grounding HF-7. No grounding or use of a damaged or nonfunctional residual current circuit breaker HF-8. Insulation breakdown in wires HF-10. No safety labels or monitoring
7	Construction-related engineering projects	CM-6. Portable electric motors or electrical hand tools	HF-5. Damaged or lack of required components in an electrical machine tool HF-7. No grounding or use of a damaged or nonfunctional residual current circuit breaker

Table 7. Items omitted in construction safety management

	Omitted item	Number of cases	%	Place of implementation	Target of implementation
1	Relevant health and safety education and training (or sufficient training hours)	82	72.6	Management (scheduled separately)	Related personnel
2	Automatic inspections	70	61.9	Construction site	Workers
3	Health and safety rules for workers	69	61.1	Management	Workers
4	Coordination of organization and affairs	43	38.1	Management	Contractors
5	Labor health and safety management staff or supervisor	40	35.4	Construction site	Managers
6	Required measures in response to hazard factors	30	26.5	Management	Contractors and workers

Table 8. The solution of TRIZ principles

Engineering Parameters (EP) (manipulate)		TRIZ Principles (TP)			
Feature to improve	Feature to preserve	Solution			
		1	2	3	4
EP38. Extent of automation	EP28. Measurement accuracy	TP28. Mechanics substitution	TP26.Copying	TP10. Preliminary action	TP34. Discarding and recovering
	EP33. Ease of operation	TP1. Segmentation	TP12. Equipotentiality	TP34. Discarding and recovering	TP3.Local quality

Description: Engineering Parameters (manipulate)
EP38. The ability of a system or object to complete a task without human operation.
EP28. The error between the measured value and the actual value of the system characteristic.
EP33. As many outputs as possible for one operation.
Description: TRIZ Principles
TP28. Change from unstructured fields to those having structure.
TP26. Instead of an unavailable, expensive object, use simpler and inexpensive copies.
TP10. Perform, before it is needed, the required change of an object.
TP34. Make portions of an object that have fulfilled their functions go away or modify these directly during operation.
TP1. Divide an object into independent parts.
TP12. In a potential field, limit position changes.
TP3. Make each part of an object fulfill a different and useful function.

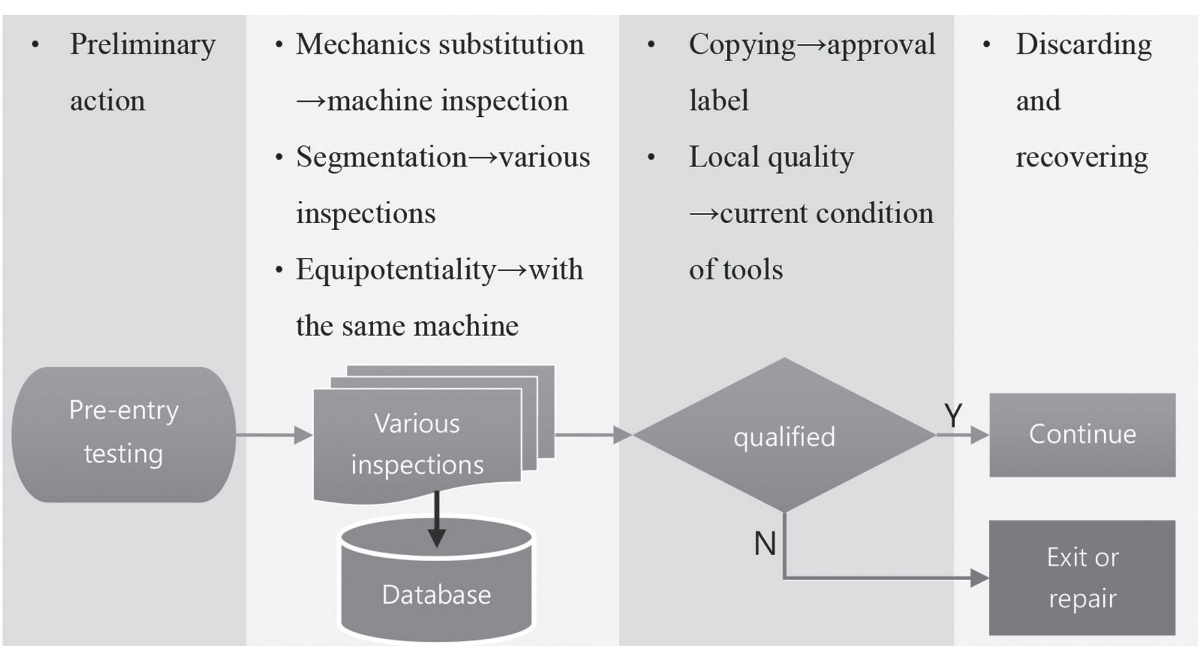

Fig. 3. Automatic inspection framework of the intervention mechanism.

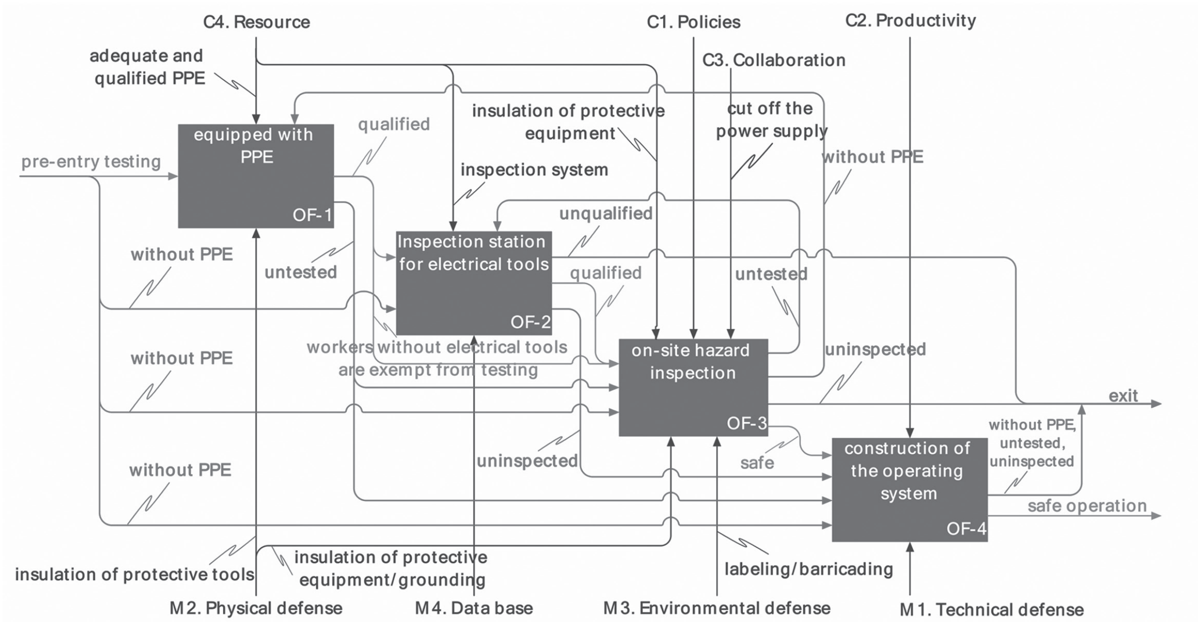

Fig. 4. Early intervention mechanism flowchart.

control of hazard factors associated with construction site safety may be introduced along with a framework of automatic inspection. As discussed in Section: *IDEF0 functional model*, the four control variables (i.e., policies, productivity, collaboration, and resource) pertaining to the six dimensions (Table 9) for determining the operating features related to electric shock hazards and the human, physical, environmental, and safety management factors of the Haddon Matrix were transformed into the four mechanism variables (Table 10): They were technical defense, physical defense, environmental defense, and database, which served as the components for function modeling.

Accordingly, a flowchart of the early intervention mechanism was constructed (Fig. 4), the process description is as follows. Pre-entry testing is required before workers enter the site. The first station (functional block) is equipped with PPE (OF-1) to maintain basic protection (i.e., M2 physical defense), and need to have adequate and qualified PPE to provide workers (i.e., C4 Resource). In the second station, the detection system (i.e., C4 Resource) of the inspection station for electrical tools (OF-2) performs the detection of each tool, and the detection result is recorded by the database (i.e., M4 Data base). The third station, carry out on-site hazard inspection (OF-3), in accordance with occupational health and safety regulations, procedural standards, and requirements (i.e., C1 policies), cooperate with power companies or partners (i.e., C3 collaboration) to power off, and check the safety labels and barricades as warnings of the construction zone (i.e., M3 environmental defense). Finally, according to the respective construction of the operation system (OF-4) to strengthen the productivity of labor skills and construction quality (i.e., C2 productivity), and maintain the professional skills and precise judgement (i.e., M1 technical protection), began to enter site and operation. Those who fail to comply with

Table 9. Control categories

Code	Control	Description
C1	Policies	Occupational health and safety regulations, procedural standards, and requirements
C2	Productivity	Strengthening labor skills and construction quality
C3	Collaboration	Communication and coordination with the third party
C4	Resources	Budget input

Table 10. Mechanism categories

Code	Mechanism	Description
M1	Technical defense	Professional skills and precise judgement
M2	Physical defense	Insulation of protective tools and equipment/grounding
M3	Environmental defense	Safety labels and barricades as warnings of the construction zone
M4	Database	Collection and archiving of electrical tool inspection data

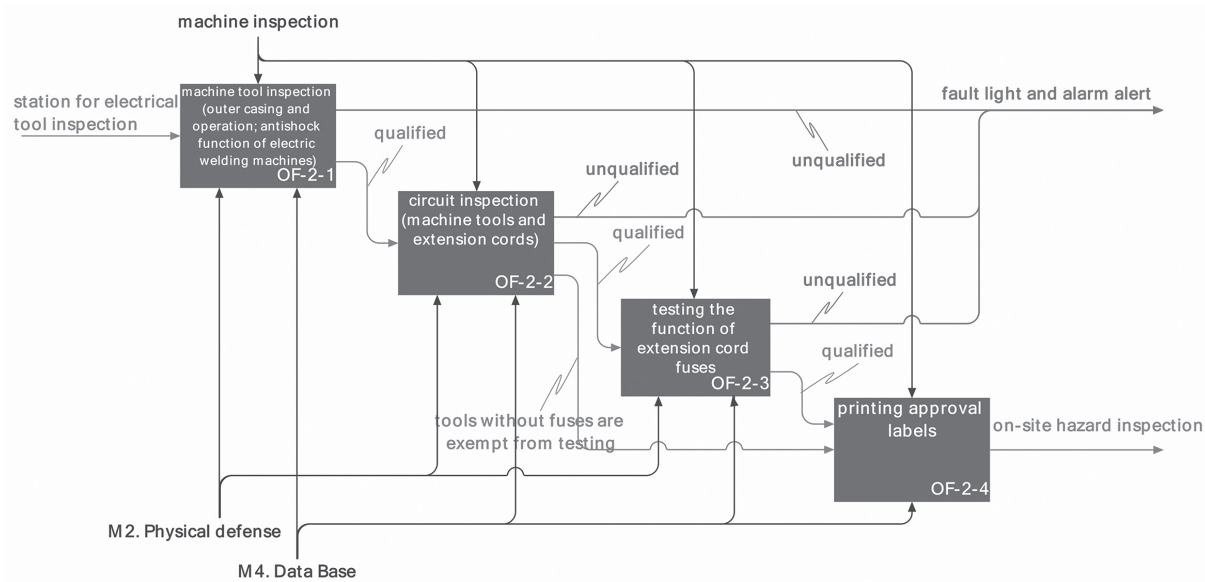

Fig. 5. Operation of electrical tool inspection station.

the regulations in the process must return to the previous station to re-test. If they are still unqualified, they are asked to leave. Each station (functional block) is described as follows.

-The OF-1 functional block: equipped with PPE

Direct contact with hazardous substances can be blocked by PPE and includes helmets, gloves, protective shoes, and goggles[31]. PPE serves as segregation between the user and the workplace and reduces the exposure of users to physical, electrical, thermal, chemical, and other hazards[32]. Therefore, adequate and qualified PPE must be provided to workers before they enter the construction site to maintain basic protection.

-The OF-2 functional block: Inspection station for electrical tools

After the OF-1 functional block has been completed, OF-2 (Fig. 5), which is related to electrical tool testing, is initiated: this comprises, in sequence, OF-2–1 machine tool inspection (i.e., inspection of outer casings, operations, and the antishock function of electric welding machines), OF-2–2 circuit inspection (i.e., machine tool circuits and extension cords), and OF-2–3 inspection of extension cord fuses. OF-2–4: A printed approval label (valid for 3 months) is placed on the machine tool that has passed the inspection, or a fault light and alarm alert are triggered for tools that do not pass. All inspection data are stored in the database.

-The OF-3 functional block: on-site hazard inspection

Turning off the power prior to an operation is an effective preventive method that complies with safety procedures and regulations[33]. A coordinated effect created with power company or partners to double confirmed that turning off the power, also can strengthen physical protection[34]. The OF-3 functional block of the on-site hazard inspection is completed after OF-2 (Fig. 6). Only after confirming the physical defense (OF-3–1 coordinated power cut-off, OF-3–2 insulation of protective equipment, and grounding) and the environmental defense (OF-3–3 locking and labeling of the switch box, OF-3–4 delineation of the safety distance, and barricading) can the operation begin. The omission of any defense requires the labor health and safety management staff or supervisor to be notified immediately for confirmation.

-The OF-4 functional block: construction of the operation system

The final level is the technical defense of personal expertise in the construction system, such as electrical safety knowledge among workers and hazard awareness and identification abilities; this reduces the risk of accidents caused by cognitive errors and thereby strengthening the productivity of labor skills and construction quality.

Discussion

To ensure the feasibility of the proposed early intervention mechanism, this study specified internal control (e.g., investing in inspection equipment resources, preparing sufficient PPE, and controlling productivity) and coordinated

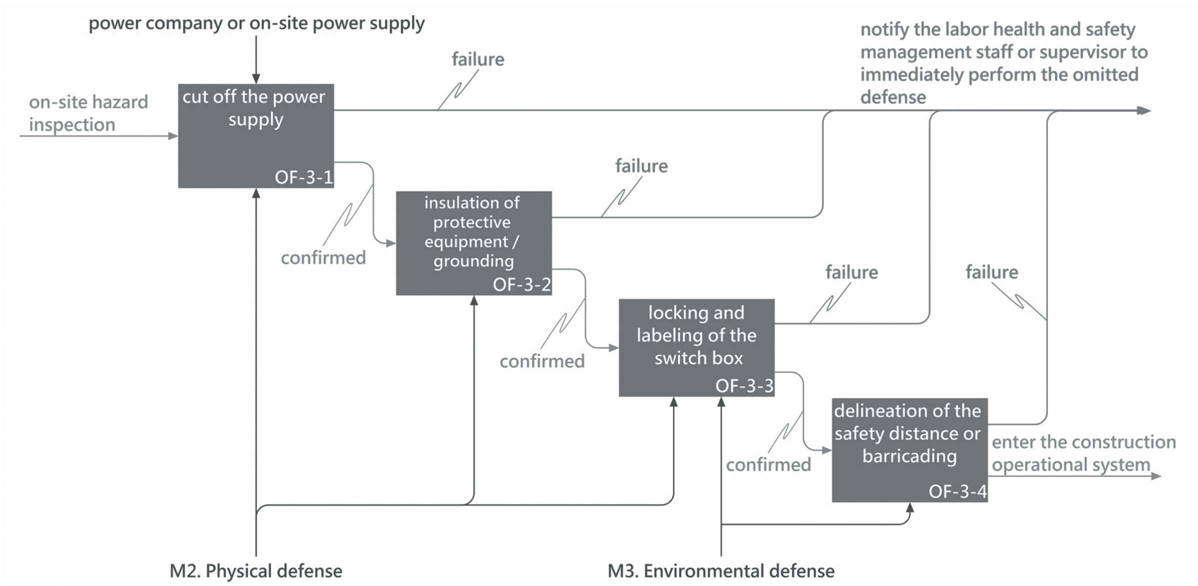

Fig. 6. Flowchart of on-site hazard inspection.

external control in accordance with occupational safety and health policies. Moreover, physical, environmental, and technological defenses and the database are incorporated into the mechanism. Following the IDEF0 process, the six operating features of the construction system are discussed.

-Feature 1 (Node 1): Regarding mobile operations such as regional power wiring, the hazard risk (from improper or non-use of insulating protective tools and equipment, lack of grounding, or a damaged or nonfunctional residual current circuit breaker) can be considerably reduced through the early intervention mechanism in the event of operation of support equipment (e.g., stepladders and scaffolds), construction vehicles (e.g., derrick cranes and bucket lifts), and other conductive media. In terms of pressure-induced insulation deterioration of cables and wires, workers who use electrical hand tools, who are often surrounded by extension cords scattered everywhere on the construction site, have high risk of an electric shock accident caused by a damaged or nonfunctional residual current circuit breaker[14)]. Use of a cable hanging system is suggested to prevent pressure-induced damage.

-Feature 2 (Node 3): Regarding fixed-point operation such as power line inspection and repair, the hazard risk (from improper or nonuse of insulating protective tools and equipment, insufficient or no operational hazard identification, and a lack of safety labels and monitoring) can be considerably reduced through the early intervention mechanism in the event of using metal materials or tools or having direct contact with conductive media such as the power supply, cables, wires, electricity generation or substation equipment, switch boxes, and junction boxes.

-Feature 3 (Node 4): For power line installation and repair, the hazard risk (from improper or nonuse of insulating protective tools and equipment, insulation failure caused by grounding, and damaged or lack of required components in an electrical machine tool) can be considerably reduced through the early intervention mechanism in the event of using or direct contact with conductive media such as electrical equipment, pipelines, utility poles, and other conductive structural materials.

-Feature 4 (Node 5): For live line operations and objects (e.g., installation, testing, maintenance of electrical panels, elevators, fuses, alternating current, low current, lighting equipment, and other electrical components in building systems), operation of hoists or mobile cranes for hanging or moving building materials, and operation of construction vehicles (e.g., ready-mixed concrete trucks and pump trucks), the hazard risk (from improper or nonuse of insulating protective tools and equipment or defects in safety procedures or preventive design) may be greatly reduced by the early intervention mechanism when using portable electric motors and electrical hand tools.

-Feature 5 (Node 6): For sporadic work (e.g., welding, drilling, chiseling, piping, hydropower engineering, and waterproofing), the hazard risk (from damaged or lack of required components in an electrical machine tool, improper or nonuse of insulating protective tools and equipment, insulation failure caused by grounding, a lack of grounding or a damaged or nonfunctional residual current circuit breaker, insulation breakdown in wires, and a lack of safety labels and monitoring) can be substantially decreased through the early intervention mechanism when using portable electric motors, electrical hand tools, or other conductive media.

-Feature 6 (Node 7): Regarding building-related construction processes and objects (e.g., installation, inspection, wall painting and maintenance, windows, roofs, steel structure assembly, hoses, formwork, sealing, fences, cleaning, and operations regarding other nonelectrical building components), the hazard risk (from damaged or lack of required components in an electrical machine tool, a lack of grounding, and a damaged or nonfunctional residual current circuit breaker) may be greatly reduced by the early intervention mechanism when using conductive media such as portable electric motors and electrical hand tools.

Branched out from Node 2, the aforementioned characteristics 4–6 (Nodes 5–7) were electrocution incidents caused by the use of low-quality portable electrical tools. These occurrences include live line operations, sporadic repair operations, sporadic construction projects, and the operation of portable construction vehicles, all of which accounted for 35.4% of the items omitted in construction safety management. Considering the statistics, the construction industry should strengthen the safety management of electrical tools. Through the determination and summarization of characteristics, all functional blocks expanded using the early intervention mechanism indicate that early intervention mechanisms function as more effective mitigation measures.

Conclusion

This study aimed to develop an effective intervention mechanism for preventing electrocution in construction engineering, thereby increasing labor safety and reducing the casualty risk. Employing NTA and the Haddon Matrix for data collection and compilation, this study analyzed cases of electrocution in 2006–2015 among major occupational disasters in the construction industry to determine the factors causing electrocution incidents. Optimal segmentation of the correlations was performed using exhaustive CHAID. In the mistake-proofing framework established on the basis of TRIZ, the IDEF0-based integration for process modeling of the early intervention mechanism was combined with a database for electrocution prevention among construction engineering units.

This study revealed six operating features related to electrocution hazards, namely regional power wiring, power line inspection and repair, power line installation and renovation, live line operations, operations of construction vehicles, and sporadic work. The process modeling composite map of the early intervention mechanism can be used to eliminate possible hazards due to human negligence in advance, achieving early intervention for electrocution prevention.

This study made three specific contributions as follows. First, according to its analysis of 113 electrocution deaths, this study determined the correlations between operating features and conductive media, revealing the entry point for interventions on electrocutions in building engineering. Second, this study employed PtD to demonstrate how source hazards can be eliminated and an electrical tool inspection station, related to electrical tool testing, established to ensure the safety of portable electrical tools carried by construction workers. Third, through the joint application of TRIZ and IDEF0, this study established an early intervention mechanism for pre-entry testing to ensure that workers can do their jobs safely, thereby strengthening the productivity labor skills and construction quality to make construction work going smoothly.

Health and safety education and training can enhance workers' understanding of related procedures and early warnings regarding hazards, thereby preventing accidents. In order to raise workers' attention to potential hazards, safety signs can be used to warn construction workers and reduce their risky behavior[35]. Therefore, in addition to strengthening the posting relevant safety signs in different work areas, engineering units should provide a manual on hazard response measures by immediately, and arrange health and safety education and training as soon as possible.

Taiwan currently has 448 inspection stations for electrical tools in construction sites, technical factories, or public utilities. They are typically installed at the site entrance to prevent electrical shocks caused by malfunctioning electrical tools and are responsible for safeguarding work sites. Installing inspection stations for sporadic or short-term constructions is difficult.

Installing inspection stations for sporadic or short-term constructions is difficult. We recommend that competent authorities install inspection stations at each district's labor inspection office for regular inspection of electrical tools.

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