An Application of Fuzzy Fault Tree Model in A Mass Transit Project

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Abstract

As the complexity of construction projects increases, construction duration, project size, and the number of accidents are likely to increase accordingly. The objective of this paper is to demonstrate the assessment of Safety Index (SI), focusing on causes of construction accidents due to complex construction works. By using Fault Tree Analysis (FTA) and Fuzzy Set Theory (FST), Safety Index is derived from the relationship between the possibility of accidents calculated from the fuzzy fault tree model and the severities of accidents calculated from the number of lost working days. Once the causes of accidents have been identified and illustrated on fault tree diagram (FTD), the possibilities of accident causes are represented on the membership functions of fuzzy sets. The possibility of accidents will be analyzed based on fuzzy rules. As each construction project is unique, the historical data of accident causes could not be appropriately used to predict the accident occurrence in the future. In addition, the historical data of accident causes could not be collected and counted directly. As a result, the possibility is more suitable to use than the probability which depends merely on the historical data. A fuzzy set, considered a subjective measure, is employed to evaluate the possibility of accidents. The Safety Index analyzed by the proposed method can be used to assess the safety in any complex construction projects.

Keywords

Safety Index, Fault Tree Analysis, Fuzzy Set Theory

1. Introduction

Construction works are hazardous. According to the accident report of construction prepared by the Department of Labor, in the year 1999 there were 231 deaths, 394 permanent disabilities, and 38,222 temporary disabilities. Table 1 shows statistics of accidents related to construction works reported to the Department of Labor. This statistics did not account for the accidents which were under-reported.

The losses from accidents are critical for the contractor, owner, and public. Construction workers are exposed to several sources of accidents. Several research works have been examined accident records to categorize most common sources of accidents that occur in specific construction projects. They reported that most fatalities in construction project occurred due to falls (Abdelhamid, 2000).

To provide safety in construction sites up to an appropriate safety level, many proactive methods such as various safety controls are employed. Safety controls can be classified into two types:

1) Personal protective equipment: safety helmets, safety goggles to protect against high energy particle, dust and radiation, face shields, footwear with/without steel toecap, fabric glove, rubber glove and harness or lifeline.
2) General protective equipment: guardrail, toe board, debris net, signage, physical barrier, fire extinguisher.

The Safety Index can be used to assess the risk of sites during construction phase. Several available methods depending on the subjective evaluation of the probability of risks are introduced. In this paper, application of Fuzzy Set Theory in Fault Tree Analysis is proposed for assessing the Safety Index to overcome problems associated with the subjective measurement.

2. Current risk assessment method

Normally, risk is referred to as a probability distribution over a set of outcomes. A combination of the probability and degree of the possible injury or damage to health in a hazardous situation can be used to define risk (BS EN 292, 1991 quoted in Pillay A., 2001). Several methods have been used to assess construction safety, including Hazard and Operability studies (HAZOP) (Villemeur, 1992 quoted in Pillay A., 2001), Failure Mode and Effect Analysis (FMEA) (MIL-STD, 1629A quoted in Pillay A., 2001), Fault Tree Analysis (FTA) (Henley & Kumamoto, 1992 quoted in Pillay A., 2001). These methods are performed to identify, assess, and control risks for reducing causes of damages that could occur during construction. The risk assessment has three key activities, namely, hazard identification, evaluation of risks, and implementing prevention and protection measures. Possible accidents occurring in construction works are identified by the hazardous identification process. After a hazard has been identified, the Safety Index is calculated to evaluate risk and to consider suitable accident prevention measures. The quantification of Safety Index typically considers two parameters: the severity of accident and the probability of accident occurrence.

$$C = P \times E \tag{1}$$

where, C = Safety Index,
P = Probability of accident occurrences, and
E = Severity of accident,

The likelihood of an accident occurrence and the consequence severity are usually estimated based on historical data, subjective reasoning, and expert judgment. Data and their interpretation in the construction industry are difficult to obtain. This problem leads to dobts in their quality, completeness, and relevance. In the case of data related to material and equipment failures, the attributes of material or equipment are rarely recorded, and insufficient data are given in the context of its operation, which may be difficult to quantify the probability and severity of an accident. Generally, subjective descriptors are used to describe the construction safety through the subjective response method. The subjective response method considers the severity of accident as a level condition that would be generated and the probability of occurrence as the frequency of hazardous condition. The appraisal criteria for the severity of accident and the probability of accident occurrence are based on bivalent set theory (Griffith, 2000). However, these subjective descriptors are fuzzy in nature. Therefore, fuzzy set modeling approach may be more appropriate to model the probability and severity of an accident occurrence.

3. Fuzzy set theory (FST)

FST was developed by Zadeh, L.A. (1965 quoted in Zadeh L.A. (1987),) and has been widely applied in several fields, including safety, reliability, project scheduling, quality management, facility location and layout, and inventory planning. Fuzzy variables significantly facilitate gradual transitions between states. Consequently, it identifies and measures uncertainties. In contrast, the crisp variables do not have this capability. Thus, uncertainties will be ignored when crisp variables are used. Humanistic problems are limited when applying bivalent set theory. Furthermore, if a variety of stochastic models or stochastic probability distributions are used to determine uncertainties in the risk factors, correct types of distribution are difficult to extract because of unavailable information. Moreover, parameters associated with the selected distribution are difficult to determine.

4. Fuzzy fault tree model

The proposed model is divided into two main processes: the accident cause identification and the safety assessment. It involves several steps, as shown in the flow chart in Figure 1. A combination of FTA and FST is used to accomplish the modeling of the two parameters (accident possibilities and cause possibilities). The severities of accidents are calculated from the number of lost working days, the outcome of which is a Safety Index.

4.1 Identifying causes of accidents by fault tree analysis (FTA)

The correctness of the proposed model depends mainly on the identification of the root causes of construction accidents. In the first part of the proposed model, the steps for constructing a fault tree diagram are as follows:

1) Investigate the accident and analyze all causes of accidents;
2) Determine the criterion of each basic event (causes of accident) that has relationship with the top event (accident);
3) Classify basic events into categories according to the relationship with the top event; and
4) Construct the FTA Logic Diagram. The symbols used in the FTA Logic Diagram are called Logic Gates (i.e., AND and OR gates).

Types of Logic Gates and a simple FTA Logic Diagram are shown in Figure 2.

Figure 2 shows a simple FTA Logic Diagram. This FTA Logic Diagram contains 13 types of accident causes, which are the input for the logic gate. The top event or the output of logic gate is the accident from working in construction sites. The gate above the events (accident causes) shows the relationship of each event within the FTA Logic Diagram. The AND gate describes an intermediate event (GTOP) that occurs only when all of underlying events (G1, G2, G3) occurs. The OR gate shows that the intermediate event (G2) and (G3) will occur when either basic events (G11, G12, G13, G14, G15, G16) or basic events (B33, B34, B35, B36, B37, B38) occurs, respectively. The name of basic events is shown in circles. The possibility of accident occurrence within the construction works can be inferred from the FTD.

4.2 Analyzing possibilities of accident caused by fuzzy set theory (FST)

In this FTA, a fuzzy set is considered a subjective measure to evaluate the failure possibility of events on the tree. A fuzzy set is defined on a unit interval [0,1], having the following properties and membership functions (F(x)) (Onisawa, T., 1996):

1) The fuzzy set is normal and convex; that is, the height of a fuzzy set being the largest membership value equal to one and any α-cut in the interval [0,1] of fuzzy set gives a convex set. Since it is easy to express a failure possibility by natural language expression.
2) $F(1) \neq 0$ and $F(0) \neq 1$, since even if the risk is quite high, an accident does not necessarily occur, and even if risk is quite low, an accident may occur.

Equation 2 provides one of the membership functions of the fuzzy set which satisfies the above properties and this paper employs this equation as a primary membership function of linguistic variables to analyze risks in the proposed model.

$$F(x)=\frac{1}{\left(1+20\left(x-x_0\right)^m\right)} \quad (2)$$

where, x_0 and m are parameters and $0 \leq x, x_0 \leq$

The parameter x_0 gives a maximal grad of F(x) and the parameter m is related to fuzziness. From this equation, if the subjective risk is low then the value of x_0 is small. In addition, if the subjective risk measure is fuzzy then the value of the parameter m is large. In the proposed model, information used to formulate fuzzy sets is delivered from two sources: numerical information and natural language information. The uncertainties can be transferred into the membership function via the transformation equation $f(P_m)$. Equation 3 shows one of transformation equation applied in this model

$$x_0=f\left(P_m\right)=\frac{1}{\left(1+\left(\frac{\log P_m}{\log P_s}\right)^3\right)} \quad (3)$$

where, P_m is a recommended value of the failure rate of a basic event, and P_s is a standard rate.

To consider these uncertainties, a failure rate is treated as an estimated parameter given by a trinomial set such as $[P_l, P_m, P_u]$ where P_l and P_u are lower and upper bounds of a recommended value of the failure rate (P_m). P_s is a standard rate determined by an analyst, meaning that the analyst considers subjectively that failure rate of basic event in a considered condition should be P_s. The standard rate P_s depends on analyst's judgment, level of education, assurance, and experience, and the nature of analyzed conditions as well as the complexity of working and conditions for judgments. Parameter m is used to express the fuzziness of an estimated parameter represented by $[P_l, P_m, P_u]$. Ratios P_m/P_l and P_m/P_u need to be considered. It is assumed that the larger the ratios, the fuzzier the estimated risk. In this paper, the parameter m is defined as shown in Table 2 where the parameter k is defined by P_m/P_l or P_m/P_u.

Natural language information is largely employed to express linguistic variables. This paper aims to apply the natural language expressions to evaluate construction risks. The proposed model represents risk estimates by natural language, where numerical information cannot be given exactly. The model is based on the assumption that when dealing with incomplete database of the failure rate, as usually found in accident evaluating process, linguistic terms are more appropriate for expressing risks from accident causes than numerical terms are. In general, four possible grades of uncertainties described by the linguistic terms: "very small", "small", "fair", and "very large", are used to represent the subjective risk parameter (x_0) and the fuzziness parameter (m). Table 3 shows the classification of natural language expressions or linguistic terms of risk estimates that represent the degree of uncertainties. This model uses natural language expression of risk estimate, as shown in Table 3. Their fuzziness shown in Table 2 is used to express uncertainties associated with linguistic variable (e.g., the failure rate of basic events).

The proposed model uses a fuzzy set with the membership function (Equation 1) to represent the meaning of the linguistic terms of the linguistic variables. The parameter x_0 and m correspond to natural represent language expressions of risk estimate and its fuzziness, respectively. To transfer uncertainties associated with the linguistic variable into membership function, the correspondence of parameters x_0 and m with the linguistic terms is defined subjectively instead of using Equation 2 and ratios (P_m/P_l or P_m/P_u). The fuzziness of an estimated parameter given by linguistic terms is expressed by using parameter "m." The definition of values for parameter m for translating either numerical or natural language information into membership function of the fuzzy variable is the same; that is, the fuzzier the estimation, the larger the parameter value.

In the proposed model, FST is applied to FTA to quantify the failure possibility resulting from accidents. Two types of gates are often displayed in FTD: AND gate and OR gate. Failures of the subsystems A and B connected by AND gate and OR gate lead to the failure of the parallel system and series system, respectively. Initially, the subsystems are treated as an independent subsystem. Failures of the parallel and series system are obtained by using intersection and union operations. Subsystems A and B are presented by the membership functions of fuzzy sets A and B. Membership functions of the union and intersection of A and B are transformed from the membership function of fuzzy sets A and B. An s-norm is used for quantifying the failure probability and possibility of a series system. The algebraic sum is one of s-norms, $S_{as} = P_A + P_B - P_A P_B$, where P_A and P_B are failure probability or possibility of the subsystems A and B, respectively. A t-norm is used for quantifying the failure probability and possibility of a parallel system. The algebraic product is one of t-norms, $T_{as} = P_A P_B$. Parametrized s-norms and t-norms are appropriate for the subjective analysis of risk within the system because the parameters can reflect the analyst's subjectivity. The classes of s-norms and t-norms cover the range of risk evaluation from the pessimistic evaluation through the optimistic one, while for a non-fuzzy set (a crisp set), only one type of operation is possible for union and intersection operations.

Simple types of operations for union and intersection of fuzzy sets have been developed. Examples for s-norms are Dombi class (Dombi, 1982), Dubois-Prade class (Dubois-Prade, 1980), Yager class (Yager, 1980), Drastic sum, Einstein sum, and Algebraic sum. Examples for t-norms are Dombi class (Dombi, 1982), Dubois-Prade class (Dubois-Prade, 1980), Yager class (Yager, 1980), Drastic product, Einstein product, and Algebraic product (Wang, L, 1997). The proposed model uses the algebraic sum and algebraic product for quantifying the failure possibility of series and parallel systems, respectively.

5. Implementation

5.1 Accident data

This paper implements the fuzzy fault tree model in the Metropolitan Rapid Transit project (MRT), Chaloem Ratchamongkhon Line, as a complex construction project. The structure of the subway consists of twin single-track tunnels with 5.7 m. in diameter constructed side by side. The vertical alignment ranges from approximately 15 to 25 m. below the existing road surface, is determined for pilot assessment.

The accident data used for a pilot study are collected by the responsible authority within the construction sites of the subway stations. According to the accidents/incidents report from subway stations, in the year 2000, there are 113 accidents/incidents in the work zones, which are divided into 9 classes, the number of accidents/incidents in each class are shown in Table 4.

5.2 Analyzing accident causes

Firstly, the specific accident causes are identified. Data resources are collected from both safety handbooks and the interviews with the safety experts and the health and safety executives in construction sites. In the FTA Logic Diagram, the top failure event is "Accident in construction site (Area 1)" (G1). The accident causes affecting workers include historical (G4), economical (G5), psychological (G6), technical (G7), procedural (G8), organizational (G9) and environmental (G10). The accidents can occur from any of these accident causes. Consequently, the criterion among these seven causes is an OR gate. Figure 3 shows FLD representing the causes of accidents associated with workers. Each cause can be expanded into sub-causes and the relationship between each cause is an OR gate since any single cause beneath each cause can be a cause of an accident.

5.3 Evaluating possibilities of accident causes

In this paper, it is assumed that two assessors (construction professional and researcher) develop the fault tree. The possibilities of basic event occurrences, which are fed to FTD, can be represented by membership functions of fuzzy sets. From the accident data and a consideration of accident causes from the interviews, both numerical and natural language information is employed to assess the failure rate and its fuzziness of these events. Fuzzy rules are performed based on relationships among events illustrated by FTD. The possibility of accident occurrence is calculated by MATLAB[1] program. This paper uses the union of the results among all assessors and then the reliability of this system is estimated as rather low by mutual agreement.

5.4 Evaluating Safety Index

The possibilities of accidents can be calculated from the fuzzy rules that are inferred from FTA Logic Diagram. From accidents/incidents reports collected within the MRTA blue line project and evaluated from the proposed model, the possibility of accident is "low" (0.20 occurrence/200,000 man-hours). The data related to severity of accident is available. The average of the severity of accidents calculated from average days lost per accident occurrence is employed to be the severity of accidents that will be input for Equation 1. The severity of accidents is 14.36 lost workdays/occurrence. From the above information, the Safety Index is computed from Equation 1, and the result is 28.72 lost workdays/occurrence. The result of the accident cause analysis suggests that the accident causes are related to the psychological aspect, such as reckless disregard for safety, which is the most dominant cause that influences the safety of workers.

6. Conclusions

This paper proposes Safety Index model by applying the Fault Tree Analysis (FTA) and the Fuzzy Set Theory (FST). The accident causes are identified and the possibility of accident is evaluated by the means of FTA. FST is used to aid the FTA in representing the possibility of each accident cause and analyzing the possibility of accident according to fuzzy rules. An advantage of FTA method is high degree of accuracy. FTA can be used to synthesize the complex relationship among each accident cause. Since the historical data of accident causes could not be collected and counted directly, the application of the FTS is used to represent the possibilities of accident causes by the membership functions of fuzzy sets. FTS can be employed to calculate the overall possibilities of accidents by reflecting either the relationship between accident causes in FTD or assessor's subjectivity. The reliability of possibility of accidents depends on membership function of basic events, types of relationships between basic events, levels of basic events in FTD, and number of basic events. Based on these benefits of FST, the possibilities of accident causes (input for FTD) and formula (used to analyze the possibility of accident) can be obtained in a relatively simple manner.

7. References

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[1] MATLAB is a commercial program in engineering and science, which can handle data acquisition and analysis to application development.

Table 1 The accident report from Department of Labor

Year	Death	Permanent Total Disability	Permanent Partial Disability	Temporary Disability > 3 Days	Temporary Disability < 3 Days	Total
1999	231	11	383	11,269	26,953	38,847
2000	168	5	252	7,577	17,017	25,019
2001	108	2	137	4,912	12,180	17,339
2002	104	8	134	3,536	9,611	13,393
2003	97	7	127	3,373	10,182	13,786

Table 2 Parameter m and natural language expressions about fuzziness of possibility estimate

Class	Parameter k	Parameter m	Natural language expressions of fuzziness
1	$k \leq 3$	2.0	Low
2	$3 < k \leq 5$	2.5	Medium
3	$5 < k \leq 10$	3.0	Rather high
4	$10 < k$	3.5	High

Table 3 Natural language expression about risk estimate and parameter x_0

Class	Expressions of risk estimate	Parameter x_0	Representative value	Class	Expressions of risk estimate	Parameter x_0	Representative value
1	Impossible (no risk)	-	0	7	Standard risk	0.45-0.55	0.5
2	Next to impossible	0.0-0.05	0.025	8	Rather high risk	0.55-0.7	0.625
3	Extremely low risk	0.05-0.1	0.075	9	High risk	0.7-0.8	0.75
4	Quite low risk	0.1-0.2	0.15	10	Quite high risk	0.8-0.9	0.85
5	Low risk	0.2-0.3	0.25	11	Very high risk	0.9-0.95	0.925
6	Rather low risk	0.3-0.45	0.375	12	Extremely high risk	-	1

Table 4 the accidents/incidents record in year 2000 from subway station in Bangkok

Class No.	1	2	3	4	5	6	7	8	9
Description	Fatal	Serious	Public accident	Public incident	Public awareness	Utility damage	Traffic stop	Work stop	General traffic incident
Number accidents/incidents	0	85	0	4	5	14	0	0	5

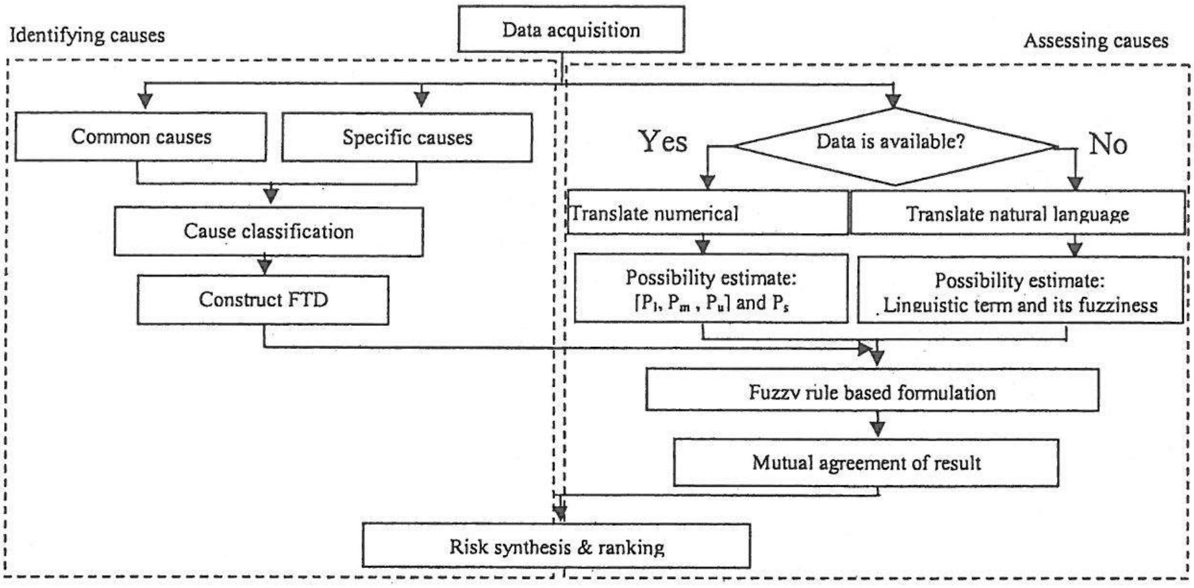

Figure 1 Flowchart of proposed safety assessment modeling approach

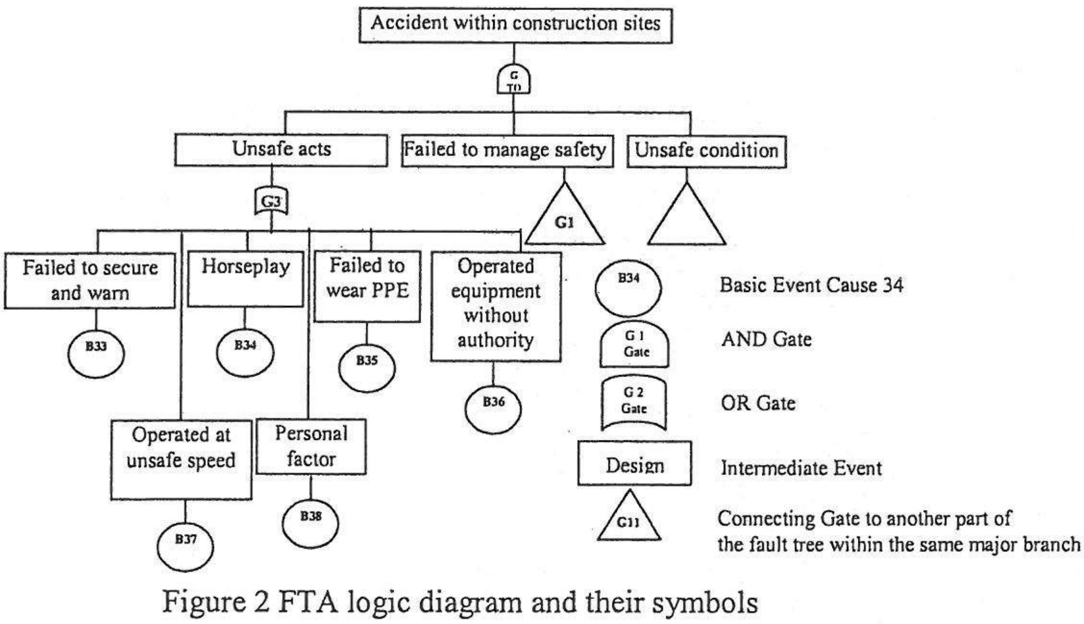

Figure 2 FTA logic diagram and their symbols

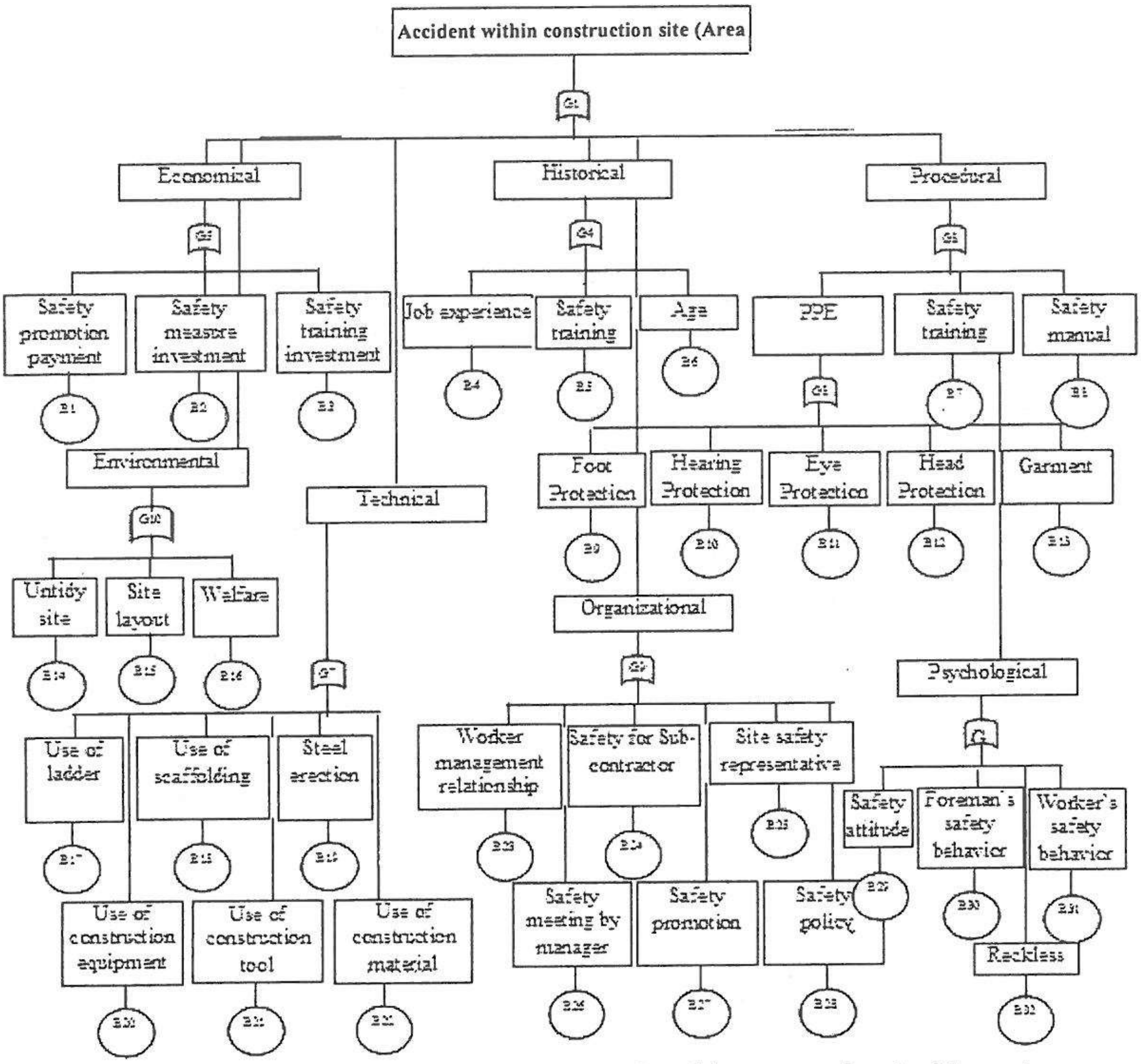

Figure 3 Fault tree diagram represents the causes of accidents associated with workers