# Using Fault Tree-Derived Bayesian Networks and Sensitivity Analysis for Probabilistic Risk Assessment of Quarry Accidents in Libya

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استخدام الشبكات البايزية المشتقة من شجرة الأخطاء وتحليل الحساسية لتقييم
المخاطر الاحتمالية لحوادث المحاجر في ليبيا

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**الملخص:**

تُشكِّل الشبكة البايزية المُستمدة من تحليل شجرة الأخطاء الأساسَ لهذا البحث في بناء إطارٍ للتقييم الاحتمالي للمخاطر، يمكن تطبيقه على الحوادث القاتلة في المحاجر. يُحدد النموذج المُقترح كميًا حوادث مثل الحرائق والمخاطر الكهربائية، ومخاطر التفجير، وحوادث النقل والآلات، وانهيارات المنحدرات. تم بناء جداول الاحتمالات الشرطية (CPTs) باستخدام بيانات مُستقاة من مُدخلات الخبراء واستشاراتهم. ثم أُدخلت هذه البيانات في برنامج GeNIe لتحليل مستويات الحساسية والاستدلال. وتُظهر نتائج التحليل أن أبرز العوامل المساهمة في وفيات المحاجر هي حوادث النقل والمرور (0.96)، تليها حوادث الآلات (0.94) ثم مخاطر التفجير (0.94). ويسهم النموذج المقترح في دعم عملية اتخاذ القرار في بيئات المحاجر من خلال ترتيب أولويات إجراءات السلامة، ولا سيما في البلدان التي تعاني من نقص في البيانات مثل ليبيا.

**الكلمات الدالة:** الشبكة البايزية، تحليل شجرة الأخطاء، ليبيا، تقييم المخاطر الاحتمالية، تحليل الحساسية.

**Abstract**

A Fault Tree Analysis-derived Bayesian Network forms the basis in this research for a probabilistic risk assessment framework that can be applied to life-threatening quarry events. The proposed model quantifies incidents such as fire and electric hazards, blasting hazards, haulage and machinery accidents, and slope failures. Conditional probability tables (CPTs) are built using data sourced from the expert input and consultation. The data are then input into GeNIe software to analyze sensitivity and inference levels. Analysis of these data shows that the main events contributing to quarry fatalities are haulage and traffic accidents (0.96), followed by machinery accidents (0.94) and blasting hazards (0.94). The proposed model contributes to the decision-making process in quarry environments by prioritizing safety, especially in data-scarce countries like Libya.

**Keywords**: Bayesian Network, Fault Tree Analysis, Libya, Probabilistic Risk Assessment, Sensitivity Analysis.

# Introduction

Quarry operations supply the materials used in a broad range of building applications. More specifically, the raw materials for activities such as cement manufacturing, road building, and large-scale construction projects all come from quarrying. The primary raw materials obtained from quarries include marble, gypsum, sand, and aggregates. In war-torn and developing countries such as Libya, quarrying is critical not only to reconstruction activities, but also to the expansion of existing infrastructure. The current rapid growth trend in urbanization has heightened the need for quarried materials globally. This need is expected to increase substantially in the coming years.

Along with being a high-demand industry, quarrying is also among the most dangerous. It includes activities such as crushing, blasting, drilling, and heavy machinery operation, all of which can be hazardous both for the equipment operators and for those in the work area and vicinity. According to the Health and Safety Executive (HSE) in the United Kingdom, the rate of quarrying-related injuries, including fatalities, is around four times higher than general construction-related injuries and death [1]. The Mine Safety and Health Administration (MSHA) in the United States has compiled similar statistics, revealing that from 2010 to 2020, more than 150 workers lost their lives in quarrying accidents. Of these, around 50% of the deaths were caused either by heavy machinery or haulage events [2].

The death toll from workplace accidents in developing countries is even higher. For example, India has recorded around 250 accidental deaths in the past decade alone from quarrying and surface mining operations. In these cases, the main hazards leading to the fatalities were determined to be unsafe blasting conditions, collisions, and slope collapses [3]. Quarries located in South Africa and China also experienced numerous blasting incidents that resulted in severe injuries and fatalities among the work force. Most of these incidents were caused by flyrock, misfires, inadequate training, and poor charge control [4-5].

Officially, there are no reported fatalities in Libyan quarries. However, rather than indicating a nation-wide exemplary work environment, the absence of fatal accident reports is most likely the result of under-reporting. There is no centralized tracking system for industrial accidents in Libya, which means that when such accidents do occur, they remain an uncompiled statistic. Having no record of safety data effectively hinders occupational risk management by preventing the development of safety policies that are evidence-based. In other words, industries in Libya cannot "learn from their mistakes" if there is no record of their mistakes to learn from.

Data-scarce environments, like Libya or to a lesser degree China, India, and other developing nations, can benefit from probabilistic risk modeling tools. Such tools provide scenario-based analysis and causal logic to make up for missing statistics [5-8]. Bayesian Networks (BNs) and Fault Tree Analysis (FTA) can be applied to industrial hazards by reasoning and representation. By leveraging new evidence, BNs support dynamic updating for risk probabilities as well as probabilistic reasoning, while FTA supports hierarchical (top-down) decomposition of the causes of accidents, framing them into logical relationships [6-7].

The present research proposes the construction of a BN risk assessment model based on an FTA, aiming to determine the primary causes of quarry fatalities in Libya. The proposed BN framework employs conditional probability tables (CPTs) as well as inference techniques. GeNIe software is used to identify and estimate hazards and accident probabilities,and to formulate and prioritize safety interventions. Such a model is urgently required in Libya due to the country's complete lack of accident data, which prevents the application of standard safety analysis strategies. The proposed model, by providing data-informed risk assessments, will contribute to the development of industrial safety policies in Libya while also helping to prevent quarry-related accidents and fatalities.

## Literature Review
### Slope Stability and Geotechnical Risks

Slope instability is a common hazard encountered during quarrying. Its chief causes include bench collapses, rockfalls, and catastrophic landslides. Slope stability is traditionally assessed using methods based on deterministic analyses, but these approaches cannot take geotechnical parameter uncertainty into account. To obtain a more accurate slope safety assessment, researchers are pivoting towards reliability-based and probabilistic strategies. For instance, in [9], Görög and Oláh performed a probabilistic stability analysis for a dolomite quarry in Hungary. The analysis of the open-pit site showed that probability distributions rather than deterministic safety factors are better

able to describe slope reliability [9]. In [10], Ankah et al. also used a probabilistic framework (Monte Carlo-based) for an open-pit mine, aiming to measure bench failure risks at a Ghanaian location. In [11], Tsevegmid et al. incorporated 3D analysis into the probabilistic model to account for excavation sequence, slope geometry, and rock heterogeneity. The researchers argued that earlier 2D models, being too simplistic, could not adequately account for failure risk.

The findings of all the above research directly relate to quarry environments, as they involve blasting vibrations, slope geometry, hydrogeological changes, and other variabilities that interact in quarrying sites. Some studies, e.g., Jia et al. [12], used Bayesian-based methods to explore how changes in pore pressure due to seismic loading and blasting significantly decreased slope reliability. Such models employ real-time data from the field to update the probability of failure dynamically.

### Blasting Hazards and Accident Consequences

Blasting is a core operation in quarrying and also the primary cause of accidents on site. Slope destabilization, flyrock, and premature (e.g., mis-timed) firings constitute the main events. Research indicates that stress redistribution due to blasts can lead to failures both localized and/or large-scale. In [13], Yang et al. showed how cumulative disturbances resulting from repeated blasting compromises the slope integrity and causes instability of jointed rock mass. To better assess hazards caused by blasting and flyrock, **BLAIR** [14] developed a hybrid framework that combined probabilistic and statistical methods.

Recent research incorporates machine-learning (ML) strategies into proposed models for predicting blast configurations that can be hazardous. In [15], Wang et al. built a prediction model that uses two metaheuristic ML algorithms along with Light Gradient Boosting Machine (LightGBM) in order to gauge flyrock distance during blasting in open-pit mining. The team's data-driven hybrid strategy showed remarkable reliability and accuracy. These kinds of predictive models complement Event Tree Analysis (ETA) through a marked improvement in input reliability. Integrating them with BNs further enhances risk assessment accuracy for blasting and other hazardous operations.

### Probabilistic and Intelligent Approaches

Along with merging ML with traditional risk analysis approaches, researchers are also leveraging artificial intelligence (AI) and Bayesian reasoning in their analyses of hazard assessments. Lyu et al. [16] built a model for slope stability prediction using Bayesian optimization and a one-dimensional (1D) convolutional neural network (CNN). This hybrid 1D-CNN model showed greatly enhanced performance over traditional equilibrium approaches when applied to measuring open-pit mining risk conditions. Specifically, the model demonstrated how AI-boosted probabilistic frameworks are not only more accurate but also more adaptable when assessing slope stability for geotechnically and geometrically complex environments.

In related work, Mahmoodzadeh et al. [17] evaluated various ML strategies (e.g., Random Forest and ensemble methods), aiming to better predict failures in rock slopes. The researchers' findings indicate that including geometrical and geotechnical data in AI models leads to substantially improved results for both prediction and accuracy. They also found that using these data-driven decision-making tools led to more viable and practical slope safety management regimes.

Similarly, in [18], Rahimdel employed a BN to measure mining truck reliability. The proposed BN model provided a suitable framework for formulating probabilities of failure for haulage systems during times of operational uncertainty. The researcher found that BN analysis both enhances safety protocol decision-making and encourages proactive maintenance for transport operations in surface mining environments.

In related work, Zheng et al.'s [19] research gave a broad overview of how causality theory can be successfully merged into system safety and reliability models. Furthermore, the authors explained how graph-based reasoning and causal discovery algorithms significantly improve the generalizability and robustness of models, especially when applied to highly complex systems like those found in mining engineering.

### Methodology

#### Overview

The present work combines BN and FTA frameworks to predict fatal quarry accident probability in Libyan Quarries. The proposed model integrates quantitative probabilistic interference with qualitative hazard decomposition, aiming to update risk estimates in real-time as the data become available. The process has five steps, as shown in the Figure (1)
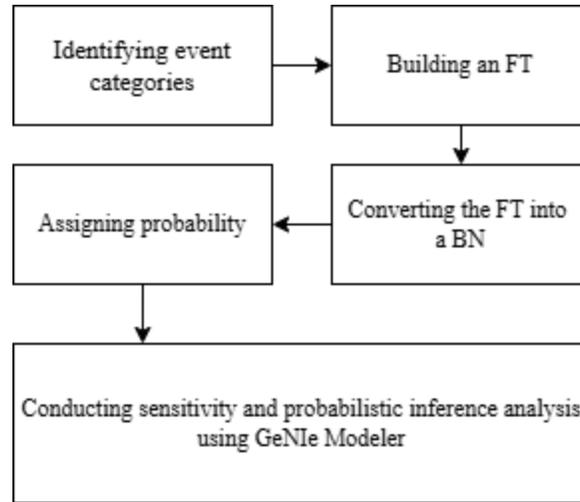
**Figure 1:** Flowchart for the proposed methodology.

## Fault Tree Construction

An FT model was built using Microsoft Visio to represent the causes underlying top events: Fatal Quarry Accidents. The six most common intermediate events were then added, as follows:

1. Machinery Accident
2. Blasting Hazard
3. Slope Failure / Rockfall
4. Traffic / Haulage Accident
5. Electrical / Fire Hazard
6. Environmental Hazard

Each of these six events was further decomposed into basic events (X1–X68). These events covered environmental, technical, operational, and human risk factors, such as X61—Heavy Rainstorm, X24—Faulty Detonator, X37—Weak Bedding Planes, and X3—Operator Fatigue / Error.

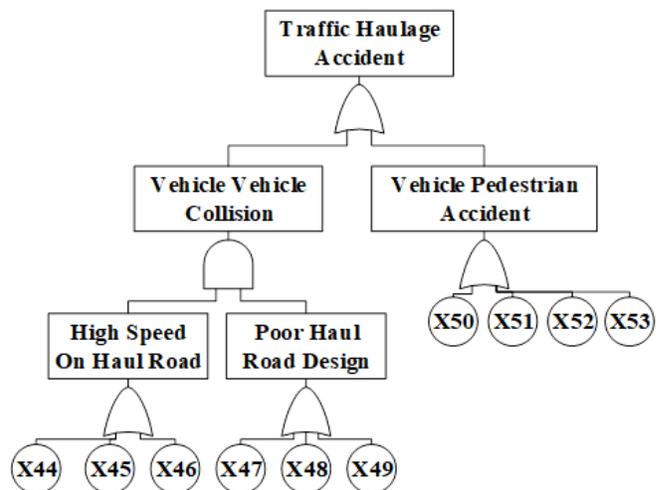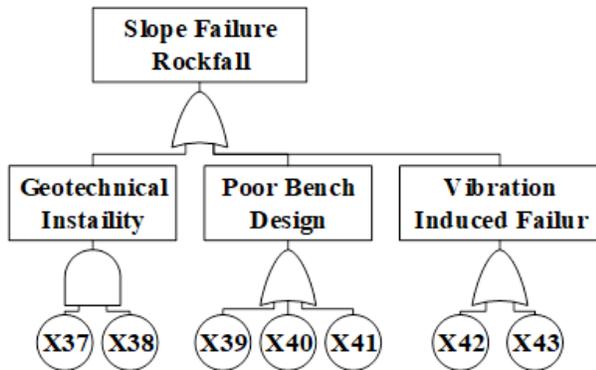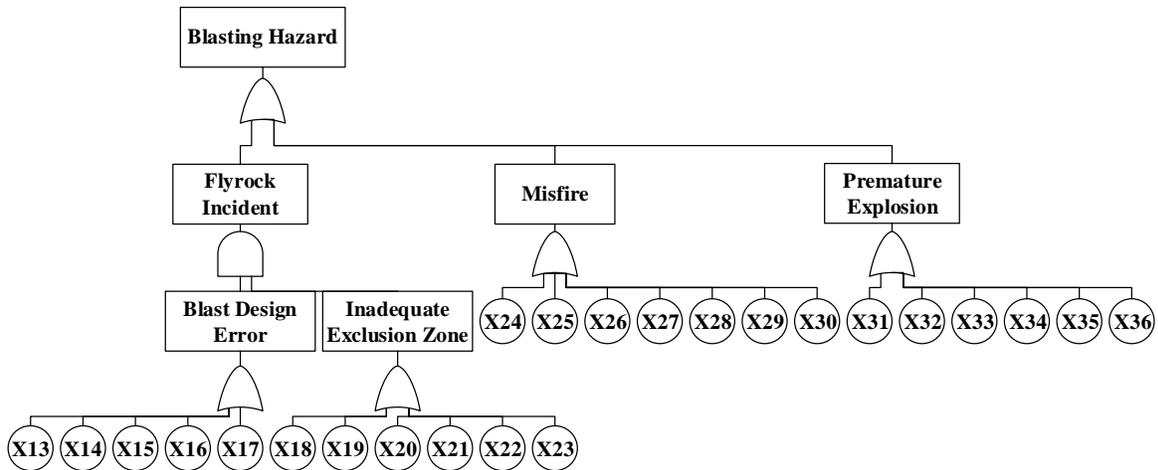The causal relationships were then modeled using logical gates. Specifically:

- AND gates denote events with numerous causes (e.g., Fuel Leak and Ignition Source → Fire Incident)
- OR gates denote events with one cause (e.g., Poor Visibility or Speeding → Traffic Accident)

A panel of five experts from the mining field (quarry operations, blasting, equipment maintenance, and geotechnical engineering) reviewed and validated the proposed FT.

Table 1. List of Basic Events (X1–X68) based on the expert knowledge

| Symbol | Basic Event Description | Assigned Probability (True) |
|---|---|---|
| X1 | **Excessive Slope Angle** | 0.06 |
| X2 | **High-Speed Machine** | 0.07 |
| X3 | **Operator Fatigue or Error** | 0.08 |
| X4 | **No Lockout / Tagout** | 0.06 |
| X5 | **Improper Tools** | 0.05 |
| X6 | **Inadequate Maintenance Training** | 0.07 |
| X7 | **Lack of PPE in Maintenance** | 0.05 |
| X8 | **No Spotter During Machine Operation** | 0.06 |

| X9 | Operator Distraction or Inattention | 0.08 |
|---|---|---|
| X10 | Malfunctioning Horn or Warning Light | 0.05 |
| X11 | Unauthorized Guard Removal | 0.04 |
| X12 | Lack of Safety Signage Around Equipment | 0.04 |
| X13 | Inaccurate Rock Density or Geology Data | 0.05 |
| X14 | Excessive Explosive Charge per Hole | 0.06 |
| X15 | Improper Selection of Stemming Material | 0.05 |
| X16 | Incorrect Burden and Spacing Calculations | 0.06 |
| X17 | Lack of Review by a Qualified Blasting Engineer | 0.04 |
| X18 | Incorrect Clearance Distance | 0.05 |
| X19 | Failure to Enforce Exclusion Area | 0.06 |
| X20 | Poor Warning Signals or Sirens | 0.05 |
| X21 | Lack of Supervision | 0.05 |
| X22 | Lack of Signage or Barriers | 0.05 |
| X23 | Untrained Personnel | 0.07 |
| X24 | Faulty Detonator | 0.04 |
| X25 | Damaged Electrical Cables | 0.04 |
| X26 | Water Ingress in Hole | 0.05 |
| X27 | Poor Priming | 0.04 |
| X28 | Cut Off Explosive Columns | 0.03 |
| X29 | Inadequate Initiation System | 0.05 |
| X30 | Incorrect Timing or Delay | 0.04 |
| X31 | Static Electricity Discharge | 0.02 |
| X32 | Stray Currents | 0.02 |
| X33 | Radio Frequency Interference (RFI) | 0.02 |
| X34 | Impact or Friction on Explosive | 0.03 |
| X35 | Lightning Strike | 0.01 |
| X36 | Improper Handling | 0.05 |
| X37 | Weak Bedding Planes | 0.05 |
| X38 | Rainfall or Water Ingress | 0.06 |
| X39 | Narrow Benches | 0.05 |
| X40 | Insufficient Bench Berms | 0.05 |
| X41 | No Scaling of Loose Rock | 0.06 |
| X42 | Blasting Vibrations | 0.05 |
| X43 | Heavy Machinery Vibrations | 0.04 |
| X44 | Driver Speeding | 0.08 |
| X45 | Inadequate Speed Limits | 0.06 |
| X46 | Downhill Gradient | 0.05 |
| X47 | Insufficient Road Width | 0.06 |
| X48 | Lack of Safety Berms | 0.05 |
| X49 | Sharp Curves Steep Grades | 0.06 |
| X50 | No Designated Walkways | 0.07 |
| X51 | Blind Spots | 0.05 |
| X52 | Lack of Warning Signals | 0.06 |
| X53 | Poor Visibility or Lighting | 0.07 |
| X54 | Damaged Electrical Cable | 0.04 |
| X55 | Overloaded Circuit | 0.03 |
| X56 | Poor Grounding | 0.03 |
| X57 | Fuel or Oil Leak | 0.05 |
| X58 | Hot Surface | 0.02 |
| X59 | Sparks | 0.02 |
| X60 | Smoking | 0.01 |
| X61 | Heavy Rainstorm | 0.05 |
| X62 | Poor Drainage System | 0.01 |
| X63 | Dam or Pipe Failure | 0.02 |
| X64 | Thunderstorm Present | 0.04 |
| X65 | Blasting During Lightning | 0.01 |
| X66 | Dense Fog Conditions | 0.06 |
| X67 | No Visibility Aids | 0.08 |
| X68 | No Traffic Control in Fog | 0.07 |

# Fatal Quarry Accident

- Machinery Accident
- Blasting Hazard
- Slope Failure Rockfall
- Traffic /Haul Accident
- Electrical Fire Hazard
- Environmental Hazard

## Machinery Accident

- Equipment Rollover: X1, X2, X3
- Maintenance Error: X4, X5, X6, X7
- Crushing Pinching Accident: X8, X9, X10, X11, X12

## Blasting Hazard

- Flyrock Incident
  - Blast Design Error: X13, X14, X15, X16, X17
  - Inadequate Exclusion Zone: X18, X19, X20, X21, X22, X23
- Misfire: X24, X25, X26, X27, X28, X29, X30
- Premature Explosion: X31, X32, X33, X34, X35, X36

## Slope Failure Rockfall

- Geotechnical Instaility: X37, X38
- Poor Bench Design: X39, X40, X41
- Vibration Induced Failur: X42, X43

## Traffic Haulage Accident

- Vehicle Vehicle Collision
  - High Speed On Haul Road: X44, X45, X46
  - Poor Haul Road Design: X47, X48, X49
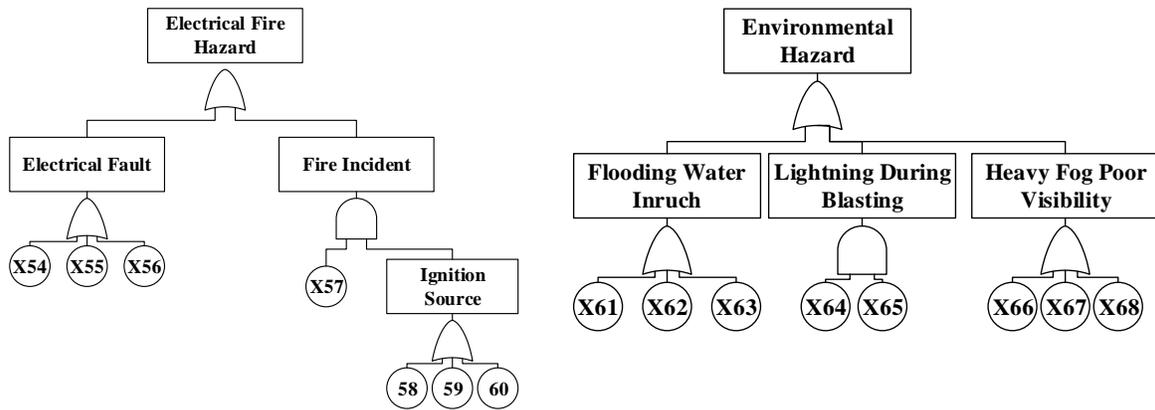- Vehicle Pedestrian Accident: X50, X51, X52, X53

**Figure 2:** Fault tree structure describing risk factors for quarry accidents using Microsoft Visio.

## Conversion to Bayesian Network

The Genie Modeler V3.0 was used to transform the FT into a BN. The Genie Modeler supports dynamic inference and probabilistic reasoning. The FT to BN transformation achieved the following:

- The basic events listed in table 1 (X1–X68) Were converted to root nodes.
- Intermediate event**s** converted to conditional nodes**.**
- fatal quarry accident—the top event—became the final output node.
- ft logic determined the internodal relationships.

Based on these changes**,** joint probability distribution (JPD) was distributed over all the nodes, as follows:

$$P(U) = P(X_1, X_{2,...,}X_n) = \prod_{i=1}^{n} P(X_i | Parents(X_i)) \qquad (1)$$

In this formulation, $P(U)$ represents joint probability for the $X_1 \ldots X_n$ set of variables, $P(X_i | Parents(X_i))$ indicates $X_i$ conditional probability, and $P_a(X_i)$ denotes $X_i$ parent nodes [18]. employing this structure enables probability updating as soon as new evidence emerges, which is one of the main features of BN models.

### Probability Assignment

In light of Libya's data scarcity concerning quarry accidents, a panel of experts was consulted to obtain information on all event probabilities. The composition of the expert panel was as follows:

- Blasting operations specialist
- Heavy equipment maintenance engineer
- Geotechnical/slope stability engineer
- Occupational safety officer
- Environmental/electrical systems expert

A detailed description for each of the 68 listed events (see Table 1) was given to the experts, with all events considered binary variables (i.e., "True/False"). Following lengthy and in-depth discussions, the experts reached a consensus regarding the assigning of probability values for the individual events.

**Noisy-OR Model:**

The Noisy-OR function was applied to conditional probability computations in cases where multiple independent causes influenced the nodes. The formula can be written as follows:

$$P(Y = 1|X_1, X_2, \dots, X_n) = 1 - \prod_{i=n}^{n}[1 - q_i^{xi}] \qquad (2)$$

where:

- $Y$ = child node (e.g., Blasting Hazard)
- $X_{i,}$ = parent nodes
- $q_i$ = each parent's causal influence strength.

The above approach encapsulates partial causation, thus allowing for uncertainty propagation modeling.

**Model Validation and Sensitivity Analysis**

- Quantitative validation: GeNIe's sensitivity to findings tool was employed to measure how the top event (*"Fatal Quarry Accident"*) was impacted by the parent nodes.
- Structural validation: Input from the panel of experts helped to guide the structural validation step with regard to logic direction, causal integrity, and node dependencies.

using excel, a tornado chart (Figure 3) was created based on the sensitivity results. The chart visualizes each hazard category according to danger level, which is critical for appropriately prioritizing risk controls.



**Figure 3:** Fault tree analysis-derived Bayesian Network model showing causal interconnections and relationships occurring in quarry accidents.

**Results and Discussion**

**Overview of Bayesian Network Results**

To analyze quarry accidents, a BN model was developed. It comprises 1 top-level hazard event ("Fatal Quarry Accident"), 6 intermediate hazard events, and 68 basic hazard events, all stylized as individual nodes. In the BN model, the nodes are presented as binary variables, with "True" indicating "occurrence" and "False" indicating "non-occurrence". In addition, conditional probability tables (CPTs) were also developed based on expert input and consultation. To better reflect quarry operations' causal structure, deterministic (AND) and probabilistic (Noisy-OR) interrelationships were used to represent logical dependencies between and among the various events.

As a baseline scenario, the developed model gave 0.74 as a prior probability for an accident-related fatality without the input of specific accident-related evidence. It is worth noting that, according to the structure of the model, the 0.74 value is a relative conditional likelihood rather than an absolute fatality measurement. Furthermore, both the risk intensity and complexity of quarrying operations are reflected in the high baseline value. From this, it is clear that even without incident data, the model is sufficiently robust to capture interrelated hazards.

The probability values used in the CPTs were obtained through structured expert elicitation due to the lack of a comprehensive national quarry accident database in Libya. Experts were selected based on predefined criteria, including more than 10 years of professional experience in quarry operations or occupational safety and direct field involvement in Libyan quarries. Their judgments were aggregated using a consensus approach to improve reliability.

The value of 0.74 is defined as a "Potential Risk Index" rather than a literal fatality rate. It represents the probability of a hazardous outcome in a "worst-case scenario" where no integrated safety barriers are active. This high value reflects the cumulative effect of 68 interconnected hazard events and emphasizes the urgent need for safety interventions in the studied quarries. Sensitivity analysis was subsequently conducted to demonstrate how this index significantly decreases when specific safety barriers are introduced.

The occurrence of any single hazard among the 68 identified events does not automatically imply a 0.74 probability of fatality; rather, the index reflects the cumulative interaction of multiple concurrent risk factors within the modeled system.

**Scenario Simulation and Evidence Updating**

GeNIe was used to conduct simulations to determine how individual hazard categories impacted the "Fatal Quarry Accident" probability. For each simulation scenario, a single intermediate hazard node was set to "active" (that is, considered "True") in order to calculate the probability of the top event occurrence.

Based on the simulation results, traffic / haulage accidents wielded the most influence, boosting fatality probability up to 0.96. This was followed in close succession by Machinery Accidents and blasting hazards (both 0.94), electrical/fire hazards (0.93) and slope failures (0.92). environmental hazards showed the lowest influence of the six hazards (0.89).

The simulation results showcase the BN model's ability to successfully measure "what-if" scenarios dynamically while also highlighting the prioritization of evidence-based safety protocols. The dynamic framework of the BN model enables real-time scenario updating and evaluation, unlike static frameworks. The capability of this model allows for rapid alterations in hazard control directives based on up-to-the-minute changing conditions.
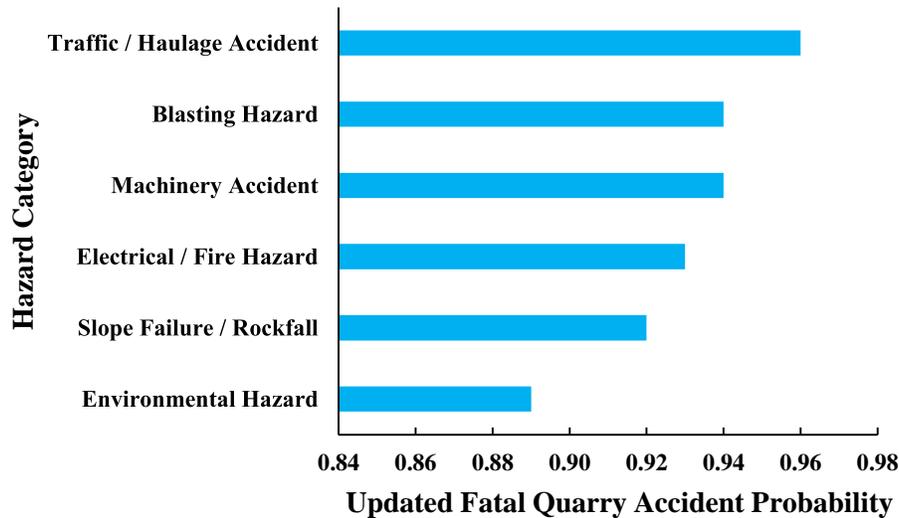
**Figure 4:** Probabilities for fatal quarry accidents based on six main hazard categories.

## Sensitivity Analysis

A sensitivity analysis based on the "Sensitivity to Findings" function in GeNIe software was conducted, aiming to measure each hazard's influence on the top event's (Fatal Quarry Accident) probability. The tool explored alterations to parent nodes and then aimed to determine how these changes impacted top-level event probability in baseline conditions. Equation (3) [20] was used to calculate accident probability percentage change by quantifying relative increases between prior and posterior probabilities, as follows:

$$Percentage\ change = \left(\frac{posterior\ probabiliy - prior\ probabiliy}{prior\ probabiliy}\right) \tag{3}$$

Results indicate that Traffic / Haulage Accidents had the most effect, boosting fatality probability 30%. This was followed by Blasting Hazards (27%), Machinery Accidents (27%), Slope Failure / Rockfall (24%) and Electrical / Fire Hazards (26%). As with previous simulations, Environmental Hazards (20%) made the lowest contribution to top event probability.

The findings of this simulation generally reflect those of previous simulations, showing that explosives- and transport-related risks contribute the most to the occurrence of top events at quarries. Furthermore, these findings also align with statistics from international mining safety reports, such as those generated by the UK Health and Safety Executive (HSE, 2024) [21] as well as by the Mine Safety and Health Administration (MSHA, 2023) [22]. Such results support the validation of BN models that rely on expert input when data is otherwise missing.
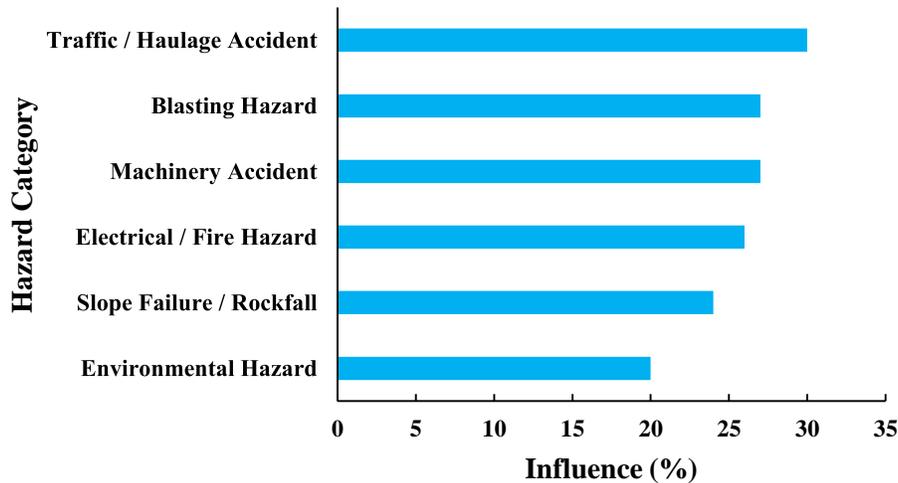
**Figure 5:** Fatal accident probability according to the influence (%) of different hazard categories.

**Discussion of Critical Hazards**

**Traffic and Haulage Hazards**

Based on the developed BN model, the category Traffic / Haulage Accident exerted the greatest influence (30%) over top event probability. This finding shows how important vehicle-related risks are in quarry operations, especially in light of the constant interactions of human operators and heavy machinery, all within a dynamically hazardous work scenario.

There are two main subcategories in the Traffic / Haulage Accident hazard group: Vehicle–Vehicle Collisions and Vehicle–Pedestrian Accidents. Details on these subcategories are listed below:

1. Vehicle–vehicle collisions have the following main contributing factors, as sourced from the BN model (Table 1):
   - Driver speeding (X44)
   - Inadequate speed limits (X45)
   - Downhill gradients (X46)
   - Poor road geometry, including insufficient width (X47), lack of berms (X48), and sharp curves or steep grades (X49)

Because haul roads in quarries are usually steep and poorly maintained, collisions and loss-of-control event likelihood is quite high. The risk is particularly high at smaller-scale sites, as these typically do not have any type of traffic control monitoring.

2. Vehicle–pedestrian accidents have the following main contributing factors, as sourced from the BN model (Table 1):
   - Absence of designated walkways (X50)
   - Blind spots around large machinery (X51)
   - Lack of warning signals (X52)
   - Poor visibility or lighting (X53)

As can be seen by the main contributors in this category, behavioral factors and design-related issues comprise the primary risks. However, such risks could easily be mitigated if not entirely eliminated by the introduction of basic

safety protocols, including better road design, reduced speed limits, and pedestrian pathways that are fully separate from roadways.

These findings agree with those reported by MSHA (2023) and HSE (2024). The data in those reports also showed that powered haulage contributed the most to quarrying fatalities. Risk could be significantly reduced by implementing basic safety interventions like formal traffic control and proximity sensors used in real-time vehicle monitoring. Also helpful would be better basic operator training combined with continuous training upgrading.

### Blasting Hazards

According to the developed BN model, blasting hazards are the second-most main contributor in top events (Fatal Quarry Accidents). Blasting includes three intermediate events, namely Flyrock, Misfire, and Premature Explosion. Each of these events is linked to basic events in the BN model presented in Table 1.

Of the three intermediate events, flyrock incidents contribute the most to the probability of death. These events are mainly caused by the following:

- Blast design errors (X13–X17): These can involve using poor-grade stemming materials, applying too much explosive charge, and miscalculating spacing or burden.
- Inadequate exclusion zones (X18–X23): These factors typically involve failures like lack of safety signage, inadequate clearance distances, poor exclusion area enforcement, and lack of supervision.

Procedural and design issues may amplify uncontrolled rock ejection risk, leading to injuries to workers and damage to infrastructure and equipment well beyond the blast zone. The MSHA has identified flyrock during blasting operations as the primary contributor to injuries and death.

misfire events also substantially contribute to serious quarry accidents. Misfirings can be caused by a range of factors, including faulty detonators (X24) and incorrect timing or delayed detonations (X30). Although relatively minor in themselves, in combination these factors pose extreme risk to workers in the post-blast phase of operations. For example, a delayed detonation resulting from a misfire is especially hazardous, as workers might assume an area is safe to re-enter and be caught unawares by a delayed blast.

As a sub-event of blasting, premature explosion is relatively rare but deadly. These low-probability events are usually caused by radio frequency interference, static discharge, stray currents, or even lightning strikes (X31–X35). Mainly because they occur suddenly and unexpectedly, premature explosions often result in multiple injuries and a high death count.

The developed BN model in the present study demonstrates that the greatest contributions to blast-related quarry injuries and deaths come from flyrock and misfire. premature explosions, although posing the greatest risk as well as the highest body count, is a much rarer occurrence than the other two events. These findings align well with those from MSHA and HSE, showing that the majority of surface mining accidents are caused by poor training and blast design, along with weak enforcement of existing rules and safety policies.

Decreasing the above risk scenarios requires certain measures to be adopted, including:

- Thorough worker training with a focus on risk perception, including misfire and system reliability.
- Improved design verification, preferably by professional engineers, to check work sites for proper spacing, charge, and burden.
- Continuous environmental monitoring to ensure conditions are safe for mining operations. Blasting should be suspended during periods of high humidity, lightning storms, and other forms of atmospheric instability.
- Rigorous enforcement of existing safety protocols around blasting, especially regarding exclusion zones. Safety protocols should include highly visible and audible warnings.

Despite being extremely hazardous, blasting can be carried out with significantly lowered risk probabilities if the risk factors are appropriately managed through proper training as well as adherence to safety protocols.

## Machinery Accidents

The developed BN model ranks Machinery-related hazards as contributing 27% to serious accident risk in quarries. The machine-related category has three main intermediate events, namely equipment rollover, maintenance error, and crushing/pinching accident, listed under X1–X12 in Table 1.

equipment rollover may be caused by issues related to excessive slope angles (X1), high machine speeds (X2), and operator fatigue or error (X3). Such risks are common during mining operations, with machines typically being operated for long periods of time and on unstable and/or uneven ground.

maintenance error refers to factors such as insufficient training of maintenance staff (X6), absence of personal protective equipment (X7), and failure to implement proper lockout/tagout procedures (X4). These types of errors are usually the result of poor safety protocol adherence and poor maintenance systems.

crushing and pinching accidents may occur due to operational oversight stemming from issues such as the absence of a spotter during machine operation (X8), operator distraction (X9), malfunctioning warning signals (X10), and the removal of safety guards (X11). Such issues can be the cause of serious injuries or even death, especially in cases where they occur in combination with lax supervision or poor visibility.

Despite having a relatively high base probability of occurrence, machinery-related accidents rarely lead to fatalities. The BN model's sensitivity risk analysis reveals that such incidents commonly result only in non-fatal injuries. Still, mitigating machinery-related risks should remain a priority on quarrying sites. This can be achieved through robust training programs for equipment handlers, along with the establishment of predictive maintenance protocols and enhanced enforcement of existing safety systems.

## Electrical and Fire Hazards

In the BN model (Table 1), hazards caused by electrical and fire-related incidents are also a major risk factor for fatal quarry accidents. The two main intermediate events within this category are Electric Faults and Fire Incidents.

electrical fault is primarily caused by problems such as damage to electrical cables (x54) **or** overloaded circuits (x55). poor grounding conditions (X56) can also contribute to this hazard. Underlying these issues is a range of quarry site problems, including non-compliance with standard safety procedures, faulty protective systems, and poor equipment maintenance. Although electrical issues do not usually directly result in injury or death, they can combine with other problems, e.g., human error, flammable materials, to escalate the seriousness of the accident.

Fire Incident**s** typically involve leaks of oil or other fuel (X57) that hit an ignition source, such as a burning cigarette butt or sparks (X58–X60). The main hazard in these types of incidents is the fuel leak, as fuel is needed for propagating fire. Quarries are typically sited in close proximity to fuel bunkers, a risk situation which is exacerbated by high temperatures and lack of onsite fire suppression. Despite being relatively rare, ignition-related incidents can be extremely serious when they do occur, as the risk for fires to combine with electrical devices or blasting components can rapidly result in secondary explosions.

The BN model shows the potential extreme hazard arising from the interconnectedness of electrical issues and fuel-driven fire incidents. Managing such risks in a quarry environment requires adherence to safety protocols around factors such as electrical grounding, fuel-handling, and restriction of ignition sources in areas designated as "high risk". Risk management in quarrying sites could also include running safety drills and upgrading fire suppression and fire detection systems.

## Slope Failure / Rockfall

Hazards caused by Slope Failure and Rockfall contributed 24% to the occurrence probability of fatal quarry accidents. According to the developed BN model (Table 1), this hazard has three important intermediate events, namely geotechnical instability, poor bench design, and vibration-induced failure. A description of each of these events is given below:

- Geotechnical instability: In the Slope Failure / Rockfall group, geotechnical instability is mainly caused from weak bedding planes (X37) as well as water ingress due to rainfall (X38). When water infiltrates slope materials, it raises pore pressure and decreases shear strength, contributing to failure likelihood. Sedimentary rock is especially affected by this issue. A constant hazard of open-pit mining environments, slope failure and rockfall are particularly prevalent in heavy rain conditions.
- Poor bench design: The unsafe design of slopes is one of the chief reasons for rockfall and other bench failures. It is characterized by issues such as overly narrow benches (X39) and inadequate berms (X40). It also includes poor maintenance of slopes, such as the regular and emergency removal of loose rock (X41). When the slope's structural integrity is compromised through design flaws and weaknesses, safety margins are decreased. This leads to a higher risk factor for bench failures, including in otherwise normal conditions.
- Vibration-induced failure: Slope deficiencies can be exacerbated by blasting activities (X42) and heavy equipment vibrations (X43). Although blast vibrations on their own are unlikely to result in slope failure, they contribute significantly, particularly when issues such as water saturation already exist. Delayed slope collapse is the product of crack propagation, which is worsened over time by vibrations.

Within this group, geotechnical instability remains the main hazard, with poor bench design and vibrations also contributing to slope failure and rockfalls. Although occurring less frequently than blasting or vehicle-related accidents, slope-related issues can still result in injury and death due to catastrophic failure and so need to be remedied proactively through better design.

## Environmental Hazards

Despite holding the lowest probability rank among the BN model's hazard categories, Environmental Hazards have strong indirect effects, acting to amplify or even trigger blasting-, electrical-, or slope-related accidents. The main intermediate environment-related events involve flooding and water inrush, lightning events during blasting, and heavy fog leading to poor visibility (x61-x68).

flooding and water inrush typically occurs during severe rainstorms or as the result of inadequate drainage leading to corruption or failure of pipes and dams. The outcome of these hazards can be sudden flooding, which can lead to unsafe working conditions due to destabilization of slopes or equipment entrapment. Inundations are especially prevalent in low-lying sites or those with poor drainage systems.

lightning during blasting (X65) may occur when blasting is conducted during thunderstorms. Although the probability of a lightning-ignited blast is relatively low, it is catastrophic when it does happen, leading to premature detonation of blasting explosives. depending on the scenario, premature detonation has a high-risk probability for serious injuries and fatalities.

heavy fog leading to poor visibility (x66) has the highest risk probability in the Environmental Hazards category. This hazard involves mainly a lack of visibility and related aids due to dense fog conditions, which sometimes can arise rapidly and without warning. Visibility issues can also negatively impact traffic control due across the work site. Such limitations substantially decrease machinery and vehicle operators' situational awareness, boosting the risk for collisions as well as for pedestrian accidents.

Despite having relatively low probabilities in comparison with the other five hazard categories, Environmental Hazards still cause a probability intensification of the more frequently occurring hazards. For instance, heavy rains may cause flooding, which may then compromise slope stability or lead to malfunction of equipment, while poor visibility due to rain or fog may result in risk amplification of vehicular and pedestrian accidents. Managing these risks requires the implementation of relevant safety strategies, starting with real-time weather monitoring. Also important are the design and maintenance of effective drainage systems, the installation of visibility aids across the work site, and emergency operational suspension in severe weather, including dense fog.

**Conclusions**

This research proposed an integrated Fault Tree Analysis and Bayesian Network risk assessment framework for fatal quarry accident probabilities. The developed hybrid model demonstrated the various causal interrelationships that may occur when dealing with several hazard categories simultaneously. This was accomplished through the identification of the main risk contributors along with the quantification of their influence via scenario and sensitivity analyses. The proposed model is viable even in data-scarce regions like Libya and other developing countries, as it operates based on dynamic inference. Specifically, the model is informed by expert opinion and advice and is driven by machine-learning GeNIe software.

According to the results of the present research, the most frequent and severe hazards that occur at quarrying sites involve Traffic / Haulage Accidents, Blasting Hazards, and Machinery Accidents. These top three hazard categories also rank highest for fatality probability. Contributing to and amplifying accident probability are the three less frequently occurring of the six hazard categories, namely Slope Failures, Electrical/Fire Hazards, and Environmental factors. Despite their seemingly low influence due to relative rarity, these three latter categories can still substantially increase the severity of quarry accidents when they do occur. It is worth noting that the findings of this study align with accident statistics compiled by international monitoring bodies, which affirms the validity of the developed BN model even amidst the lack of relevant local data.

Along with its excellent performance despite the lack of historical quarrying accident data, the developed framework uses probabilistic reasoning to prioritize control measures for simulated risk scenarios. Such a capability provides a strong and flexible decision-making tool for intervention strategies. For instance, quarry managers can use the simulated sensibility results as a premise to introduce speed limits, improve equipment maintenance, draw exclusion zones, and install site-wide visibility aids. In areas unserved by a formal reporting system for accidents, the developed BN model can provide a realistic pathway to improve occupational safety in high-risk industries.

In the future, research could pivot towards establishing more robust reporting mechanisms and systematic data collection for Libyan quarry accidents. Such a focus could assist in validating and continuously refining later iterations of the model. At the same time, research could consider the further integration of ML methods, including real-time monitoring, to enhance the model's adaptability and predictive capabilities in ever-changing, high-risk quarry environments.

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