

# Fault Tree Analysis and Event Tree Analysis: Theory, Comparison and Application in Risk Assessment

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### Abstract:

Amid the escalating complexity of contemporary industrial and engineering systems, risk evaluation that is both accurate and systematically structured has become increasingly necessary to ensure system safety and to avert major accidents. Fault Tree Analysis (FTA) as well as Event Tree Analysis (ETA) are distinct foundational approaches within probabilistic risk assessment that are taken as the central objects of study. The discussion sets out the theoretical underpinnings, logical analytic procedures, and typical application domains of FTA and ETA; on that basis, a systematic comparison is developed regarding their respective strengths in risk identification, causal analysis, and consequence forecasting. Within this analytical framing, FTA employs deductive reasoning to trace top failure events back to underlying basic causes as well as to the logical combinations of contributing factors that produce those events. ETA proceeds conversely through inductive reasoning: beginning from initiating events, it projects accident evolution pathways and estimates the eventual outcomes associated with those initiating conditions. Widely are these methods deployed across high-risk sectors. In synthesis of these considerations, the paper provides a dependable theoretical foundation for selecting risk assessment models rationally while supporting scientifically grounded decision-making in system safety management together with risk prevention and control.

**Keywords:** Fault tree analysis; Event tree analysis; Risk assessment

## 1. Introduction

Modern engineering systems are becoming larger and

more interconnected, bringing various risks that can trigger chain reactions and serious accidents. Traditional safety management is no longer sufficient to

handle such complex uncertainties. Therefore, systematic risk assessment methods are widely needed to identify hidden dangers, analyze accident mechanisms, and improve the reliability and safety of industrial systems [1]. In addition to Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), several advanced risk assessment methods have been proposed in international research.

As characterized by Neil et al. and Marquez et al. [2,3], the Bayesian Network (BN) constitutes a probabilistic graphical formalism in which prior information is combined with empirical observations so as to represent uncertainty and interdependent risk mechanisms. Relative to Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), BN frameworks permit both diagnostic and predictive inference; with evidence available at any node, posterior probabilities can be propagated through the graph, enabling iterative revision as additional information becomes available. Under conditions typical of tightly coupled, interaction-rich engineered systems, this inferential flexibility renders BN modelling more defensible than strictly unidirectional tree-based schemes. Yet a material constraint persists: network topology and the associated conditional probability tables are commonly elicited from domain specialists, and the resulting dependence on expert judgement restricts robustness where data are sparse and elicitation uncertainty is non-trivial.

Monte Carlo Simulation (MCS) is another widely used method. As noted by Fishman and used by Du and Chen [4,5], MCS measures risk uncertainty through repeated random sampling and gives reliable probability distributions and confidence intervals. This method fixes the weakness of FTA and ETA in uncertainty representation, especially for high-dimensional and nonlinear systems. However, MCS needs a lot of computer power and cannot directly find accident root causes. ETA is good at forward consequence path analysis, while FTA allows deductive root-cause deduction, giving clear and systematic risk assessment benefits.

This paper aims to introduce history, basic theory and further application of Fault Tree Analysis and Event Tree Analysis, showing their effects on risk-analyzing. Section 2 will talk about basic theory of ETA and FTA model; section 3 will compare them and assess their applications individually. The last section will devote to the conclusion. Firstly, this paper not only reviews the basic theories of FTA and ETA but also integrates their historical evolution to clarify the logical context and practical value of the two classical risk analysis methods. Secondly, it conducts a direct comparative analysis of FTA and ETA, quoting real and iconic accidents as examples, which provides a clearer selection basis for practical risk assessment. Finally, it summarizes the core functions and typical effects of the

two methods in risk analysis.

## 2. Basic theory of ETA and FTA model Introduction of ETA model

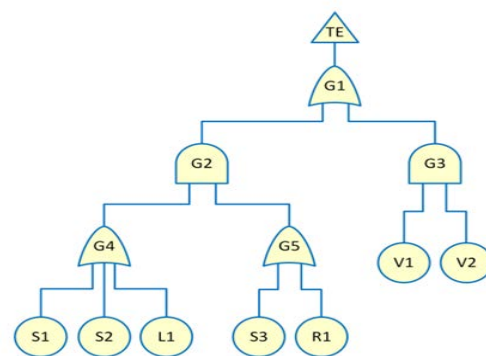
### 2.1 FTA theory

#### 2.1.1 History and introduction of FTA

Fault Tree Analysis (FTA) is recognized as a deductive, top-down methodology designed to identify the root causes of specific undesired events in complex systems. Using a graphical fault tree diagram as shown in Fig. 1, it maps logical relationships among potential failures, enabling engineers and managers to assess failure modes and their probabilities. In this sense, it strengthens system safety and reliability.

Originating from Bell Labs in the 1960s for the U.S. Air Force, FTA was quickly adopted for the entire Minuteman missile system. Recognizing its value, Boeing extended FTA to commercial aircraft design. Later on, Boeing co-hosted the first System Safety Conference with the University of Washington, where multiple FTA papers sparked global interest [6].

By 1966, Boeing had developed BACSIM, a simulation program capable of evaluating multi-phase fault trees with 12 phases at most, incorporating repair and failure-rate K-factor adjustments. Another in-house program enabled fault tree plotting on a Calcomp 26-inch drum plotter. However, both ran on IBM 370 mainframes, developed internally by Bob Schroeder, remaining largely unknown outside Boeing.



**Fig. 1 A complete toolchain for fault tree analysis**

#### 2.1.2 Procedures of building FTA model

First, the system boundaries and operational conditions are clearly defined to establish the scope of analysis. The undesired top event is then specified, followed by con-

structuring the initial fault tree structure to identify events leading to this event. Each branch is expanded in detail until basic events are reached, after which the minimal cut sets contributing to the top event are derived. Dependent failure potentials are identified and the model is adjusted accordingly. Quantitative analysis is performed using historical statistical data to assess system reliability, and the results are finally applied to identify critical hazards and support risk-mitigation decision making.

### 2.1.3 Calculation of probability

For an AND gate expressed by  $C = A \wedge B$ , the probability reads as  $Pr(C) = Pr(A) \cdot Pr(B|A) = Pr(B) \cdot Pr(A|B)$

where  $Pr(X)$  means the probability of event  $X$  occurring, and  $A|B$  means event  $A$  occurring on condition that event  $B$  has already occurred. In cases where events  $A$  and  $B$  are totally different, one finds that  $Pr(B|A) = Pr(B)$  and  $Pr(A|B) = Pr(A)$ . They thus can be simplified as  $Pr(C) = Pr(A) \cdot Pr(B)$ .

In contrast to AND gates that stands for the conjunction of events, an OR gate develops their disjunctions. Regarding the OR gate  $D = A \vee B$ , the probability of  $D$  occurring is given by  $Pr(D) = Pr(A) + Pr(B) - Pr(A \wedge B) = Pr(A) + Pr(B) - Pr(A) \cdot Pr(B|A) = Pr(A) + Pr(B) - Pr(B) \cdot Pr(A|B)$

However, if  $A$  and  $B$  are mutually exclusive, then  $Pr(A \wedge B) = 0$ . In this sense,  $Pr(D) = Pr(A) + Pr(B)$  If  $A$  and  $B$  are independent, then  $Pr(B|A) = Pr(B)$  and  $Pr(A|B) = Pr(A)$ , and thus:  $Pr(D) = Pr(A) + Pr(B) - Pr(A) \cdot Pr(B) = 1 - (1 - Pr(A))(1 - Pr(B))$ .

## 2.2 ETA theory

### 2.2.1 History and introduction of ETA

Event Tree Analysis (ETA) is a forward, top-down inductive method used to explore possible consequences following an initiating event. First prominently applied in the WASH-1400 nuclear power plant safety study in 1970s, ETA was adopted because traditional fault tree analysis became impractical for extremely large systems. Although ETA was not originally developed during WASH-1400, this study marked one of its earliest comprehensive applications. ETA systematically identifies all event sequences originating from an initial event. Sequences with negligible frequency or impact can be excluded from further analysis. A key paper detailing this methodology was pre-

sented at the 1970s in Germany [7].

Nevertheless, initiating events may include technical failures or human errors. Throughout sequence development, barriers and safety functions designed to prevent or mitigate consequences are considered. Thus, ETA encompasses both qualitative and quantitative analysis: qualitative analysis visualizes different scenarios, while quantitative analysis provides occurrence frequencies for various outcomes. The procedure of ETA is shown in Fig. 2.

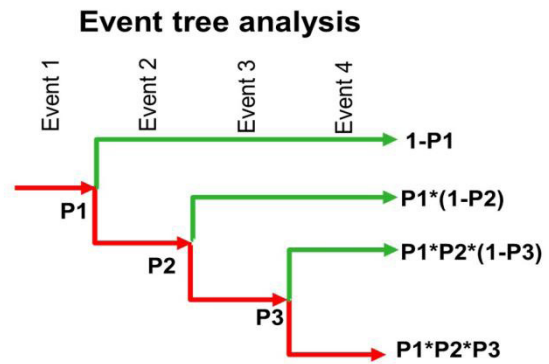


Fig. 2 Illustration of event tree analysis

### 2.2.2 Procedures of building ETA model

Initially, the system scope and boundaries are clearly defined, followed by assessing the system to identify potential hazards and accident scenarios. Appropriate hazard analysis is then applied to determine initiating events, while relevant countermeasures are recognized as intermediate events for each scenario. An event tree diagram is constructed accordingly, and event failure probabilities are obtained, often supported by fault tree analysis where direct data are unavailable. The overall probability of each event path is calculated to assess the corresponding risk, which is further evaluated for acceptability. Where risks are unacceptable, design modifications and corrective actions are proposed. Finally, the entire ETA process is documented on diagrams and updated as new information emerges.

### 2.2.3 Calculation of probability

To perform quantitative ETA, the frequency of the initiating event and the failure probabilities of all relevant barriers should be determined. For each barrier  $i$ , there are two parameters are defined:  $r_i$ , the probability that barrier  $i$  fails (the "No" outcome), and  $s_i = 1 - r_i$ , the probability that barrier  $i$  operates as intended (the "Yes" outcome). The initiating event frequency is denoted as  $\lambda$ . Barrier probabilities and initiating event frequencies are typically obtained through supplementary analyses, including fault tree analysis (FTA) for active safety systems, failure sta-

tistics, and load--strength assessment methods.

The frequency of each end consequence is calculated by multiplying the initiating event frequency by the corresponding probabilities of all barriers along the path leading to that consequence. For a given consequence  $C_m$ , let  $G$  be the set of barriers that function successfully (the "Yes" outcome) and  $F$  be the set of barriers that fail (the "No" outcome). The frequency of  $C_m$  is then given by  $f(C_m) = \lambda \times \left( \prod_{i \in G} s_i \right) \times \left( \prod_{i \in F} r_i \right)$ . This formulation enables both qualitative visualization of accident sequences and quantitative estimation of consequence frequencies.

### 3. Comparison and application of ETA and FTA

#### 3.1 Comparison of ETA and FTA

Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) occupy adjacent, not interchangeable, positions within probabilistic risk assessment. From an initiating disturbance---equipment failure, human error, or an exogenous perturbation---ETA initiates inductively, enumerating subsequent system actions and end states in cause-to-effect order. Its graphical notation is frequently a left-to-right (horizontal) construction in which each node splits off into success/failure (or yes/no) paths, making the consequence-centered comparison between different paths straightforward. For a given path, the path probability can be computed as the product of conditional branch probabilities; in many practical applications, statistical independence among events is imposed to make the computation tractable, despite its being an approximation. By contrast, Fault Tree Analysis has a deductive approach. Starting from a given undesirable top event, analysis proceeds downward (often drawn vertically) from a top causal decomposition, using AND and OR logic gates to relate basic failure events to the top event [8].

#### 3.2 Application of ETA

The study also presents a typical high-altitude fall accident that occurred at Henan Zhonglv Construction Engineering Co., Ltd. in 2016. Event Tree Analysis (ETA) is the only analytic technology used within, i.e., accident propagation mechanism reconstruction of the accident, and node reliability probability determination within the analysis, thereby providing decision-relevant evidence for avoidance and control of fall accidents in construction environments. At the beginning of the narration, the initiating event is defined as a structural misfeature observed in

the settling-tank roof during demolition works; from that deviation, the roof collapse occurred and the exposure to the high-altitude risk occurred. With this trigger "locked", the accident course can be deconstructed into sequential decision/condition nodes and deduced accordingly.

Firstly, the timeliness of response to the roof misfeature on-site is a gatekeeping factor: timely disposal has probability 0.57, and if so, it arrests the next escalation; a delay in handling sends the worksite towards the subsequent higher-risk state. Secondly, it goes to the effectiveness of maintenance measures. Temporary isolation has probability 0.60 to control the hazard state; conversely, ineffective long-term repair amplifies the latent defect and, practically speaking, generates the antecedent condition for the subsequent failure. Third, the worker-level barrier, whether using personal protective equipment, is assessed: non-use reaches 0.62, a value that shoots up the likelihood of fall injuries; yet even if equipment is worn, insufficient protection and incorrect operations are non-negligible, with a probability of 0.58, so the residual risk remains, rather than vanishing. From the values assigned to these nodes, the whole event tree is drawn to represent the accident branching paths. Working stepwise through probability multiplication and addition along the paths, the overall probability of the high-altitude-fall outcome is estimated to be about 0.62 (i.e., 62%). Within the tree, three major risk chains in the direct line leading up to the terminal event are displayed that represent an internally consistent progression from incipient risk to specific casualty and thus isolate the links nearest to injury occurrence.

Within this real-world application, Event Tree Analysis (ETA) offers several demonstrable advantages. First, by rendering accident development as an explicit branching sequence of intermediate events and outcomes, ETA makes the progression of risk legible and, in turn, isolates the specific initiating conditions and barrier failures that drive escalation. Of greater methodological consequence, ETA supports numerical treatment: probabilities can be assigned to pivotal events and propagated across pathways, yielding scenario-specific accident frequencies rather than judgments derived principally from professional intuition. The implication is a more auditable and reproducible basis for risk interpretation and for selecting mitigation measures than is typically achievable through experience-led assessment alone.

#### 3.3 Application of FTA

There is also a study which examines the Qingdao explosion triggered by a leak from Sinopec's Donghuang crude-oil pipeline in 2013, an event associated with substantial fatalities and extensive property damage [9]. Within the

accident-oriented investigation, a Fault Tree Analysis (FTA) model is constructed in accordance with the conventional procedural framework. The top event (TE) is explicitly defined as "oil leakage during the operation of petrochemical storage and transportation equipment." From this initiating failure mode, environmental contamination and equipment impairment may follow, with escalation pathways extending to fire and explosion. Taking this top event as the core, the research establishes a fault tree layer by layer and decomposes it into three first-level intermediate events (IE1): equipment structural failure, improper human operation, and inadequate safety supervision.

Each first-level intermediate event is further decomposed into second-level intermediate events and specific basic events (BE). For IE1-1 (equipment structural failure), the second-level intermediate events include pipeline corrosion, seal failure, valve damage, and material aging, which are decomposed into basic events such as long-term medium erosion of pipelines (BE1), incomplete replacement of sealing parts (BE2), valve wear caused by long-term use (BE3), and unqualified equipment materials (BE4). For IE1-2 (improper human operation), the second-level intermediate events are illegal operation, improper pressure control, and insufficient pre-operation inspection, corresponding to basic events such as operator lack of professional training (BE5), failure to follow operating procedures (BE6), and inaccurate pressure monitoring (BE7). For IE1-3 (inadequate safety supervision), the second-level intermediate events include delayed maintenance and incomplete daily inspection, decomposed into basic events such as unreasonable maintenance plans (BE8) and missed inspection of key parts (BE9) [10].

All intermediate events and basic events are connected through logical gates: for example, equipment structural failure (IE1-1) is formed by the occurrence of any of the four second-level intermediate events (connected by OR gate); improper human operation (IE1-2) requires the simultaneous occurrence of operator unskilledness and non-compliance with procedures (connected by AND gate). Based on the collected on-site data, the failure probability of each basic event is determined: BE1 (pipeline erosion) is 0.12, BE2 (seal replacement omission) is 0.08, BE5 (insufficient training) is 0.15, BE8 (unreasonable maintenance) is 0.10, and so on. The model calculates the occurrence probability of each intermediate event layer by layer through logical operation, and finally obtains the total occurrence probability of the top event (oil leakage) as approximately 0.28.

FTA shows obvious advantages in this scenario: it adopts a top-down deductive logic, which is highly targeted for accident root cause investigation; the fault tree structure

makes the risk factors hierarchical and clear; quantitative calculation makes risk assessment more scientific. This application enriches the practical cases of FTA in petrochemical oil leakage analysis, proving that FTA is a reliable and operable tool for oil leakage risk assessment and accident prevention.

## Conclusion

Across this study, the conceptual underpinnings, differentiating features, and practical deployments of Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) have been examined as two core instruments within risk and reliability engineering. From initiating events onward, ETA proceeds by forward, inductive reasoning, mapping branching sequences of conditional system responses and thereby enumerating plausible accident progressions and end states. By contrast, beginning with an undesired top event, FTA applies backward, deductive logic to disaggregate that outcome into contributing failures and enabling conditions, rendering explicit the causal structure and points of vulnerability. Different in directionality yet convergent in purpose, the two approaches yield analytically distinct views that, when considered together, sharpen diagnosis as well as prevention.

However, it is far from flawless. This study is limited to a general overview and theoretical comparison of FTA and ETA, and does not take into account human factors and environmental uncertainties in real risk scenarios. As such, the analysis remains idealized and cannot fully reflect the actual complexity of practical risk assessment. Another limitation is that the research only reviews traditional applications of the two methods, without examining their performance in emerging intelligent or large-scale interconnected systems. Therefore, the conclusions lack sufficient reference value for modern high-complexity risk analysis contexts.

Looking ahead, a natural line of inquiry lies in tighter ETA–FTA coupling. This can be achieved through shared event definitions and consistent success-criteria modeling. It also requires bidirectional translation between consequence pathways and causal decomposition. In this way, a single workflow can preserve coverage of both propagation and origin. Parallel extensions into domains beyond traditional safety-critical engineering also merit attention. Taken as a pair, ETA and FTA remain central to contemporary safety and reliability assurance, their complementarity sustaining their role as a durable component of modern risk-management practice.

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