International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Fault Tree Analysis and its Modifications as Tools for Reliability and Risk Analysis of Engineering Systems – An Overview

Frederick Ojiemhende Ehiagwina[a], Olufemi Oluseye Kehinde[b], Abubakar Sidiq Nafiu[c], Lateef Olashile Afolabi[d], IkeolaSuhurat Olatinwo[e]

[a,b,c]*Department of Electrical/Electronics Engineering, The Federal Polytechnic Offa, Kwara State, Nigeria*

[c]*Department of Computer Engineering, The Federal Polytechnic Offa, Kwara State, Nigeria*[e]*Department of Computer Science, The Federal Polytechnic Offa, Kwara State, Nigeria*

A B S T R A C T

Fault Tree Analysis (FTA) converts the physical system into a Boolean logical diagram with a view of deducing the top event, thus making it a veritable tool in reliability and risk assessment. This paper reviews the procedures and uses of FTA. FTA normally deals with events from hardware failure or malfunctioning, or combinations of predictable contributions to the events arising from assigning a system hazard rate to branches or cut sets of the systems. FTA can be used as a valuable tool to identify potential hazards, elimination of wasteful design alterations. It can be used as a diagnostic tool, predicting the top event in a system breakdown or failure. The fault tree shows all the different relationships that are necessary to result in the top event resulting in a thorough understanding of the logic and basic causes leading to the top event. The fault tree provides a framework for qualitative and quantitative evaluation of the top event. The steps for carrying out FTA involves the definition of the system top event and structure, exploration of each branch of the tree, solving the fault tree for the combination of events, performance of qualitative analysis and using the result in making decisions. There have been modifications to the standard FTA to cater for the uncertainties associated with the data of some basic events in some fields. This study reports an overview of FTA and its modifications. It also highlights commercially available software applications for FTA and finally application cases of FTA and its variants.

Keywords: Fault tree analysis, Fuzzy fault tree analysis, Boolean algebra, Failure rate, Minimal cutsets, Reliability study

1. Introduction

Fault tree analysis (FTA) converts the physical system into a Boolean logical diagram because of this it is a good method deployed in reliability and risk assessment. Although both FTA and reliability engineering model the same major aspect, they arose from two different fields. Reliability engineering was, for the most part, developed by mathematicians. Engineers were on the other hand responsible for the development of FTA since a thorough knowledge of the design and fabrication of a system under analysis is needed in FTA(Alvehag, 2008; Andrew, 1998; Mohammed, Azim, & Ali, 2011). It was conceptualized by H. Watson at the Bell Telephone Laboratory in 1961, to be used by the aerospace industry(Andrew, 1998) and then later adapted by researchers in the nuclear power plant field to qualify and quantify the hazards and risks involved in the generation of nuclear power.

FTA has been deployed in a vast field of human endeavours in the assessments of system risk and reliability. Examples are the power industry, marine engineering, oil and gas sector, process and chemical industries. Other areas of applications include fire hazard prevention, railway transportation, drinking water system, drilling of tunnels, cybersecurity and management of medical waste.

In FTA attempts are made to deduce the causes of failure of a top event.According to Baig, Ruzli and Buang(2013), FTAprovides a graphic representation of how equipment failure, human error, and external factors all played a role in causing an accident or occurrence. It employs logical gates and minor events to present the course of an accident in various steps, resulting in the construction of a fault tree for the specific occurrence. Technical failures can be viewed as a fundamental event, whereas human errors can be viewed as intermediary events that can lead to a technical failure.Fault tree analysis can be used as a valuable design tool to identify potential hazards and can eliminate wasteful design changes. It can also be used as a diagnostic tool, predicting the top event in a system breakdown or failure. FTA is used in safety engineering and all major fields of engineering (Bollen, 2000). FTA helps to exhaustively identify the causes of a failure, thereby identifying weaknesses in a system; to assessing a proposed design for its reliability or safety. It may also be used to identify the effects of human errors. Fault Tree Analysis can be used to prioritize contributors to failure, identify effective upgrades to a system, and quantify the failure probability and contributors with a view of optimizing tests and maintenances (Vesely, 2002).

Fault Tree Analysis normally deals with events from hardware failure or malfunctioning or combinations of predictable contributions to the event arising from assigning a system hazard rate to branches or cut sets of the systems. Typically, hazard rates are derived from substantiated historical data, such as Mean Time Between Failure (MTBF) of the components, unit, subsystem or function (Mohammed, Azim, & Ali, 2011). However, for several basic events, applicable data are not available or within reach, hence, expert opinion and engineering judgment need to be used to estimate the basic event (BE) hazard rate, while documenting a basis for the estimates, including, a sufficient range with each estimate to cover uncertainties, and performing sensitivity studies to check the impact of the estimates.

Well, structured expert-elicitation approaches can be employed to enhance the fidelity of the BE hazard rate estimates, via the concept of importance measure (Vesely, 2002).The importance measure provides a quantitative perspective on the major contributors to risk and the sensitivity of risk tochanges in input values. Examples of importance measures are Fussell-Vesely, risk reduction, risk increase or risk achievement worth (RAW) and Birnbaum (Chacko, 2021; Fayaz& Pahuja,2018; Shadiah, Arshad, Mohamed & Olagoke, 2019). A tutorial on how to determine the various importance measure may be seen in **https://www.nrc.gov/docs/ML1216/ML12160A479.pdf**

The general steps for FTA are shown in Figure 1.

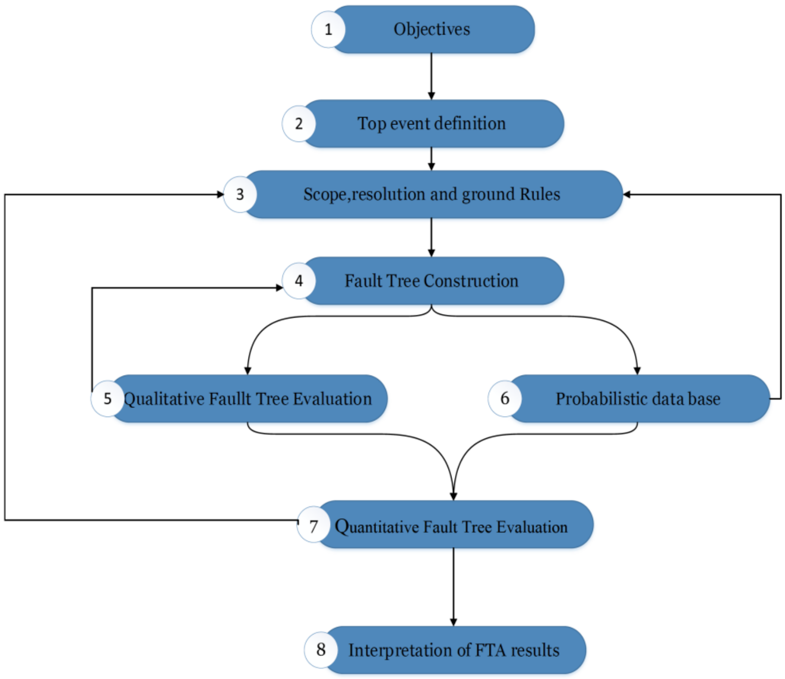


Figure 1- General procedure of fault tree analysis. Source: Akinode and Oloruntoba (2017)

2. Methodology of Fault Tree Analysis

Events in a fault tree are associated with statistical probabilities. For example, component failures are assumed to occur at some constant failure rate λ . Failure probability is a function of λ and the time of exposure t is given by equation (1)(Mohammed, Azim, & Ali, 2011; Vesely, 2002):

$$P(t) = \begin{cases} \lambda\tau, & \lambda\tau < 0.1 \\ 1 - e^{-\lambda\tau}, & otherwise \end{cases} \quad (1)$$

For extreme time dependency equation (1) no longer applies, instead, the Weibull distribution can be used(Vesely, 2002).

Equation (1) is for non-repairable components, the failure probability for repairable components is given by equation (2) for repair time of τ :

$$P(t) = \begin{cases} \lambda\tau, & \lambda\tau < 0.1 \\ \frac{\lambda\tau}{1+\lambda\tau}, & otherwise \end{cases} \quad (2)$$

When FTA is used for defining the probability of particular incident scenarios, the computation can be done manually, or by computer software models such as Visual Paradigm, DPL9 Fault Tree, ITEM ToolKits Fault Tree, Fault Tree Analyser, RAM Commander's FTA Software Module, Eclipse Modeling Framework for FTA (EMFTA), Relyence Fault Tree and TopEvent FTA. Most of these are licensed based.

A fault tree is often normalized to a given time interval, such as a flight hour or an average mission time to space. Event probabilities depend on the relationship of the event hazard function to this interval. Unlike conventional logic gate diagrams in which inputs and outputs hold the binary values of TRUE (1) or FALSE (0), the gates in fault tree output probabilities are related to the set operations of Boolean logic. The probability of a gate's output event depends on the input event probabilities. An AND gate represents a combination of independent events. That is, the probability of any input event to an AND gate is unaffected by any other input event to the same gate in set-theoretic terms, this is equivalent to the intersection of the input event sets, and the probability of the AND gate output is given by:

$$P(AandB) = P(A \cap B) = P(A)P(B) \quad (3)$$

An OR gate, on the other hand, corresponds to a set union:

$$P(AorB) = P(A \cup B) = P(A) + P(B) - P(A)P(B) \quad (4)$$

Figure 2 shows the basic Fault Tree Structure, showing some of the most common gate symbols.

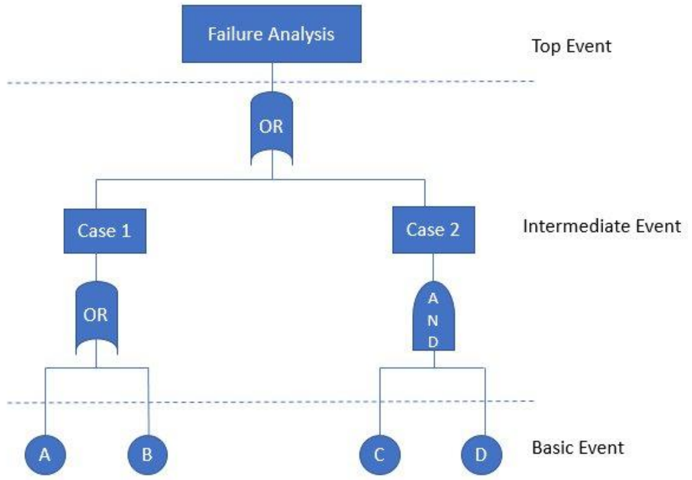
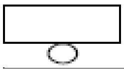
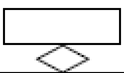
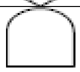
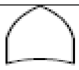
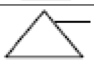
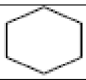
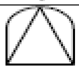
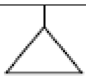
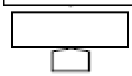
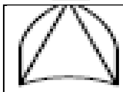


Figure 2- Basic Fault Tree Structure (Ibrahim, 2018)

2.1. Gate Symbols

Table 1: Fault Tree Analysis Symbols and Events

Symbols	Event
	BASIC EVENT-a basic initiating fault requiring no further development
	CONDITIONING EVENT – specific conditions or restriction that applies to any logic gate sed primarily with PRIORITY and INHIBIT gates)
	UNDEVELOPED EVENT – an event which is not further developed either because it is of insufficient consequence or because its information is unavailable
	AND – output fault occurs if all other input faults occur
	OR – output fault occurs if at least one of the input faults occur
	COMBINATION – output fault occurs if n of the input fault occurs
	TRANSFER OUT – Indicates that this portion of the tree must be attached at the corresponding TRANSFER IN
	INHIBIT -Output fault occurs if the (single) input fault occurs in the presence of an enabling condition (the enabling condition is represented by a CONDITIONING EVENT drawn to the right of the gate)
	PRIORITY AND-Output fault occurs if all of the input faults occur in a particular order (the order is represented by a CONDITIONING EVENT drawn to the right of the gate)
	TRANSFER IN-Indicates that the tree is developed further at the occurrence of the corresponding TRANSFER OUT (for example on another page)
	HOUSE EVENT-An event which is normally expected to occur
	XCLUSIVE OR-Output fault occurs if exactly one of the input faults occurs

2.2. Minimal Cutsets and Pathsets

Minimal cutsets are minimal combinations of basic event conditions resulting in system failure. They are also called prime implicants (Kohda, 2006) and are useful for reliability analysis and design. If any basic event is removed from the minimal cutsets, in that case, the remaining events collectively no longer constitute a cutset. Minimal cutsets are used to reduce the size of the fault tree, and to estimate the reliability bound of a system. See equation 5. The dual of the cutset is called the path set. To obtain the path set, the OR gates are replaced by AND gates and vice-versa. This agrees with De Morgan theorem. The theorem goes as follow: De Morgan's theorem involves a pair of rules involving group complementation in Boolean algebra. It states that inverting the output of any gate produce the same function as the opposite of the gate –AND becoming OR and vice visa, with inverting inputs. That is: $\bar{A} + \bar{B} = \overline{AB}$

De Morgan's theorem thus means that a NOR gate is equivalent to a Negative-AND gate, and a NAND gate is equivalent to a Negative-OR gate.

$$\left(1-\sum_{i=1}^{c}\prod_{j=1}^{n}\left(1-R_j\right)\right) < R < \left(1-\sum_{i=1}^{p}\prod_{j=1}^{n}R_j\right) \quad (5)$$

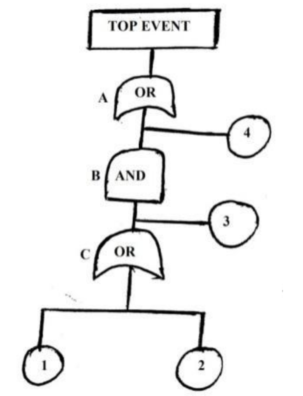
Where R = the reliability of the system, c = number of cutsets i , p = number of path sets i , R_j = the reliability of the jth subsystem, and n = number of subsystems or gates.

The number of elements in the cutset depends on the number of parallel paths or AND combinations. While the number of cutsets depends on the series path or OR combination.

Methods of Generating Cutsets

Several methods have been proposed for generating cutsets. Kara-Zaitri (1996), and Akinode and Oloruntoba (2017) reviewed the procedures for the following techniques: Method of Obtaining Cut Sets (MOCUS) (Fussell,Henry& Marshall,1974), Boolean Top-Down Algorithm, the set equation transformation system (SETS) computer code, SIFTA algorithm, Minimal Cut Sets Upward (MICSUP), WAMCUT fault tree evaluation method, ALLCUTS algorithm, **Fa**ult **t**ree **r**eduction **a**lgorith**m** (FATRAM) (Rasmuson& Marshall,1978), Efficient Logic Reduction Analysis of Fault Trees (ELFRAT) and Binary Decision Diagram (BDD) method (Rebaiaia& Ait-Kadi, 2013). An example is used to illustrate three of these methods. Consider the fault tree is shown in Table 1 and the corresponding solutions.

Table 1 - Selected minimum cut set illustrative examples

Fault tree	Minimum cut set examples
	(1) Boolean Top-Down Algorithm $A = 4 \cup B = 4 \cup (3 \cap C) = 4 \cup \left(3 \cap (1 \cap 2)\right)$ $\therefore Cutsets\ are\ \{4\}, \{1,3\}\ and\ \{2,3\}$
	(2) Minimum Cutset Upward (MICSUP) $C = 1 \cup 2$ $B = 3 \cap C = 3 \cap (1 \cup 2)$ $A = 4 \cup B = 4 \cup 3 \cap (1 \cup 2)$ $\therefore Cutsets\ are\ \{4\}, \{1,3\}\ and\ \{2,3\}$
	(3) Methods of Obtaining Cutsets (MOCUS) $A = 4 \cup B$ $3 \cap C$ $1 \cup 2$ $\therefore Cutsets\ are\ \{4\}, \{1,3\}\ and\ \{2,3\}$

Quantifying Components Failure Probabilities

The steps in quantifying component failure probabilities were given by(Vesely, 2002) as determining whether the failure is demand related or time-dependent, ascertaining the environment of operation, choosing the suitable failure rate value from professional data sources e.g. MIL-HBK-217F, identifying the specific component failure mode, determine the exposure time and if the failure is repairable determine the repair time for a time-dependent failure, determine the number of demands if greater than 1 for a demand-related failure, compute the probabilities using the appropriate formula and input into the computer application or if a manual evaluation use the appropriate formula to quantify.

The following are noted when using generic failure data. (a) the generic data needs to be screened for the relevant failure mode and environment, (b) operational factors or environmental factors are given to scale reference failure data, and (c) the generic data can also be updated using mission-specific mission-specific data. Bayesian statistical approaches are used in this updating to appropriately handle the information

3. Selected Fault Tree Analysis Modifications

The standard FTA is limited to the analysis of a system that isis complex-in terms of units and variables since the Fault tree becomes unusually unwieldy and the analysis time consuming to conclude. It is difficult to consider all the failure modes and the accuracy of the result cannot be ascertained. This has led to the development of computer software such as probabilistic fault trees (PROFAT I and II). SFTs are commonly used for dependability study, although they are unable to capture a system's dynamic failure behaviour. By permitting the dependability assessment of dynamic systems, dynamic dependability assessment overcomes many of the constraints of static dependability analysis. It can simulate various possible interactions between system components and factors and record system behaviour for different states. Furthermore, it can capture systems' time- or sequence-dependent behaviour. SFTs have been expanded in several ways to assist dynamic dependability analysis, including dynamic fault trees (DFTs), state-event fault trees, and Stochastic Hybrid Fault Tree Automaton (SHyFTA). The DFT is one of the most extensively used dynamic extensions of the SFT because it can capture sequence-dependent behaviour, functionally dependent component behaviour, and event priority. SHyFTA is a new approach to dynamic reliability evaluation that combines DFT and Stochastic Hybrid Automaton approaches(Kabir,2017).Dynamic FTA has been developed to enable the computation of time-dependent risk profiles. This modifies the conventional FTA that is time-invariant(Kabir, Aslansefat, Sorokos,Papadopoulos& Konur, 2020; Lukowicz, Magott, & Skrobanenk, 2011).Human Error Identification in Systems (HEIST) or Fuzzy failure rates can be used in the analysis of systems where low accuracy is caused by human error(Baig et al., 2013; Doytchev & Szwillus, 2009).

4. Case Study Review of Applications of Fault Tree Analysis

Although a review of FTA application was reported by Cepin (2011), Mahmood, Ahmadi, Verma, Srividya, and Kumar (2013), Baig et al. (2013) and in the book co-authored by Lai,Sujeet and Fan(2018), there is a need for the present study. Baig et al. (2013) considered 25 publications and restricted to pre-2013 and Lai,Sujeet and Fan(2018) presented FTA from a theory and applications point of view. The fault trees' evolution was discussed by Cepin (2011), as well as their qualitative and quantitative evaluation. The importance measures, such as Fussell-Vesely importance, risk achievement worth, risk reduction worth, and Birnbaum important, were applied in illustrated situations. Mahmood et al. (2013) focused on the review of FFTA. A thorough list of related references is provided, as well as the applications of fault tree analysis. This present study is wider in scope than Baig et al. (2013) in terms of literature considered, the years covered. It is also more recent than Cepin (2011) and Lai et al. (2018). In this paper, we highlight software tools for FTA and some common modifications to the FTA along with their use cases.

4.1. Power System and Energy Sources

The FTA has been used by several researchers in the evaluation of risks associated with diverse aspects of power generation and distribution. Volkanovski, Čepin and Mavko (2009) used it for power system reliability, Rahman, Varuttamaseni, Kintner-Meyer and Lee(2013) used it for customer reliability assessment of distribution power system, and Vicenzutti, Menis and Sulligoi (2019) utilised it in the risk assessment of an electric ship-integrated power system. Other authors such as Yousfi Steiner et al. (2012), Bhangu, Pahuja and Singh (2015), Akhtar and Kirmani (2020) and Cheng, Li, Mang, Neupane, Wauthelet and Huba (2014) utilised the FTA or its modification for the analysis of faults associated with fuel cells, thermal power plant, wind energy system and biogas system respectively.

In (Volkanovski et al., 2009), the FTA approach is used to establish a novel method for power system reliability analysis. The method is based on fault trees that are generated for each power system load point. The fault trees are related to energy transmission from generators to specific load sites being disrupted. The identification of the most essential parts in the power system is made possible by quantitative examination of fault trees, which serves as a vantage point for assessing the reliability of power delivery. The IEEE test system has been used to test the algorithm of the computer code, written to simulate the system to facilitate applications of the approach. The reliability of the power system was evaluated, and the key contributors to power system reliability were identified in both qualitative and quantitative terms.

Rahman et al. (2013)pointed out that traditional electric grid customer reliability prediction uses the system average (SA) component failure frequency and downtime, which are weighted solely by the number of components in the system. These SA parameters are then utilized to compute the system's component reliability and availability, as well as the effect on customer reliability. Although this approach is straightforward, when customer information is not used in the SA parameter computations, information about customer disturbance experiences is lost, adding to mistakes when estimating customer reliability indices in the study. When applied to the reliability model with fault tree and two-state Markov chain formulations, the approach directly incorporates customer disturbance information in component failure frequency and downtime calculations by weighting these parameters with information of customer interruptions, with significant improvement in the prediction of customer reliability indices. The approach was successfully used in a real-world distribution power system with over 2.1 million users.

For ships with high power requirements, the all-electric ship idea is becoming the norm. Currently, a well-proven process is used to develop the onboard power system [i.e., the integrated power system (IPS)]. To address the ship's complexity, this process draws on historical data and trial-and-error procedures built over nearly 30 years of design experience. The evolution of IPSs is currently being pushed ahead by the introduction of more stringent standards that can only be met by employing new power system architectures and including onboard novel subsystems. Introducing innovation through a design approach based on previous experience, on the other hand, is inefficient. As a result, new design paradigms are required. In this regard, concepts and methods from other technical disciplines might be applied to produce a "reliable design process" that will make it easier to introduce innovation into ship IPSs. The trustworthy design process is offered in this work by Vicenzutti et al. (2019) after a brief overview of the conventional method and the actual causes driving its revolution. The latter combines strategies for imposing reliability as well as dynamic power system modelling. An application example is utilized to demonstrate the usefulness of the suggested strategy, while insights into process integration in the overall ship design process are provided.

The goal of Bhangu et al. (2015) was to use the FTA to assess the reliability and risk of a thermal power plant. To achieve this goal, failure data from the plant was collected, and this information was utilized to run a Pareto analysis to identify the key causes of failure. Finally, a fault tree was created, which includes the components of the steam flow process that are accountable for major failures. The economic value of dependability persuades the employment of a strategic maintenance approach to increase the plant's reliability. The fault tree analysis was discovered to be an excellent method for evaluating, visualizing, and appraising failure paths in systems, hence offering a framework for effective system reliability and risk assessments. It was subsequently recommended that to deal with the risk of failures and protracted downtimes, a maintenance policy that provides a formal framework for identifying potential failure modes and developing a periodic maintenance plan is critical.

For the development and commercialization of fuel cell technologies, reliability and lifetime are common concerns. Improving them is a huge problem, and over the last decade, there has been a surge in interest in efforts aimed at understanding degradation mechanisms and creating diagnostic tools for fuel cell systems. It is mostly used in safety and reliability engineering. The goal of Yousfi Steiner et al. (2012)was to provide an overview of the use and contribution of FTA in diagnostics of both solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEFCs). It was noted that stack flooding and membrane drying out are among the most frequently encountered faults in PEFCs stacks. These problems are mostly caused by a lack of equilibrium in the fuel cell's water balance. High temperature and high gas flow helps to prevent flooding by encouraging liquid water evaporation and membrane drying, but high current density causes high water production, which, like low flow rate and high relative humidity, promotes flooding.

In (Akhtar & Kirmani, 2020) an FFTA technique for wind energy system reliability evaluation is provided. For wind energy system setup, the technique integrates the influence of operational failures and faults in a fuzzy environment. The standard FTA could not be used because the acceptance of risk probability values is not taken into account. Furthermore, due to a lack of proper data, it is extremely difficult to make a clear estimate of wind system failure rates or the risk of undesirable occurrences occurring. Therefore, an FTA based on fuzzy set theory was described and used in the wind energy system. In the case when the wind energy system fault probabilities are not exact values, the fault probabilities are treated as a fuzzy number, and the fuzzy failure rate is calculated using fuzzy rules. A risk analysis method based on the fuzzy risk index (FRI) is used to determine the exact influence of each fundamental event on the top event. As a result, the fuzzy-based fault tree technique, which combines the probabilities of imprecision and technical inaccuracy, is more flexible and adaptive, and it has a lot of applications in reliability engineering.

Biogas technology is gaining traction around the world, particularly in nations where governments encourage the use of residential biogas systems. Despite its popularity, biogas technology has issues such as poor construction, pipeline leakage, limited biogas production, and a lack of maintenance. These issues must be identified and analyzed for small-scale biogas systems to be implemented and operated effectively (SBS). Based on a statewide field survey in Nepal conducted by Cheng et al. (2014), FTA was used to identify problems and analyze their effects on SBS operation from a technical standpoint. Ninety-four SBS sets were chosen and sampled in specific areas.

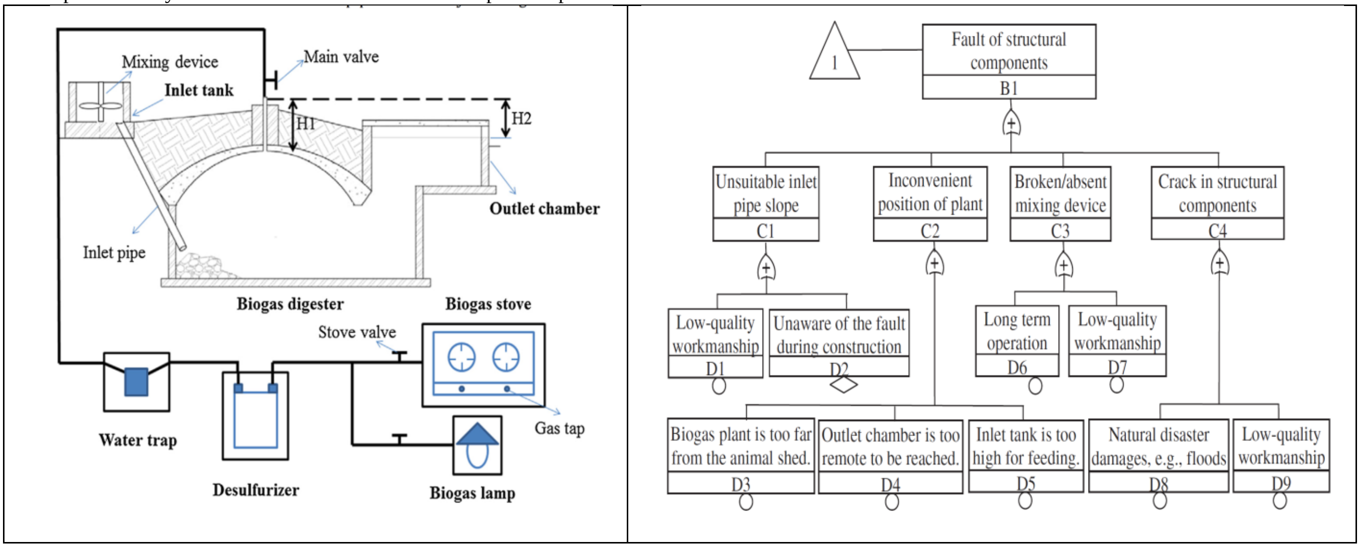


Figure 3-Schematic of the SBS and its fault tree of structural components

Structural components, biogas use equipment, piping system, biogas generation, and effluent disposal system are the five subsystems of SBS. The fault probabilities of the five subsystems are 0.67, 0.48, 0.73, 0.26, and 0.64, respectively, based on a statistical analysis of the 94 targeted cases. The Delphi technique is used to estimate the weights of five subsystems, and the SBS fault probability is calculated. The schematic of the SBS and its fault tree of structural components are shown in Figure 3.

The findings suggest that piping system failures are the most common and that adequate bio-slurry disposal and reuse are usually overlooked. Regardless of the social and economic benefits of SBS, the following deployment options in Nepal are analyzed from a technical standpoint: (1) SBS's operational status is not ideal. (2) In practice, the well-operation ratio is around 53% based on failure criteria. (3) Skilled masons are required for SBS to function properly. (4) Maintenance is essential for optimum operation. The findings show that FTA is an excellent analysis technique for technical evaluation in the field of biogas technology and is particularly suitable for SBS evaluation.

4.2. Marine Engineering

There are various aspects of the marine transportation system that are prone to risk or fault. Examples will be the transportation of chemical products (Senol, Aydogdu, Sahin, & Kilic, 2015), ship mooring systems (Mentes&Helvacioglu, 2011; Kuzu, Akyuz& Arslan,2019) and the ship engine itself (Laskowski, 2015) are all prone to risk.

Chemical products are without a doubt the most difficult goods to transport by ship, as they necessitate specialized knowledge in terms of handling, storage, and transportation. As a result, such cargoes may be explosive, poisonous, corrosive, and polluting to the environment, as well as hazardous to human health. Careful and expert operations are always required. Because shipping activities have the potential to destroy human life, commodities, and the maritime environment, risk assessment has long been a major concern in maritime transportation. In this context, maritime safety researchers are attempting to improve risk mitigation strategies (Kuzu et al.,2019).

The chemical transportation industry is dedicated to addressing the core causes of cargo contamination and has developed stringent solutions and procedures to reduce chemical cargo contamination. The procedures that have been implemented are based on practical experience. Therefore, Senol et al. (2015) were to find a suitable management method to reduce the risk of cargo contamination by lowering the root cause occurrence probabilities via FTA. FTA is a method for obtaining qualitative and quantitative dependability of complex systems by employing exact values of root cause occurrence probability. Probabilistic values, on the other hand, are insufficient for using the FTA approach. As a result, they deployed the FFTA method to determine the main causes of contamination and their probability of occurrence.

A fuzzy fault tree analysis methodology for spread mooring systems is provided in the work of Mentes and Helvacioglu (2011) and Kuzu et al. (2019). The framework proposed by Mentes and Helvaciogluis shown in Figure 4. For spread mooring arrangements, the methodology integrates the effects of operational failures and human errors in a fuzzy environment. The ambiguous and imprecise events such as human errors cannot be handled efficiently in traditional FTA. This is because the tolerances of the likelihood values of dangers are not taken into consideration and a lack of data to make an exact estimate of the failure rates of system components or the probability of undesired events occurring. Thus, fault tree analysis based on fuzzy set theory was devised and applied to the spread mooring system options to overcome these drawbacks. In addition, sensitivity analysis is performed using the fuzzy weighted index (FWI) to assess the impact of each fundamental event on the top event. The results obtained reveal that for fault diagnosis and hazard estimation of spread mooring systems, the FFTA is more flexible and adaptive than conventional fault tree analysis.

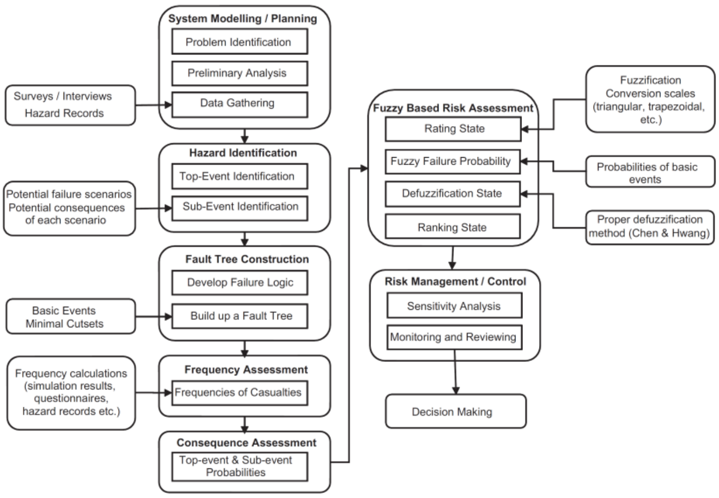


Figure 4- Framework for tanker-buoy mooring fuzzy risk analysis. Source: Mentes and Helvacioglu (2011)

Kuzu et al. (2019)aimed to provide insight into a process of accident development connected to dangers in ship mooring operations, which poses a significant challenge to the crew. In the instance of a ship mooring operation, an FFTA was used to do a systematic risk analysis. The instance of M/T Zarga, which occurred during berthing manoeuvre at a liquefied neutral gas port was examined in terms of potential risks. During the accident, a member of the ship's crew was critically hurt on his head. To that purpose, a risk model was created, as well as certain risk management choices. The authors further gave practical contributions to marine professionals in the course of risk mitigation and accident prevention, in addition to dealing with data shortages in maritime risk assessment.

Because of the nature of the work, risk analysis is critical in maritime transportation. The International Maritime Organization established a formal safety assessment as a standard for risk assessments on ships. However, it makes no recommendations about how to analyze the hazards. As a result, maritime transportation safety researchers are looking for comprehensive risk analysis methodologies. Akyuz et al. (2020) utilised the bow-tie approach in a fuzzy logic context to do a comprehensive risk analysis. The fuzzy logic method deals with the ambiguity and imprecision of expert judgments, whereas the bow-tie method analyzes potential causes and repercussions of failures. Because the repercussions of cargo liquefaction on-board ships are exceedingly harmful to the crew, ship, and environment, it was chosen as a case study. Aside from providing theoretical knowledge, the study assists marine personnel in raising cargo liquefaction safety awareness.

Laskowski(2015)employed FTA to assess the dependability of a standard two-stroke, slow-speed ship cross-head diesel engine for ship propulsion. A qualitative examination of the tree was carried out, leading to the identification of the system's minimal cut sets.

4.3. Petroleum Industry

Areas with the petroleum industry where FTA and its modifications have been applied include the assessment of the risk associated with oil and gas pipelines (Miri, Wang,Yang, &Finlay, 2011; Badida, Balasubramaniam, &Jayaprakash, 2019; Gao, Wang, Zhao, &Yan, 2009), oil wells (Lavasani, Ramzali, Sabzalipour, & Akyuz, 2015) and oil storage (Halloul, Chiban, &Awad, 2019). The current state of technology for assessing the safety of gas pipelines was discussed by Gao, Wang, Zhao and Yan (2009). The Chinese gas pipeline safety evaluation system was investigated. The implementation of FTA was examined, as well as several approaches utilized for gas pipeline safety assessment. The leaking influence factors were then triggered based on gas pipeline accidents, and various fault tree models were described. The qualitative and quantitative safety assessment techniques, as well as some improvement suggestions, were developed based on the FTA. But because the traditional FTA method requires a sound database of failure of all basic events to calculate the chance of system failure, and such a database is not accessible in the offshore pipeline industry, hence, a fuzzy FTA methodology is presented by Miri et al.(2011) to address this issue. In the lack or presence of data, the suggested model can quantify the fault tree of an offshore pipeline system. The use of important metrics in sensitivity analysis is also demonstrated in theproposition through a case study. These pipelines are sensitive to natural disasters and have the potential to cause significant environmental damage. Damage to the pipeline infrastructure could raise the chance of a spill, which would have an impact on the environment. Because of the potential environmental, infrastructure, and financial consequences in the event of a structural collapse, the structural integrity of these pipelines is of major concern to oil and gas corporations, governments, and other stakeholders. The failure probabilities of the components are treated as exact numbers for evaluating the chance of a top event in fault tree analysis, which is an important risk assessment technique. Due to a paucity of historical data for calculating pipeline failure rates due to natural hazards, the goal of this work by Badida et al. (2019)was to use FFTA and expert elicitation to estimate the possibility of pipeline failure. Fussel-Vesely The cutsets were ranked using importance metrics. Even in the absence of historical probability data, the proposed FFTA framework was used to examine the incidence of top events. The findings are intended to aid safety professionals in making judgments on how to manage the risk of oil and gas pipelines. A considerable proportion of drilled wells are abandoned each year, and this is a fact. Permanently abandoned wells, or PA wells, may pose some dangers with potentially disastrous outcomes. Furthermore, abandoned leaking oil and natural gas wells can cause significant environmental damage. The failure probabilities of system components are treated as exact numbers in traditional Fault Tree Analysis (FTA) for evaluating the failure probability of the Top Event (TE). In the drilling sector, there is always a scarcity of data for assessing component failure rates. As a result, fuzzy theory can be employed to solve the problem. The purpose of the work by Lavasani et al. (2015a) was to use Fuzzy Fault Tree Analysis to investigate leakage via PA oil and natural-gas wells in the drilling sector (FFTA). As a result, the researchers claimed to have contributed to marine safety and ocean environmental conservation on both a theoretical and practical level.

Halloul et al. (2019) opined that one of the most serious threats to the occupational safety of oil storage tanks is a crude oil tank fire and explosion (COTFE). The authors presented a unique method of FFTA paired with expert interviews to identify and estimate the risk of COTFE. Using this process, many COTFE likely causes were discovered, and a fault tree was created. A fuzzy set theory was used to address the discomfort of the lack of exact probability data for the basic events (BEs), and the probability data of each BE was considered as trapezoidal fuzzy integers. In addition, to reduce mistakes during the aggregation process, owing to the difficulty associated with gathering sufficient probability data of BEs in fault trees in practice and probabilities of bottom events in FTA are usually calculated based on the opinions of experts or engineers. However, in many circumstances, numerous experts are differing in their viewpoints, the work introduced a new approach for merging the varied perspectives of experts. To estimate the COTFE risk and learn more about the fault tree, a detailed quantitative analysis of the FFT was performed, including structure importance, Fussell-Vesely importance for BEs, and minimum cut sets importance. A case study and analysis, as well as a comparison with an in-literature case study utilizing an existing FFTA, are provided to demonstrate the usefulness of the suggested method. Some recommendations were made to take preventative actions ahead of time to avoid COTFE accidents and to assist in prioritizing safety procedures.

Additionally, the engineering use of the fault tree method has a challenge in reasonably aggregating expert opinions. A fuzzy fault tree analysis strategy based on the similarity aggregation method (SAM-FFTA) was thus proposed by Yin et al. (2020). This method uses SAM and fuzzy set theory to handle a wide range of expert opinions to calculate the probabilities of bottom events in a fault tree. Finally, a natural gas spherical storage tank with a volume of 10,000 m^3 was studied, and the relevance of each bottom event was identified, to validate the applicability and flexibility of the suggested method. Flame, lightning, electrostatic spark, impact spark, mechanical breakdown, and deformation/breakage have the most impact on the explosion of the natural gas spherical storage tank, according to the findings.

4.4. Fire Hazard Prevention

Fire outbreaks usually result in the loss of life and the very least valuable properties. There is a need to be ing able to forecast the occurrence of such fire hazards when one is working in a fire-prone environment. Relevant works in this regard include those of Ruilin and Lowndes (2010), Hu (2016), Shi, Jiang and Meng (2018) and Yazdi, Korhan and Daneshvar (2020). Ruilin and Lowndes (2010) and Shi et al. (2018) examined fire outbreak prevention via FTA and its modifications for coal mines. Hu (2016) looked at fire prevention in a hotel. Whereas, Yazdi et al. (2020) examined fire and explosion prevention in the process industry.

To improve the forecast of the potential danger of coal and gas outburst events during underground mining of thick and deep Chinese coal seams, Ruilin and Lowndes (2010) proposed using a combined fault tree analysis (FTA) and artificial neural network (ANN) model according to Figure 5. The generated model was utilized to explore the gas emission characteristics as well as the geological conditions in the Huaibei coal mining region in China's Anhui province. There are a lot of coal and gas outbursts in this region's coal seams. Eight prominent model characteristics relating to the gas concentration or geological conditions of the coal seams, which represent the potential danger of in situ coal and gas outbursts, were found through a study of the data obtained from an initial application of an FTA model. The FTA approach was used to identify the eight most important model parameters, which were then employed as input variables in an ANN model. The results of the ANN model were utilized to create a qualitative risk rating that characterizes the probable danger of coal and gas outburst events occurring. SAFE, Possible, HIGH, and STRONG are four separate potential risk alarm levels. The prediction model's solutions were derived from a combination of quantitative and qualitative data, such as the gas content or gas pressure, as well as the geological and geotechnical features of coal seams. Using this combined solution strategy, more explicit and precise model linkages between in situ geological conditions and the danger of coal and gas outbursts were discovered. The hybridized model gave a solid alternative way to forecast the possible risk of coal and gas outbursts, according to an examination of the model solutions.

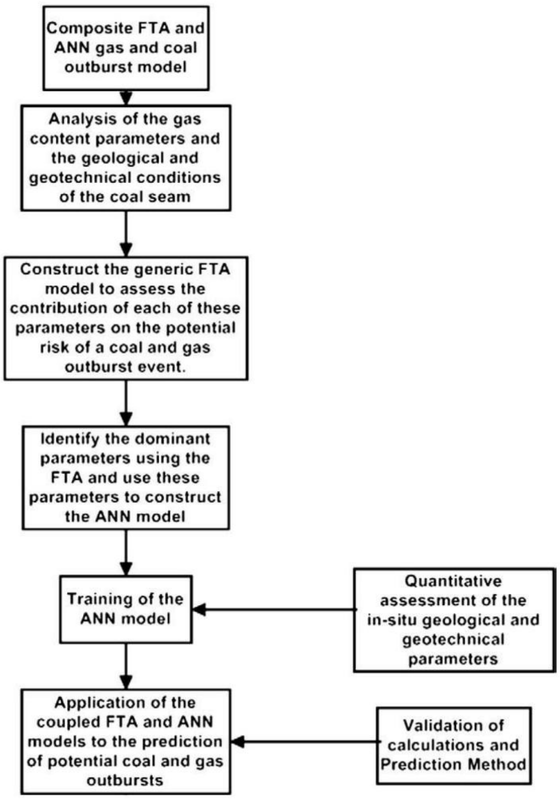


Figure 5- Structure of the neural network coupled FTA. Source: Ruilin and Lowndes (2010)

In the study done by Shi, Jiang and Meng (2018), the Xingli Coal Mine, China was used as a study site to develop an evaluation model of coal dust and gas explosions based on a fuzzy fault tree to determine the risk factors of coal dust and gas explosions. In addition, the risks connected with such explosions were assessed for this specific coal mine. The fuzzy probabilities of basic events were gathered through expert scoring after an on-site inquiry, and these expert judgments were then aggregated as trapezoidal fuzzy numbers to calculate the degrees of importance of all basic events. Finally, these importance levels were sorted. The basic occurrences with greater probabilities were chosen based on the resultant order to identify major hazards in the daily safety management of this particular coal mine. Furthermore, effective preventative methods for gas and coal dust explosions were developed. The fuzzy fault tree analysis approach is critical in the investigation of coal mine explosions that occur by accident, and it gives theoretical direction for enhancing the effectiveness of coal mine safety management scientifically and practically.

Strengthening the building fire safety of hotels has become one of the hottest subjects addressed by an increasing number of professionals and researchers to prevent large-scale tragedies and considerable property losses in society. The fault tree of a building fire was built following the hotel building fire system analysis, taking into account the entire fire accident process. The minimal cut set, the minimal radius set, and the importance of structure were used to analyze the link between primary and secondary components. According to Hu (2016), building fires in hotels are caused by three main factors: dangerous behaviour by hotel employees, electrical equipment and wiring failures, and the ignition of flammable and combustible materials. Also mentioned are essential steps for preventing building fires, such as enhancing daily fire safety management, key positions, and key staff, which can improve the safety and operational reliability of hotel structures. The results obtained suggested that the FTA method yielded a full exposition of many causes causing hotel fires and their logical relationships, as well as a reference for improving the design and construction of safety technical measures in other industries.

The goal of Yazdi, Korhan and Daneshvar (2020) was to establish FTA by calculating the probability of a fire and explosion occurring in a process industry using expert opinion. When the FTA is drawn, all probabilities of the BEs should be available to find the probability of the TE. In this circumstance, expert judgment was employed instead of failure data to solve the difficult problem. To assign specific weight to each expert, the fuzzy analytical hierarchy process was employed as a common technique, and fuzzy set theory is used to aggregate expert opinion. In this case, the likelihood of BEs was calculated, and the probability of the TE will be calculated using Boolean algebra. In addition, the importance measurement technique and modified Technique for order of preference by similarity to ideal solution (TOPSIS) were used to lower the probability of the TE in terms of three criteria (safety effects, cost, and benefit). A real-life case study is used to demonstrate the effectiveness of the recommended approach.

4.5. Internet of Things Systems Deployed for Aquaculture

The internet of things (IoT) has been utilised in a vast array of fields. An example of its usage is in precision agriculture (Ehiagwina, Kehinde, Iromin, Nafiu and Punetha (2018). Precision agriculture may help to minimize expended resources and maximize yield using internet-connected wireless sensor nodes. As shown by Chen, Zhen,Yu, and Xu (2017), IoT has been deployed to aquaculture. Aquaculture equipment is frequently implemented in outdoor ponds in remote places using the Internet of Things (IoT). In these demanding environments, errors are common, and the workforce often lacks professional experience and pays little attention to these details. When issues occur, qualified workers must perform maintenance outside. As a result, based on the FTA and a fuzzy neural network, Chen, Zhen,Yu, and Xu (2017) proposed an intelligent method for defect identification. The possible locations of the fault in the intelligent system are shown in Figure 6. First, the fault tree in the suggested technique displays a logical structure of defect symptoms and faults. Second, by extracting rules from fault trees, duplicate and redundant information is avoided. Third, the association mapping between fault symptoms and faults is trained using a fuzzy neural network. One defect can create a range of fault symptoms in aquaculture IoT, and one symptom can be caused by a variety of faults. There are four-fault correlations discovered. The findings demonstrate that one symptom-to-one fault, two symptom-to-two faults, and two symptom-to-one fault links may be swiftly diagnosed with high precision, although one symptom-to-two fault patterns do not perform as well but are still worth investigating. In the aquaculture IoT, this paradigm implements diagnosis for the majority of failures.

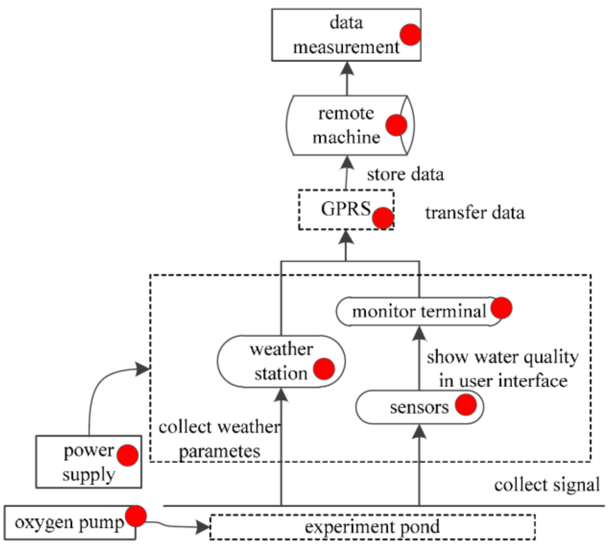


Figure 6- The possible locations fault occurs in the aquaculture IoT. Source: Chen, Zhen,Yu, and Xu (2017)

4.6. Railway Transportation System

Train accident reports have been the topic of extensive investigation, and many methods have been employed to extract useful information from these reports to improve safety. The association between train length and accident rate, for example, has been studied (Heidarysafa, Kowsari, Barnes & Brown, 2018). All players involved in the design, development, and operation of a rail transportation system use one or more safety approaches to detect hazardous situations, their causes, prospective accidents, and the severity of the resulting repercussions. The major goal is to justify and ensure that the transportation system's design architecture is safe and does not pose any special risk to users or the environment. Domain specialists are brought in as part of the certification process to examine the system's safety and to conceive new scenarios of potential mishaps to assure the thoroughness of such safety investigations (Hadj-Mabrouk, 2019). There has also been a need to underscore the necessity of having proper knowledge of causality.

The FTA may be used in this causal analysis. The probability of the BE is typically treated as either an exact point value or a random time-dependent variable in the traditional approach. However, it is often hard to acquire a precise estimate of an event occurrence rate or its distribution function due to the inherent imprecision and uncertainty of the given data. In such instances, the fuzzy technique is one of the finest options for system analysis. Jafarian and Rezvani (2012) give a thorough and honest investigation into the use of the fuzzy FTA to assess rail safety hazards. A method for quantifying and evaluating the fault tree in a fuzzy environment is proposed for this aim. The strategy given in this article is based on using the levels defuzzification method to modify weighted averaging. As a result, during the defuzzification process, it recommends a new importance distribution function for the level sets. Furthermore, it incorporates the fuzzy environment into the conventional approach's minimal cut-set and Fussell–Vesely significance metrics. These significance metrics can be used to rank the minimal cut-sets and basic events according to their contribution to the top event probability. The minimal cutset, which includes fundamental events such as "broken rail" and "technical defects in some areas of the track that are not recognized," was determined to have the greatest impact on the likelihood of a passenger train derailment. Furthermore, the important basic events for the train derailment likelihood and uncertainty were identified as 'Switch erroneously set ahead of the train' and 'Technical defects in some areas of the track that are not detected.'

Szkoda and Kaczor(2016)discussed how a method based on fault tree analysis and Monte Carlo simulation can be used to evaluate the rail system's dependability and availability. The primary goal of the proposed technique is to determine the origin and effect of undesirable events, as well as to determine selected reliability indices and identify the rail vehicle's weakest components that have the greatest impact on downtime and technical availability. The results of a project employing a 6Dg diesel locomotive, carried out in collaboration with the largest Polish rail carrier, are shown to demonstrate the implementation of the presented technology. The assessment of availability and reliability was based on real-world data from 75 locomotives. The times-to-failure and times-to-repair models were developed using data obtained during the operation of the 6Dg locomotives. To examine the impact of component defects on the vehicle's reliability, a fault tree model of the locomotive was created. According to the authors, a discrete simulation method can be used to acquire desired features and values of selected metrics, which can then be used to assess the reliability and availability of rail vehicles. Calculations were supported by specialist software such as Weibull++, BlockSim, and Minitab. Advanced solutions in the area of reliability and availability simulations are included in the program. The test results show that the proposed approach has a wide range of applications.

Huang et al. (2020) observed that an explicit and effective prior accident analysis and accident control method is vital and necessary to successfully manage the railway dangerous goods transit system. To evaluate the railway dangerous goods transit system accident, a combined Fault Tree and Fuzzy D-S Evidential Reasoning approach were proposed to tackle the uncertainty modelling and information fusion difficulties that exist in railway dangerous goods transit system accident analysis. The approach was examined against the backdrop of a historic lithium battery railway transportation catastrophe that occurred in China in 2016. The findings suggested that the transportation staff's professional skills and attitudes are the weakest links in this lithium battery train transportation mishap. The author thus recommended that managers of China's railway dangerous goods transit system should pay more attention to transportation personnel's professional qualifications and attitudes. Some actions, such as raising safety and security awareness, training and evaluating transportation personnel's professional skills, may be useful in reducing transportation personnel's irresponsible working attitude.

Jong, Lai, Young and Chen (2020) reported that on October 21, 2018, a Puyuma express train derailed in Yilan, Taiwan, after speeding through a tight bend. There were 18 fatalities and 267 injuries in this tragedy. Although such accidents happen regularly all over the world, this instance of an Overspeed derailment from a train set equipped with automatic train protection (ATP) system (similar to the function of Positive Train Control (PTC) in the United States) is unusual. The Executive Yuan, Taiwan's highest administrative institution, created a temporary inquiry team, and the probe was concluded in less than two months. The process, analysis, conclusions, and suggestions from the accident inquiry were reported in this paper. The accident was first investigated utilizing FTA to determine possible causes and contributing factors. Using a Swiss cheese model, the results were then grouped into layers of defence. By integrating the timestamps of crucial events, the authors modified the original Swiss cheese model to a "time-dependent Swiss cheese model" to show how the barriers were overcome at different times. To further demonstrate the causal linkages, a modified Swiss cheese model called the "causal relationship Swiss cheese model" was proposed. The proposed process and models allowed the immediate causes and contributing elements to be immediately discovered and presented in a fashion that the general public could understand. The findings revealed that the ATP system (or the PTC) cannot ensure complete safety. To ensure the safety of railway operations, a review of the safety culture and procedures is necessary.

4.7. Miscellaneous Applications

Other areas of the applications of FTA are highlighted next. This includes tunnel drilling, management of medical waste, drinking water system, etc.

Tunnel Drilling

When determining project feasibility and cost, the risk level of the horizontal directional drilling (HDD) project is an important factor to consider. It's also a good place to start when it comes to introducing the risk management approach, which attempts to limit the number of installation failures and the negative repercussions that come with them. Tunnels can be used to transport water from a basin to other places across varied distances in the water business. The building of such tunnels is inherently dangerous, and unexpected events and incidents can occur. As a result, rigorous risk assessments must be performed as a top priority by the owner, contractor, and consultant organization. This is so that they can mitigate the risk caused by these unplanned events and incidents by following a methodical and logical plan (Ardeshir, Amiri, Ghasemi and Errington, 2014; Gierczak, 2014).

The goal of Gierczak(2014) was to create a new mathematical model for assessing the qualitative and quantitative risk of HDD projects of various sizes (MINI, MIDI, and MAXI), which takes installation specificity into account (the optional possibility of applying various tools and machines). The FFTA was used to do the risk assessment. Unwanted events were grouped into four categories: ground issues, machine issues, environmental issues, and management issues. The use of fuzzy set theory in the suggested model reduced the ambiguity, lack of accuracy, and difficulty in obtaining crisp values of the probability of the basic event that can occur in traditional Fault Tree Analysis. Four cases were used to demonstrate the practical use of the suggested methodology for the MINI, MIDI, and MAXI HDD projects.

The following 21 unfavourable events were discovered to have an impact on the risk level for MINI HDD projects: incorrect load and stress calculations that exceed the product pipe capacity during installation, failure to consider the allowable bending radius of the drill pipes or the product pipe, an incorrect choice of the external pipe coating, a loss of communications with the drill rig, drill tool failure due to material fatigue, drill rig breakdown, a mud, etc.

The hazards and their main sources that are frequently faced in such tunnel drilling initiatives are recognized and appraised by Ardeshir, Amiri, Ghasemi and Errington (2014). To identify the major causes of events and incidents, a fault tree method is used. By its very nature, a risk assessment cannot be characterized by absolute values, hence fuzzy data must be employed to calculate the risk's chance of occurrence and severity. Time, cost, quality, and safety are the four key criteria used. The Analytic Hierarchy Process (AHP) is used to determine the significance of the entire influence of risk and to estimate the significance of each criterion. The case study of the Dasht-e Zahab water conveyance tunnel was chosen for consideration in the research because it was subjected to severe and multiple dangers. Different interviews with field specialists were conducted to validate the results produced utilizing the strategy. It was determined that by employing the proposed approach on the case study, the project's risks could be assessed in a more rigorous and precise manner than could be done without it. As a result, this method is recommended for similar projects including complex risks that must be thoroughly studied and understood.

Drinking-Water System

Drinking water systems are susceptible and face a variety of threats. Risk studies must incorporate the complete drinking water system, from source to tap, to avoid sub-optimization of risk-reduction solutions. Tools that can represent relationships between distinct events are required for such an integrated approach. Fault tree analysis is a risk estimation tool that can model inter-event relationships. A probabilistic risk analysis of a large drinking water system in Sweden was carried out using FTA on an integrated level. Lindhe, Rosén, Norberg and Bergstedt (2009) main goals were to (1) establish a method for integrated and probabilistic risk analysis of complete drinking water systems, and (2) assess the usability of Customer Minutes Lost (CML) as a risk indicator. The study looked at both number and quality failures. The odds of events and uncertainty in the estimates were estimated using hard data and expert judgments.

Monte Carlo simulations were used to calculate the results. CML is a useful indicator of drinking water system hazards. The presented method offers data on the system's risk levels, failure probabilities, failure rates, and downtimes. This data is provided for both the whole system and its many subsystems. In addition, the method allows for the comparison of the outcomes to performance targets and risk levels that are acceptable. As a result, the method supports integrated risk analysis and, as a result, aids decision-makers in minimizing risk-reduction choices that are under-optimized. A similar study was reported two years later by Tchorzewska-Cieslak, Boryczko and Eid (2011).

Aerospace

Li, Huang, Zhu, Liu and Xiao (2012) did a fuzzy fault tree analysis of uncontained events for an aero-engine rotor. In addition, in fault tree analysis, a new methodology based on fuzzy set theory is employed to estimate the failure probabilities of basic events. First, the fuzzy fault tree idea is presented. The fault tree for uncontained events of an aero-engine rotor is then created, with the minimal cut sets determined using the descending technique. Furthermore, utilizing the symmetrical L-R type fuzzy number to express the failure probability, the interval representation and calculation approach is described, and the resulting fault tree is quantitatively investigated in the case study.

Cheng, Li, Chu, Yeh and Simmons (2013) reported that an aerospace firm aims to reduce inventory and increase turnover by using FTA. Material capacity planning, material need planning modules provided as part of Enterprise Resource Planning, and a self-developed inventory management system were formerly used to manage the company's inventory. The inventory turnover rate has been on the rise in recent years, and the total inventory cost is high, up to US$260 million. The analysis prioritizes improvement alternatives based on risk reduction using an FTA approach. The findings of the study revealed that risk-based decision-making, aided by FTA, is effective in dealing with the inventory problem. The FTA has improved inventory levels by 30%, according to the inventory turnover rate.

Medicine

Medical waste management is one of the most important environmental concerns facing not only healthcare institutions but also a broader variety of organizations and communities. Medical waste generated in health care is a unique type of trash that, if not properly handled, can pose a variety of health and safety risks to individuals and the environment. Makajic-Nikolic et al. (2016) offered an application for risk assessment of infectious medical waste management in the Clinical Centre of Serbia, which is the largest health facility in South-East Europe. To assess the three parts of the assessment – functional, qualitative, and quantitative – the FTA technique was utilized. The quantitative study based on expert judgments specified the probability of both basic and top events, while the qualitative analysis gave the system's structural function and minimal cut sets (spreading of infection with medical waste). Finally, the events were prioritized based on their impact on the undesirable event connected to infectious medical waste management using Birbaim's RAW (Risk achievement worth), RRW (Risk reduction worth), and Fussell–importance Vesely's metrics. They chose the FTA approach for this research because it not only allows us to analyze individual risks (as do other risk assessment methodologies used in medical waste management – FMEA, HACCP, PHA, CREA), but it also allows us to analyze risk linkages and interdependencies. The authors identified the basic flaws in medical waste management systems based on the acquired results, and it found that preventing or mitigating these failures has the greatest impact on the observed system improvement.

Another area of application is the investigation of the risk of infection of the coronavirus disease (COVID-19). Bakeli and Hafidi(2021) accurately observed that the coronavirus (COVID-19) pandemic has had a detrimental influence on the engineering and construction business, and there is a lot of uncertainty about whether the industry will recover. While waiting for an effective recovery, which might take a long time, science must come up with ways to coexist with the virus and resume construction work. Many guidelines address how to limit the risk of infection to at-risk individuals in construction, remodelling, installation, and maintenance operations, so this isn't the first time health and safety science has dealt with such a danger of infection. The goal of this article is to conduct an infection risk analysis, taking into account the unique characteristics of COVID-19, and to identify control measures to ensure COVID-19 infection prevention and management on site. The study will employ a probabilistic methodology based on Fault Tree Analysis.

Process and Chemical Plants

Lavasani, Zendegani and Celik (2015) applied the FFTA methodology to the petrochemical process industry, which has recognized fire, explosion, and toxic gas emissions as potential threats. To show the proposed methodology, the case study focuses on deethanizer failure in petrochemical plant operations. As a result, the research has presented theoretical and practical solutions to the problem of operational data scarcity in risk assessment.

Yazdi, Nikfar and Nasrabadi (2017) consider the chemical storage tank as one of the most significant units in a chemical plant, both theoretically and practically, by extending FFTA common causes of failure and dependency between the components.

Hauptmanns (2018) reported on FTA and how it may be used to ensure the safety of process plants. Many systematic processes for plant safety assessments have been created in the quest to improve the safety of technical systems. In fault tree analysis, a human mistake is regarded similarly to technical component failure. After the undesired event or events have been resolved, the initiating events (events that could cause the undesired event) must be identified. The author observed that the analyst must have a deep understanding of the system under study as well as strong expertise in physics, chemistry, and engineering to hunt for unwanted and starting events.

Yazdi and Zarei (2018) provided an integrated method to fuzzy set theory and FTA for dealing with uncertainty in chemical process plant risk analysis. The worst-case scenario is chosen first, based on qualitative risk analysis, and then the FFTA is built. Finally, several fuzzy aggregations and defuzzification algorithms are used to calculate the likelihood of each BE and TE, and the output of each approach is compared to the occurrence probability of TE to determine which BEs are critical. The proposed methodology was used to perform a fuzzy probabilistic analysis of hydrocarbon emission in the March 2005 BP oil spill. The results showed that the proposed method was quite helpful in risk analysis when it comes to reducing or handling uncertainty.

Cybersecurity Risk Assessment

In industrial control systems, cybersecurity is critical. The study of de Gusmão, Silva, Poleto, e Silva and Costa (2018) provided a model that combined FTA, decision theory, and fuzzy theory to identify current reasons for cyberattack prevention failures and assess cybersecurity system's susceptibility. The model was used to assess the cybersecurity risks associated with attacking a website, e-commerce site, or enterprise resource planning (ERP) system, as well as the potential consequences of such attacks; we evaluate these consequences, which include data dissemination, data modification, data loss or destruction, and service interruption, in terms of financial losses and restoration time. The model application's results confirm its use and show how, in comparison to websites or ERP, e-commerce is more vulnerable to cybersecurity threats, owing to frequent operator access, credit transactions, and user authentication issues that are common in e-commerce.

Robotics

A methodology named integrated factor evaluation–analytic hierarchy process–T-S fuzzy fault tree analysis (IFE-AHP-T-S fuzzy FTA) was proposed by Bai, Xie, Liu, Li, and Zhong (2021) to allocate the reliability index of industrial robot systems (IRSs) with multiple fault states, aiming at the defects (only two kinds of state, i.e., normal or fault) of existing reliability allocation methods without considering the intermediate degradation process. First, the IRS reliability model is created, and the reliability index allocation principle is described. Second, a two-layer IFE model was developed to assess the technical merit of various subsystems, taking into account mechanical structural degradation and IRS multi-state faults. To lessen the subjectivity of expert evaluation processes, the hesitant fuzzy language set is used, which can deal with uncertain information. The T-S fuzzy FTA is then provided to calculate fault probability and mean time between failures (MTBF) in the process of weight allocation of reliability index for IRSs and six subsystems using the AHP. Finally, IRSs have been assigned to multi-state reliability indexes. This study is significant in terms of minimizing fault likelihood and dangerous elements, as well as providing a theoretical foundation for the entire life cycle design of IRSs.

5. Conclusion

This overview of FTA can provide insight to the recent risk and reliability researchers pointing out potential areas where FTA may be applied. The procedure for application, modifications to the FTA and areas of applications have been reviewed in this paper.FFTA usually employs a triangular or trapezoidal possibility and takes into consideration the uncertainty in computations, but standard FTA does not provide information about the tolerances and volatility of the probability values, as well as the interdependence of the events. The relevance of the fundamental event is quantified in traditional FTA based on its direct contribution to the top event, whereas in FFTA, the impact of uncertainties is also taken into account. Given this, we have noted that the FTA is an evolving technique.

The potential applications are endless, because of the modifications of the FTA especially for large systems with too many gates and events to be considered. It is expected that this useful technique will continue to evolve and see other applications to the technological system.

REFERENCES

Abdollahzadeh, G., & Rastgoo, S. (2015). Risk assessment in bridge construction projects using fault tree and event tree analysis methods based on fuzzy logic. *ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg*, *1*(3).

Akhtar, I., & Kirmani, S. (2020). An application of fuzzy fault tree analysis for reliability evaluation of wind energy system. *IETE Journal of Research*, 1-14.

Akinode, J. L., & Oloruntoba, S. A. (2017). Algorithms for Reducing Cut Sets in Fault Tree Analysis. *International Journal of Advanced Research in Computer and Communication Engineering*, *6*(12).

Akyuz, E., Arslan, O., & Turan, O. (2020). Application of fuzzy logic to fault tree and event tree analysis of the risk for cargo liquefaction on board ship. *Applied Ocean Research*, *101*, 102238.

Alvehag, K. (2008). *Impact of dependencies in risk assessments of power distribution systems* (Doctoral dissertation, KTH).

Andrews, J. (1998). Fault Tree Analysis. In *Proceedings of the 16th International Safety Conference, www. fault-tree. net/papers/andrews-fta-tutor. pdf (Stand 12/2004)* (pp. 1-101).

Ardeshir, A., Amiri, M., Ghasemi, Y., & Errington, M. (2014). Risk assessment of construction projects for water conveyance tunnels using fuzzy fault tree analysis. *International Journal of Civil Engineering*, *12*(4), 396-412.

Badida, P., Balasubramaniam, Y., & Jayaprakash, J. (2019). Risk evaluation of oil and natural gas pipelines due to natural hazards using fuzzy fault tree analysis. *Journal of Natural Gas Science and Engineering*, *66*, 284-292.

Bai, B., Xie, C., Liu, X., Li, W., & Zhong, W. (2021). Application of integrated factor evaluation–analytic hierarchy process–TS fuzzy fault tree analysis in reliability allocation of industrial robot systems. *Applied Soft Computing*, 108248.

Baig, A. A., Ruzli, R., & Buang, A. B. (2013). Reliability analysis using fault tree analysis: a review. *International Journal of Chemical Engineering and Applications*, *4*(3), 169.

Bakeli, T., & Hafidi, AA (2021). COVID-19 infection risk management during construction activities: An approach based on Fault Tree Analysis (FTA). *Journal of Emergency Management (Weston, Mass.)* , *18* (7), 161-176.

Bhangu, N. S., Pahuja, G. L., & Singh, R. (2015). Application of fault tree analysis for evaluating reliability and risk assessment of a thermal power plant. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *37*(18), 2004-2012.

Bollen, M. H. (2000, May). Effects of adverse weather and aging on power system reliability. In *2000 IEEE Industrial and Commercial Power Systems Technical Conference. Conference Record (Cat. No. 00CH37053)* (pp. 63-68).

Chacko, V. M. (2021). On Birnbaum type joint importance measures for multistate reliability systems. *Communications in Statistics-Theory and Methods*, 1-20.

Chen, Y., Zhen, Z., Yu, H., & Xu, J. (2017). Application of fault tree analysis and fuzzy neural networks to fault diagnosis in the internet of things (IoT) for aquaculture. *Sensors*, *17*(1), 153.

Cheng, C. Y., Li, S. F., Chu, S. J., Yeh, C. Y., & Simmons, R. J. (2013). Application of fault tree analysis to assess inventory risk: a practical case from aerospace manufacturing. *International Journal of Production Research*, *51*(21), 6499-6514.

Cheng, S., Li, Z., Mang, H. P., Neupane, K., Wauthelet, M., & Huba, E. M. (2014). Application of fault tree approach for technical assessment of small-sized biogas systems in Nepal. *Applied Energy*, *113*, 1372-1381.

Doytchev, D. E., & Szwillus, G. (2009). *Combining task analysis and fault tree analysis for accident and incident analysis: A case study from Bulgaria. Accident Analysis & Prevention* , *44*(6), 1172–1179.

Fayaz, F., & Pahuja, G. L. (2018). Cost Based Importance Measures for Reliability Analysis of Wind Turbine System. In *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)* (pp. 1720-1724). IEEE.

Fussell, J. B., Henry, E. B., & Marshall, N. H. (1974). *MOCUS: A computer program to obtain minimal sets from fault trees* (No. ANCR-1156). Aerojet Nuclear Co., Idaho Falls, Idaho (USA).

Gao, W. X., Li, J. X., Wang, Q., Zhao, Z. J., & Yan, R. S. (2009). Application of Fault Tree Analysis to Urban Gas Pipeline Safety Assessment. *Gas & Heat*, *12*.

Gierczak, M. (2014). The quantitative risk assessment of MINI, MIDI and MAXI horizontal directional drilling projects applying fuzzy fault tree analysis. *Tunnelling and Underground Space Technology*, *43*, 67-77.

de Gusmão, A. P. H., Silva, M. M., Poleto, T., e Silva, L. C., & Costa, A. P. C. S. (2018). Cybersecurity risk analysis model using fault tree analysis and fuzzy decision theory. *International Journal of Information Management*, *43*, 248-260.

Hadj-Mabrouk, H. (2019). Contribution of artificial intelligence to risk assessment of railway accidents. *Urban Rail Transit*, *5*(2), 104-122.

Halloul, Y., Chiban, S., & Awad, A. (2019). Adapted fuzzy fault tree analysis for oil storage tank fire. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *41*(8), 948-958.

Hauptmanns, U. (2018). Fault tree analysis for process plants. In *Engineering risk and hazard assessment* (pp. 21-60). CRC Press.

Heidarysafa, M., Kowsari, K., Barnes, L., & Brown, D. (2018, December). Analysis of Railway Accidents' Narratives Using Deep Learning. In *2018 17th IEEE International Conference on Machine Learning and Applications (ICMLA)* (pp. 1446-1453). IEEE.

Huang, W., Liu, Y., Zhang, Y., Zhang, R., Xu, M., De Dieu, G. J., ... & Shuai, B. (2020). Fault Tree and Fuzzy DS Evidential Reasoning combined approach: An application in railway dangerous goods transportation system accident analysis. *Information Sciences*, *520*, 117-129.

Ibrahim, S. K. M. (2018). *Spacecraft performance analysis and fault diagnosis using telemetry-mining* (Doctoral dissertation, Faculty of Engineering, Zagazig University, Egypt).

Jafarian, E., & Rezvani, M. A. (2012). Application of fuzzy fault tree analysis for evaluation of railway safety risks: an evaluation of root causes for passenger train derailment. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *226*(1), 14-25.

Jong, J. C., Lai, Y. C., Young, C. C., & Chen, Y. F. (2020). Application of fault tree analysis and Swiss cheese model to the overspeed derailment of Puyuma Train in Yilan, Taiwan. *Transportation research record*, *2674*(5), 33-46.

Kabir, S. (2017). An overview of fault tree analysis and its application in model based dependability analysis. *Expert Systems with Applications*, *77*, 114-135.

Kabir, S., Aslansefat, K., Sorokos, I., Papadopoulos, Y., & Konur, S. (2020). A hybrid modular approach for dynamic fault tree analysis. *IEEE Access*, *8*, 97175-97188.

Kara- Zaitri, C. (1996). An improved minimal cut set algorithm. *International Journal of Quality & Reliability Management*.

Kohda, T. (2006). A Simple Method to Derive Minimum Cutsets for a Non-Coherent Fault Tree. *International Journal of Automation and Computing , 2, 151-156.*

Kuzu, A. C., Akyuz, E., & Arslan, O. (2019). Application of fuzzy fault tree analysis (FFTA) to maritime industry: a risk analysing of ship mooring operation. *Ocean Engineering*, *179*, 128-134.

Lai, F. S., Sujeet, S., & Fan, L. T. (2018). Fuzzy fault tree analysis: Theory and application. In *Engineering risk and hazard assessment* (pp. 117-138). CRC Press.

Laskowski, R. (2015). Fault Tree Analysis as a tool for modelling the marine main engine reliability structure. *Zeszyty Naukowe Akademii Morskiej w Szczecinie*, (41 (113)), 71-77.

Lavasani, S. M., Ramzali, N., Sabzalipour, F., & Akyuz, E. (2015). Utilisation of Fuzzy Fault Tree Analysis (FFTA) for quantified risk analysis of leakage in abandoned oil and natural-gas wells. *Ocean Engineering*, *108*, 729-737.

Lavasani, S. M., Zendegani, A., & Celik, M. (2015). An extension to Fuzzy Fault Tree Analysis (FFTA) application in petrochemical process industry. *Process Safety and Environmental Protection*, *93*, 75-88.

Li, Y., Huang, H. Z., Zhu, S. P., Liu, Y., & Xiao, N. C. (2012). An application of fuzzy fault tree analysis to uncontained events of an areo-engine rotor. *Int. J. Turbo Jet-Engines*, *29*(4), 309-315.

Lindhe, A., Rosén, L., Norberg, T., & Bergstedt, O. (2009). Fault tree analysis for integrated and probabilistic risk analysis of drinking water systems. *Water research*, *43*(6), 1641-1653.

Lukowicz, M., Magott, J., & Skrobanenk, P. (2011). Selection of Minimal Tripping Times for Distance Protection Using Fault Tree with Time Dependencies. *Electric Power Systems Research* , *81*(7), 1536-1571.

Makajic-Nikolic, D., Petrovic, N., Belic, A., Rokvic, M., Radakovic, J. A., & Tubic, V. (2016). The fault tree analysis of infectious medical waste management. *Journal of Cleaner Production*, *113*, 365-373.

Mavko, B., Ã, A. V., & Marko, C. (2009). Application of the Fault Tree Analysis for Assessment of Power System Reliability. *Reliability Engineering & Systems Safety* , *94*(4)*, 1116-1127.*

Mentes, A., & Helvacioglu, I. H. (2011). An application of fuzzy fault tree analysis for spread mooring systems. *Ocean Engineering*, *38*(2-3), 285-294.

Miri, L. M., Wang, J., Yang, Z., & Finlay, J. (2011). Application of fuzzy fault tree analysis on oil and gas offshore pipelines.*Int. J. Mar. Sci. Eng.*, *1*(1), 29-42,

Mahmood, Y. A., Ahmadi, A., Verma, A. K., Srividya, A., & Kumar, U. (2013). Fuzzy fault tree analysis: a review of concept and application. *International Journal of System Assurance Engineering and Management*, *4*(1), 19-32.

Mohammed, S. J., Azim, N., & Ali, M. (2011). Fault Tree Analysis Approach in Reliability. *International Journal of Multidisciplinary Sciences and Engineering* , *2*(6)*, 46-50.*

Rahman, F. A., Varuttamaseni, A., Kintner-Meyer, M., & Lee, J. C. (2013). Application of fault tree analysis for customer reliability assessment of a distribution power system. *Reliability Engineering & System Safety*, *111*, 76-85.

Rasmuson, D. M., & Marshall, N. H. (1978). FATRAM-A core efficient cut-set algorithm. *IEEE Transactions on Reliability*, *27*(4), 250-253.

Rebaiaia, M. L., & Ait-Kadi, D. (2013). A new technique for generating minimal cut sets in nontrivial network. *AASRI Procedia*, *5*, 67-76.

Ruilin, Z., & Lowndes, I. S. (2010). The application of a coupled artificial neural network and fault tree analysis model to predict coal and gas outbursts. *International Journal of Coal Geology*, *84*(2), 141-152.

Shadiah, H. N., Arshad, A., Mohamed, A. K., & Olagoke, O. (2019). Integration of fault tree and importance measure for toxic prevention barrier. In *E3S Web of Conferences* (Vol. 90, p. 02007). EDP Sciences.

Shi, S., Jiang, B., & Meng, X. (2018). Assessment of gas and dust explosion in coal mines by means of fuzzy fault tree analysis. *International Journal of Mining Science and Technology*, *28*(6), 991-998.

Senol, Y. E., Aydogdu, Y. V., Sahin, B., & Kilic, I. (2015). Fault tree analysis of chemical cargo contamination by using fuzzy approach. *Expert Systems with Applications*, *42*(12), 5232-5244.

Szkoda, M., & Kaczor, G. (2016). Reliability and availability assessment of diesel locomotive using fault tree analysis. *Archives of transport*, *40*.

Tchorzewska-Cieslak, B., Boryczko, K., & Eid, M. (2011). Failure scenarios in water supply system by means of fault tree analysis. *Advances in Safety, Reliability and Risk Management: ESREL 2011*, 408.

Vesely, B. (2002). Fault tree analysis (FTA): Concepts and applications. *NASA HQ*.

Vicenzutti, A., Menis, R., & Sulligoi, G. (2019). All-electric ship-integrated power systems: Dependable design based on fault tree analysis and dynamic modeling. *IEEE Transactions on Transportation Electrification*, *5*(3), 812-827.

Volkanovski, A., Čepin, M., & Mavko, B. (2009). Application of the fault tree analysis for assessment of power system reliability. *Reliability Engineering & System Safety*, *94*(6), 1116-1127.

Wangdee, W., & Billinton, R. (2007). Reliability assessment of bulk electric systems containing large wind farms. *International journal of electrical power & energy systems*, *29*(10), 759-766.

Yazdi, M., Nikfar, F., & Nasrabadi, M. (2017). Failure probability analysis by employing fuzzy fault tree analysis. *International Journal of System Assurance Engineering and Management*, *8*(2), 1177-1193.

Yazdi, M., Korhan, O., & Daneshvar, S. (2020). Application of fuzzy fault tree analysis based on modified fuzzy AHP and fuzzy TOPSIS for fire and explosion in the process industry. *International journal of occupational safety and ergonomics*, *26*(2), 319-335.

Yazdi, M., & Zarei, E. (2018). Uncertainty handling in the safety risk analysis: an integrated approach based on fuzzy fault tree analysis. *Journal of failure analysis and prevention*, *18*(2), 392-404.

Yin, H., Liu, C., Wu, W., Song, K., Liu, D., & Dan, Y. (2020). Safety assessment of natural gas storage tank using similarity aggregation method based fuzzy fault tree analysis (SAM-FFTA) approach. *Journal of Loss Prevention in the Process Industries*, *66*, 104159.

Yousfi Steiner, N., Hissel, D., Mocoteguy, P., Candusso, D., Marra, D., Pianese, C., & Sorrentino, M. (2012). Application of fault tree analysis to fuel cell diagnosis. *Fuel cells*, *12*(2), 302-309.