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FAULT AND EVENT-TREE TECHNIQUES IN OCCUPATIONAL HEALTH-SAFETY SYSTEMS – PART I: INTEGRATED RISK-EVALUATION SCHEME

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Abstract

Fault-Trees (FT) and Event-Trees (ET) are well recognized techniques worldwide, which have been used by reliability experts in failure analysis of complex technical systems. In risk assessment (RA) of Occupational Health-Safety Systems (OHSS), the situation is absolutely different, since their application is not quite expanded and has not been extensively incorporated in the main risk assessment methodologies of OHSSs, despite their significance. In this article, we review and classify FT/ET methods, and also study and elaborate their characteristics (i), and on the other side, we propose an alternative risk-evaluation scheme (ii), in order to (a) depict the subsistent situation of FT/ET application in various occupational fields, and (b) enhance their handling and usage in RA of OHSS. To reinforce the second aim, we implement a new risk-evaluation framework by the combination of a FT (or ET) process with a stochastic quantified risk-evaluation model. The paper consists of tree sections, including: (1) a literature review of thirteen representative scientific journals, published by Elsevier_B.V. and IEEE_Inc., during the years 2000-2012, and concentrated on the main categories of FT/ET techniques concerning OHSS RA, (2) an overview for the FT/ET techniques in RA and (3) a proposed risk-evaluation concept using FT/ETs.

Key words: event-tree techniques, fault-tree techniques, occupational health and safety systems, risk assessment

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1. Introduction

Fault-Tree (FT) analysis is a graphical technique that ensures a systematic-description of the combinations of possible occurrences in a system, which can result in an undesirable outcome. The most serious effect (such as toxic release, explosion, etc.) is selected as the *Top-Event*. This approach can associate hardware-failures with human-failures. A fault tree is constructed by relating the sequences of events, which individually (or in combination), could lead to the top-event. As an example, this may be illustrated by considering the probability of a crash at a road-junction and constructing a tree with AND and OR logic gates (Fig. 1). The tree is constructed by deducing in turn the preconditions for the top event and then successively for the next levels of events, until the basic causes are identified (IET, 2010a).

Furthermore, Event-Tree (ET) analysis by using event-trees (also known as "consequence-trees") is based on binary-logic, in which: an event either has (or has not) happened (i), or a component has (or has not) failed (ii). An event-tree begins with an initiating-event, like a component failure. Other initiating-events could be an increase in temperature/pressure or a release of a hazardous substance. ET is precious in analysing the consequences arising from a failure or undesired event. The consequences of the event are followed through a series of possible paths, where each path is assigned, a probability of occurrence, while the

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probability of the various possible outcomes can be calculated (IET, 2010b). In the example of Fig. 2a, fire protection is provided by a sprinkler system. A detector will (or will not) detect the temperature raise. In case of detector's success, the control-box will (or it will not) work correctly and so on. There is only one branch in the tree that indicates that all the subsystems have succeeded (Fig. 2b).

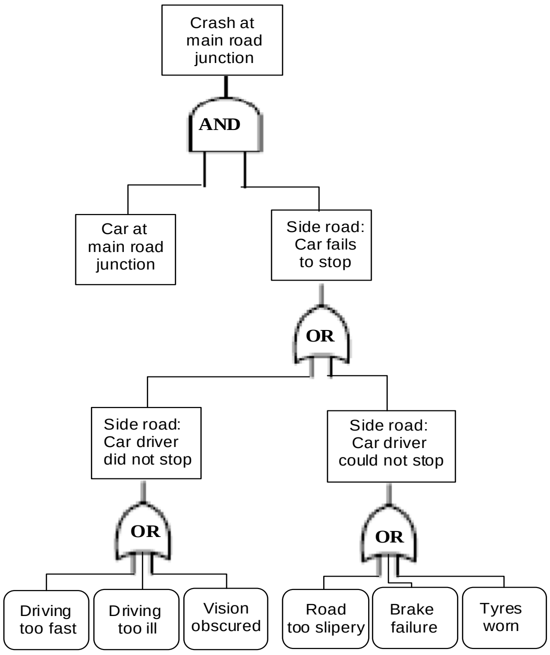


Fig. 1. Fault-Tree analysis of a crash at a road-junction by constructing a tree with "AND" and "OR" logic-gates (adapted from IET, 2010a)

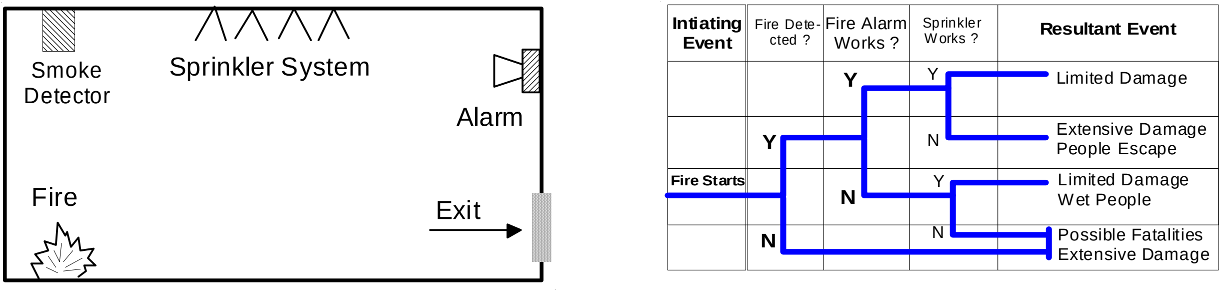
We have to note, that FT is deductive; Logic diagram-'top-down', whereas ET is generally inductive; It works in the opposite way to FT. The analysis starts by considering an "initiating event" (instead of a "final event") and then the interaction with other events attributable to the elementary systems, constructs the so-called consequence trees. ET searches for consequences (different final scenarios), whereas FT searches for basic causes.

Fault-tree and event-tree techniques are widely used by reliability experts, as failure analysis tools, in technical-systems. On the other side, in safety science and mainly in risk assessment (RA) concerning occupational worksites, the situation is absolutely different, i.e. the application of ET and FT techniques is not expanded.

Public interest in the field of safety science has expanded in leaps and bounds during the last three decades, while risk analysis has emerged as an effective and comprehensive procedure that supplements and complements the overall management of almost all aspects of our life. In addition, risk assessment is an essential and systematic process for assessing the impact, occurrence and the consequences of human activities on systems with hazardous characteristics (van Duijne et al., 2008) and constitutes a needful tool for the safety policy of a company.

It is worth noting that whenever the occupational accidents' data (as being recorded by safety managers) are sufficient for the production of adequate time-series, then they could be used in occupational risk assessment of a company by studying the stochastic behavior of the single-component occupational health and safety system (OHSS) of its workplace (Haimes, 2009; Limnios, 2007; Marhavilas and Koulouriotis, 2012a/b/c, their Appendix). In other words, we can consider that the worksite of any company constitutes a simple stochastic system or model (called as OHSS), which is implemented by FT/ET techniques, described by the accident time-series and subjected to failures (breakdowns).

To simplify things, we assume that the system is put to work at the instant t = 0 for the first time and that it presents a single mode of failure. The component, starting a lifetime period at t = 0, is functioning for a certain period of time X_1 (random) at the end of which it breaks down (Limnios, 2007). It remains in this state for a period of time Y_1 (random) during its replacement (or repair) and, at the end of this time, the component is again put to work and so on. In this case, the system is called as "repairable". In the contrary case, when the component breaks down and continues to remain in this state, the system is characterized as "non-repairable". So, we can study the behavior of a company's worksite by observing its OHSS over a period of time (Marhavilas and Koulouriotis, 2012a; Haimes, 2009). Let X be a random variable (r.v.) representing the lifetime of the system with F its cumulative distribution function (c.d.f.): $F(t)=P(X \leq t)$. If F is absolutely continuous, the random variable X has a probability density function (p.d.f.) f. The complementary function of F, noted as $\overline{F}$, is the reliability of the system, noted as $R(t)$.



(a) (b)

Fig. 2. (a) A fire-protection system, and (b) a simplified event-tree (adapted from IET, 2010b)

One of the most usual and frequently used probability-distributions, that deals with the reliability of systems and gives good modeling for the lifetime, is the exponential distribution, which we can be used in the study of the stochastic behavior of a company's single-component OHSS. The variety of risk-analysis procedures is such that there are many appropriate techniques for any circumstance and the selection has become more a matter of taste.

We can consider the risk as a physical entity, which can be measured and expressed by a mathematical equation, under the help of real accidents' data (Marhavilas et al., 2011a/b, 2013; Marhavilas and Koulouriotis, 2008, 2012a/b/c). A basic classification of the risk assessment methodologies incorporates the deterministic (DET) and the stochastic (STO) approach. Moreover, DET techniques are classified into three main categories (qualitative, quantitative, and hybrid), while STO methods includes the Classic Statistical Approach (CSA) and the Accident Forecasting Modeling (AFM) (Marhavilas et al. 2011a; Marhavilas Koulouriotis, 2012a,b). We note that, FTs/ETs are physically embodied in DET techniques.

Taking into account that: (i) FT and ET techniques are very important for risk assessment, concerning occupational health/safety systems and worksites (Marhavilas et al., 2011a, 2012b), and (ii) the fact, they have not been incorporated sufficiently, in the main RA-methodologies, we: (a) study and determine, elaborate and analyze, classify and categorize, the main FT/ET techniques and their characteristics by reviewing the scientific literature, concerning 13 representative scientific journals of Elsevier B.V. and IEEE Inc. covering the period of 2000-2012, and (b) try to amplify their usage in OHSS's RA by presenting a new FT/ET RA-framework. The paper consists of three sections: a) a literature reviewing of thirteen representative scientific journals, b) the presentation of the theoretical background and the classification of the various FT/ET techniques, and c) a proposed risk-evaluation scheme using FTs/ETs.

2. Literature review of FT/ET Techniques in RA

The review of the scientific literature was achieved by the investigation f 13 representative scientific journals published by Elsevier B.V. and IEEE Inc (Table 1). The journals #1-11 are published by Elsevier B.V., while the journals #12-13 are published by IEEE Inc. More specifically, we studied and investigated all the published papers of the above referred journals, gathering a total number of N=31793 papers, concerning 2000-2012.

Having in mind the results of a previous paper by Marhavilas et al. (2011a), and in particular the classification of the occupational risk assessment techniques, we concentrated, through this work, on FT/ET techniques applied in OHSSs. The procedure of reviewing the scientific literature, revealed a plethora of published articles on FT/ET techniques referred to many different fields (like engineering, computer science, transportation, chemistry, medicine, biology etc. These articles address concepts, tools and methodologies that have been developed and practiced in such areas as design, development, quality-control and maintenance, in association with occupational RA.

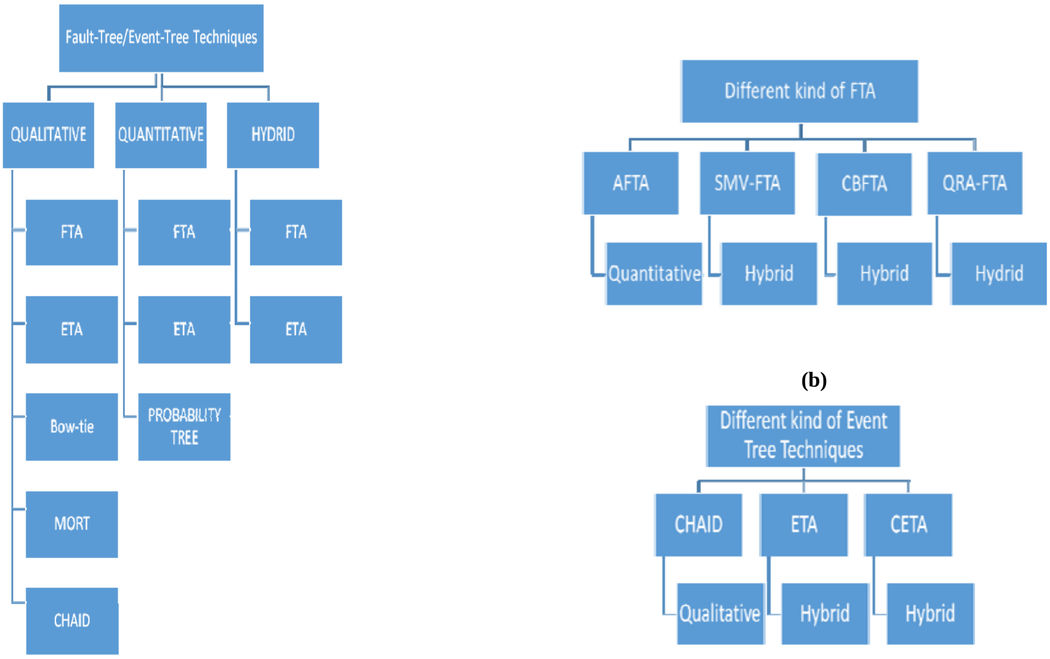
In particular, our review shows that FT/ET techniques are classified into three main categories: (a) the quantitative (QN), (b) the qualitative (QL), and (c) the hybrid techniques (HB). According to QN techniques, the risk can be estimated and expressed plainly by a mathematical relation, under the help of real accidents' data recorded in a work site. In other words, these techniques compare and classify safety based on calculation results using certain mathematical models, and provide a means to calculate the safety performance parameters. The QL techniques are based on analytical estimation processes in association with safety-managers' ability and the analysts' experience (Rouvroye and Bliek, 2002). A HB technique mixes in a single framework both a quantitative and qualitative method.

The different techniques followed in the different analysis processes, start with different actions, end with different actions, and follow different paths between start and finish. Although, this kind of categorization for FT/ET techniques is not unique, it is simple and useful for RA, and has been used in the scientific literature (Marhavilas et al., 2011a, 2012b; Niskanen et al., 2012; Shen and Jia, 2011). Moreover, it will reinforce (or help) the enhancement of their application in OHSS's risk assessment.

Table 1. The 13 investigated journals (during 2000-2012)

Nr	Journal/Acronym	Nr	Journal/Acronym
1	Accident Analysis and Prevention (AAP)	8	Journal of Hazardous Materials (JHM)
2	Applied Ergonomics (ApE)	9	Enginnering Application of Artificial Intelligence (EAAI)
3	International Journal of Industrial Ergonomics (IJIE)	10	Expert Systems with Application (ESwA)
4	Journal of Loss Prevention in the Process Industries (JLPPI)	11	Structural Science (StS)
5	Journal of Safety Research (JSR)	12	Transactions on Reliability (ToR)
6	Reliability Engineering and System Safety (RESS)	13	Trans. on Instrumen. & Measurement (IaM)
7	Safety Science (SS)		

In Fig. 3 we illustrate the results of our scientific-literature review by depicting the classification of the main FT/ET techniques, while a descriptive summary of them is presenting below. Table 2 depicts an overview of their characteristics, comparatively with several settled evaluation-criteria, taking into account other comparative studies (Marhavilas and Koulouriotis, 2008; Marhavilas et al., 2011a, 2013; Rouvroye et al., 2002; Reniers et al., 2005; Zheng and Liu, 2009).



(a) (b) (c)

Fig. 3. The classification of the main fault-tree and event-tree techniques (a), the different kind of FTA techniques (b), and event-tree techniques (c), according to the scientific literature

Table 2. An overview of the characteristics of the various FT/ET techniques, comparatively with settled evaluation criteria

Evaluation criteria	***BOW-TIE***	***CHAID***	***MORT***	***PROBABILITY TREE***	***FTA***	***ETA***	***CETA***	***AFTA***	***CBFTA***	***SMV-FTA***	***QRA-FTA***
Data collection	√	√		√	√	√	√	√	√		√
Identification of hazardous situations	√	√	√	√	√	√	√	√	√	√	√
Multidisciplinary experts team for the application		√	√						√	√	√
High level of structuring	√	√	√		√	√				√	
Applicable to any process or system	√	√	√	√	√	√	√	√	√		√
Possibility of incorporation in integrated risk analysis schemes	√		√	√	√	√		√	√	√	√
Time-consuming		√	√	√					√	√	√
Safety audits	√				√	√	√		√		
Human orientation	√	√	√		√	√	√	√		√	
Equipment orientation	√	√							√		
Proactive use	√	√	√		√	√		√	√	√	√
Reactive use	√		√	√			√	√		√	
Mathematical background				√	√	√	√	√			√
Graphical illustration	√	√		√	√	√	√	√	√		√
Possibility of incorporation in databases			√	√		√		√	√	√	√
Possibility of incorporation in computer automated toolkits	√	√		√	√		√	√	√	√	
Prediction of potential risks	√				√	√				√	
Individual risk orientation	√	√						√	√		√
Societal risk orientation		√					√			√	

3. An overview of FT and ET Techniques in RA

3.1. Fault-Tree Analysis

Fault-Tree Analysis (FTA) models and evaluates the unique interrelationship of events leading to: failure and undesirable (or unintended) states. It focuses on one particular accident event and provides a method for determining causes of that event; it is a methodical-analysis that visually models the logical relationships between equipment-failures/human-errors/external-events, which cause specific accidents. FTs are constructed from events and gates. Basic events can be used to represent technical-failures that lead to accidents, while intermediate events can represent operator errors which may intensify technical failures.

The logical-gates can be used to represent several ways, in which machine and human-failures can be combined, to give rise to the accident. For instance, an AND-gate implies that both initial events need to occur in order to give rise to the intermediate event. Conversely, an OR-gate means that either of two initial events can give rise to the intermediate event (Haimes, 2009; Harms-Ringdahl, 2001; Hong et al., 2009; Kontogiannis et al., 2000; Reniers et al., 2005; Vesely et al., 1981; Yuhua and Datao, 2005). Fig. 3b presents the different kind of FTA techniques, resulting from our scientific-literature review:

(a) **AFTA** (Augmented FTA) augments traditional FTA with potential human/computer working contexts. This method can indentify the potential invocation of unintended functions, which either originates from the software or the human operator, for the given safety-critical software. It traces the reasons back to software interface design defects (Fan and Chen 2000).

(b) **SMV-FTA** technique is equivalent with an exhaustive verification of the possible input signals space. It uses the verification model which is named as model checking, where the specifications are sets of properties to be verified. These properties are presented with temporal logic, a special notation used to simply express temporal relations between signals. The properties have to meet some specifications connected to "legal" input signals, the allowed combinations of the circuit inputs. The combinations are generated by a set of interconnected finite state machines, with the result of producing all possible legal inputs for the tested circuit. An important principle implemented by SMV to produce the legal inputs is the non-determinism. Using this concept, the finite state machines generating the inputs are able to produce the whole area of values. This exhaustive verification model is appropriate for small size circuits. In practice, the circuits have much bigger dimensions. To verify such a circuit, the user has to decompose it in small enough modules, which can be explored exhaustively with model checking. SMV integrates some other techniques to adjust complex circuits in order to verify them both by model checking: symmetry reduction, temporal case splitting, data type reduction, induction, etc. (Koh and Seong 2009).

(c) **CBFTA** (Condition-Based FTA) is a tool for updating reliability values of a specific system and for calculating the residual life according to the system's monitored conditions. It starts with a known FTA. Condition monitoring techniques applied to systems are used to determine updated failure rate values of sensitive components, which are then applied to the FTA. CBFTA recalculates periodically the top-event failure rate, therefore determining the probability of system failure and the probability of successful system operation. CBFTA is for use, during the systems operational phase, including maintenance, not just during design (Shaleva and Tiran, 2007).

(d) **QRA-FTA** technique combines quantitative RA with FTA. In fact, QRA helps industries in two ways: it identifies the dominant contributors to the total risk, and it quantifies the benefits of possible changes. The first step is to analyze the total risk associated with the base case and to calculate the contributions. These findings lead naturally to the specification of possible measures to improve reliability or reduce the damage potential. FTA analyzes systematically and logically how equipment failures, operator errors, and external factors can cause an incident. FTs are used to estimate the probability of these events with the existing safeguards. The results of the FT are analyzed and conclusions and recommendations are determined (Krishna et al., 2003).

3.2. Event tree analysis

Event tree analysis (ETA) is a technique that uses decision trees and logically develops visual models of the possible outcomes of an initiating event. Furthermore, it is a graphical representation of the logic model that identifies and quantifies the possible outcomes following the initiating event. The models explore how safeguards and external influences, called lines of assurance, affect the path of accident chains (Ayyub, 2003; Beim and Hobbs, 1997; Hong et al., 2009). In this method, an initiating event such as the malfunctioning of a system, process, or construction is considered as the starting point and the predictable accidental results, which are sequentially propagated from the initiating event, are presented in order graphically. ETA is a system model representing system safety based on the safeties of sub events. It is called an event tree because the graphical presentation of sequenced events grows like a tree as the number of events increase. An event tree consists of an initiating event, probable subsequent events and final results caused by the sequence of events. Probable subsequent events are independent to each other and the specific final result depends only on the initiating event and the subsequent events following. Therefore, the occurrence probability of a specific path can be obtained by multiplying the probabilities of all subsequent events existing in a path. In an event tree, all events in a system are described graphically and it is very effective to describe the order of events with respect to time because the tree is related to the sequence of occurrences. In the design stage, ETA is used to verify the criterion for improving system performance; to obtain fundamental information of test operations and management; and to identify useful methods to protect a system from failure.

The main characteristics of the technique are briefly summarized as follows: (i) It models the range of possible accidents resulting from an initiating event. (ii) It is a risk assessment technique that effectively accounts for timing, dependence, and domino effects among various accident contributors that are cumbersome to model in fault trees. (iii) It is an analysis technique that generates: (a) QL descriptions of potential problems as combinations of events producing various types of problems from initiating events, (b) QN estimates of event frequencies or likelihoods and relative importance of various failure sequences and contributing events, (c) lists of recommendations for reducing risks, (d) quantitative evaluations of recommendation effectiveness. In Fig. 3c we present the different kind of ET techniques, resulting from of our scientific-literature review.

3.3. Chi Square Automatic Interaction Detection

Chi Square Automatic Interaction Detection (CHAID) is a technique that determines how variables can best be combined in order to explain the result in a given dependent variable. The results are displayed as a tree, showing the hierarchical association between variables, using CHAID. The steps for its application are the following: (i) The procedure begins by finding survey variables that have a significant association with employee satisfaction. (ii) It then assesses the category groups, or interval breaks to pick the most significant combination of variables. (iii) The variable having the strongest association with employee satisfaction becomes the first branch in a tree with a leaf for each category that is significantly different relative to satisfaction. (iv) The process is repeated to find the predictor variable on each leaf most significantly related to satisfaction, until no significant predictors remain. An exceptional advantage of CHAID analysis is its capability to visualize the relationship between the dependent variable (target) and the related factors with a tree image. CHAID analysis is especially useful for data of categorized values instead of continuous values. For this kind of data, some common statistical tools such as regression are not applicable and CHAID analysis is a perfect tool to discover the relationship between variables. Another advantage of CHAID analysis is its ability to analyze employee satisfaction and risk analysis. Finally the advantages in looking for patterns in complicated datasets using CHAID methods include the level of measurement for the dependent variable and predictor variables. CHAID is primarily a step-forward modeling fitting method.

Known problems with step-forward regression fitting models are probably applicable for this method of analysis. Moreover, it is a sequential fitting algorithm and its statistical tests are sequential with later effects being dependent upon earlier ones, and not simultaneous as would be the case in a regression model or analysis of variance where all effects are fit simultaneously (Chi and Chen 2003; SM Research, 2012; TMG, 2012).

3.4. Concurrent Event Tree Analysis

(CETA) is an accident-analysis technique used not only in identifying but also evaluating the sequence of events in a potential accident scenario following the occurrence of an initiating event. Its objective is to determine whether the initiating event will develop into a mishap or if it is sufficiently controlled by the safety systems. CETA has as a purpose to evaluate all of the possible outcomes that can result from an initiating event. Furthermore, it provides a Probabilistic Risk Assessment, of the risk associated with a potential outcome. The CETA technique is ideal in modeling an entire system and it can be conducted at different abstraction levels. What is more, it has successfully been applied to nuclear power and chemical plants and spacecraft. CETA is very easy to be learnt and understood and its proper application depends on the complexity of the system and how skillful the analyst is (Fan and Chen 2000).

3.5. Bow-tie

Bow-tie is a combination (or an integration) of a fault tree, leading from various hazards to a top event, and an event tree leading from the top event to different sorts of damage as is shown in Fig. 4. The idea is a simple; we combine the cause (fault tree) and the consequence (event tree). When the fault tree is drawn on the left-hand side and the event-tree is drawn on the right-hand side with the hazard drawn as a "knot" in the middle the diagram looks a bit like a bow-tie, as shown in Fig. 4 (Ale, 2002; Bruin and Swuste, 2008; Chevreau et al., 2006; Hollnagel, 2008; Hudson, 2009; Jacinto and Silva, 2010; Kim et al., 2003; Targoutzidis, 2010). A bow-tie diagram can easily be created by defining the (i) event to be prevented, (ii) threats that could cause the event to occur, (iii) consequences of the event occurring, (iv) controls to prevent the event occurring, and (v) controls to mitigate against the consequences. Bow-Tie methodology can be used for any type of hazard analysis, from major accidents, through occupational and environmental to business. Its main advantages are: (i) The graphical representation can give a clear picture of what are often complex safety management systems (ii) Clear links between management systems and safety are shown. On the other side, the main disadvantage is: bow-tie analysis requires a high level of knowledge regarding a system and the components of the system that relate to its safety (Scribd, 2012). This technique is very useful for QL analysis, however it would be characterized as QN too (since it was developed for probabilistic RA and is still used as probabilistic in many instances).

In fact, bow-tie was born around 1999 to be used as a QN approach (it is considered probabilistic by nature), but in our work we include this solely in QL FT/ET techniques, because the corresponding papers associated with RA, through the literature review, used the bow-tie only as qualitatively.

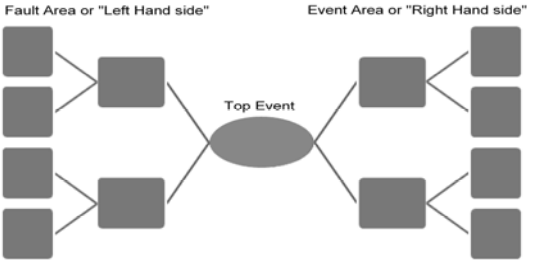


Fig. 4. A drawing for the bow-tie technique

3.6. Management Oversight and Risk Tree

Management oversight and risk tree (MORT) is an analysis technique for identifying safety related oversights, errors, and/or omissions that lead to the occurrence of a mishap. It is primarily a reactive analysis tool for accident/mishap investigation, but it can also be used for the proactive evaluation and control of hazards. MORT analysis is used to trace out and identify all of the causal factors leading to a mishap or undesired event. It is a very specific fault tree. It utilizes the logic tree structure and rules of fault tree analysis, with the incorporation of some new symbols; it provides decision points in a safety program evaluation where design or program change is needed. MORT attempts to combine design safety with management safety but falls under the system design hazard analysis type (SD-HAT).

Furthermore, MORT is used to determine what failed in the management system. It can be applied to all types of systems and equipment, with analysis coverage given to systems, subsystems, procedures, environment, and human error. The primary application of MORT is in mishap investigation to identify all of the root causal factors and to ensure that corrective action is adequate. The use of MORT is not recommended for the general system safety program as there are other techniques available which provide more effective results. It is based on energy transfer and barriers to prevent or mitigate mishaps (Ferjencik and Kuracina, 2008). In particular, it is a root cause analysis tool that provides a systematic methodology for planning, organizing, and conducting a detailed and comprehensive mishap investigation. It is used to identify those specific design control measures and management system factors that are less than adequate and need to be corrected to prevent the reoccurrence of the mishap or prevent the undesired event.

By meticulously and logically tracking energy flows within and out of a system, MORT analysis compels a thorough analysis for each specific energy type. The analyst must have the ability to understand energy flow concepts, for which at least a rudimentary knowledge of the behaviors of each of the basic energy types is necessary. The ability to logically identify energy sources and track flows in systems is an essential skill. The theory behind MORT analysis is fairly simple and straightforward. The analyst starts with a predefined MORT graphical tree that was developed by the original MORT developers. The analyst works through this predefined tree, comparing the management and operations structure of his or her program to the ideal MORT structure, and develops a MORT diagram modeling the program or project. MORT and FTA logic and symbols are used to build the program MORT diagram (Lindhout et al., 2011; Pasman, 2009; Santos-Reyes et al., 2010).

3.7. Probability Trees

Probability tree diagrams allow us to see all the possible outcomes of an event and calculate their probability. The first event is represented by a dot. From the dot, branches are drawn to represent all possible outcomes of the event. Each branch in a tree diagram represents a possible outcome. The probability of each outcome is written on its branch. If two events are independent, the outcome of one has no effect on the outcome of the other; for example, if we toss two coins, getting heads with the first coin will not affect the probability of getting heads with the second. In the scientific literature, probability trees offer a way to visually see all of the possible choices, and to avoid making mathematical errors (Engkvist, 2004).

4. A proposed Stochastic-Deterministic risk-evaluation scheme using FT/ET techniques

In order to strengthen the application of FTs/ETs on OHSS's RA, we propose in this section a new quantified risk-evaluation concept, which is based on a stochastic-deterministic (STODET) combination in association with FT/ET techniques. More specifically, Fig. 5 illustrates, using safety aspects–guidelines of Høj and Kröger (2002), BS 8800 (1996, 2004), and van Duijne et al. (2008), the flowchart of the risk-management (RM) process, within which we have incorporated a new-proposed quantified risk-evaluation scheme (the colour-painted module).

The RM framework consists of three distinct phases: (a) risk analysis, (b) quantified risk-evaluation and c) risk assessment and safety-related decision making (Chen et al., 2013). The first phase includes the hazard sources' identification and the risk consideration/calculation, while the second one the stochastic-deterministic approach. The coloured module focuses on the application of the STODET quantified risk-evaluation, that we have implemented by the simultaneous application and the jointly evaluation of a stochastic model and the deterministic approach of FT/ET, in association with acceptance criteria.

4.1. Identification of hazard sources

It is usually comprised of specifying one or more scenarios of risks. A risk scenario describes an interaction between a person and a system (or product) that possesses hazardous characteristics. It describes the activity of the person(s) involved, the hazard(s), the external factors of the situation and the potential injury. Injury (real accidents') data are the primary source of evidence to establish risk scenarios that describe critical pathways to injury. Expert opinions are significant sources for creating risk scenarios (BS8800:1996, 1996; BS8800:2004, 2004; BS18004:2008, 2008; BS OHSAS18001:2007, 2007; ILO-OSH, 2001; Lu et al., 2013; OHSAS 18002:2008, 2008).

4.2. Risk consideration

In general, it is achieved by the estimation of the (a) likelihood of hazard sources occurrence, (b) consequences' severity, and (c) frequency-level of exposure to hazard sources. This likelihood depends on the (hidden) potential energy that may become active during unsafe behaviour, the energy absorbing capacity, resilience and other qualities of the human body. The probability that a dangerous scenario may occur, depends on the frequency of exposure to the hazard sources, while severity is a subjective issue, because some events, such as cuts, possibly have non-serious effects, while others, such as injuring due to slips, may become more significant.

4.3. Quantified risk-evaluation (QRE)

It enables risk assessors to scale their appreciation of the severity of the short and long term consequences of accidents and the factors that influence the occurrence of an accident scenario. The QRE methods need to be as precise as possible to differentiate the risk level of various activities.

In Fig. 5 we depict a new quantified risk-evaluation process, which we have implemented by combination and jointly evaluation of a stochastic model (like “Time at Risk Failure” (TRF), ”Time-Series Process” (TSP) etc.) with the deterministic FT/ETs techniques, in association with acceptance criteria.

4.4. Decision making

In RM it is fundamental to distinguish the risk assessment process and the decision-making process (ISO/IEC Guide-73, 2009). The first one: (i) is a part of RM process, ending up with the decision making (Salvi and Gaston, 2004), (ii) a tool for measuring the risk, characterized by the likelihood and severity of specific events, and (iii) can further be a basis for decision-making (Høj and Kröger,2002). Risk-based decision-making processes are naturally based on the risk assessment criteria, but could integrate also other criteria that can be cultural, economical, ethical etc. (Salvi and Gaston, 2004; Stezar et al., 2013).

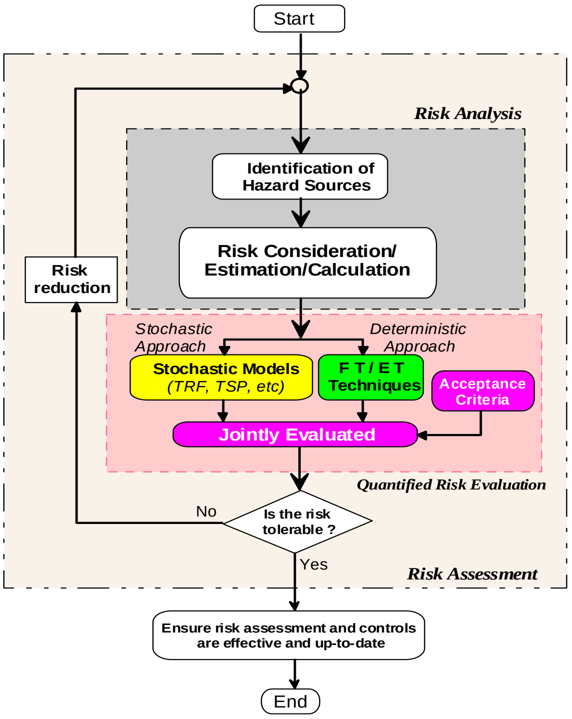


Fig. 5. The flowchart of the risk-management process, within which we have incorporated a new-proposed quantified risk-evaluation scheme (colour-painted module)

5. Discussion and results

5.1. Discussion

Fault-tree (FT) and/or event-tree (ET) analysis is now about 54 years old, has become a well recognized tool worldwide, and is widely used by reliability experts, in technical systems, as failure analysis tools. Many improvements have been made since the first inception of FTA in 1961 and many people have been involved. An overview of the historical aspects of FT analysis in industry, including important developments through the years and improvements in the process, constitutes the work of Ericson (1999).

Moreover, an interesting paper which reviews and classifies FT-analysis methods developed since 1960 until 1985 for system safety and reliability is the one by Lee at al. (1985).

It scattered, through *conference proceedings* and *company reports*, the literature on fault-tree analysis, for the most part. In addition, they classified the literature according to system definition, fault-tree construction, qualitative evaluation, quantitative evaluation, and available computer codes for fault-tree analysis.

On the other side, in risk assessment (RA) concerning Occupational Health and Safety Systems (OHSS) and worksites, the situation is absolutely different, i.e. (i) the application of FT/ET techniques is not so developed, that means the subsequent FT/ET techniques have not been extensively incorporated in the main RA methodologies (Marhavilas et al., 2011a), and (ii) there is not any recent scientific review for FT/ET techniques concentrating on RA.

More specifically, occupational accidents are stochastic events since the moment of their occurrence cannot be predicted. However, their rate of occurrence may be reduced, albeit not to zero. Considerable effort has been invested into this objective. The potential of presently used methods approaches for evaluating and producing recommendations for reducing occupational hazards has apparently been exhausted. Hence, further improvement of the injury rates is expected only from the use of in-depth analysis methods.

Therefore, FT/ET analysis is applied to occupational safety (Hauptmanns et al., 2005). One of the essential stages for the evaluation of the reliability of a system is the construction of its structure-function, which we introduce in a model of probabilities for evaluating its reliability. Obtaining the structure-function from the system is a difficult task and, except in the case of simple systems (i.e. in systems of elementary structure), this cannot be done without special tools for the majority of complex systems. Thus, the system's modeling is obtained through standard graphs, of which FT/ET is a part, for obtaining in a systematic manner the structure function. As a result, the FT/ET is employed right from the first stages of safety analysis for the functioning of the systems.

The safety study of a system through FT/ET includes three stages: the construction of the tree, qualitative analysis and quantitative analysis. This construction should be highly exhaustive, that is, representing all the (significant) causes for the failure of the system. The construction technique can be obtained quite quickly, which greatly facilitates the collaboration of specialists of diverse domains (Limnios, 2007).

Taking into account: (i) that FT and ET techniques are very important for risk assessment, concerning occupational health-safety systems and worksites (Marhavilas et al. 2011a; 2012a,b,c), (ii) the fact that they have not been used widely enough, in the main RA methodologies, and (iii) the deficiency of any scientific review about FT/ET techniques concentrating on OHSS RA, we try in this work to determine and study, analyze and elaborate, classify and categorize the main FT/ET techniques and their characteristics by reviewing the scientific literature, in order to (i) depict the subsistent situation of FT/ET application in various occupational fields, and (ii) increase their usage in in OHSS's risk assessment.

To reinforce the second aim, we suggest an alternative risk-evaluation scheme, implemented by the combination of a FT (or ET) process with a stochastic quantified risk-evaluation model. The paper contains three sections: a) investigation, presentation and elaboration of the main FT/ET techniques, b) a literature review of thirteen representative scientific journals published by Elsevier B.V. and IEEE Inc. covering the period 2000-2012, and c) a proposed new risk-evaluation scheme using FT/ET techniques.

5.2. Main results

The main results of this work are summarized to the following points (Fig. 6):

- Our review of the scientific literature, revealed for the occupational health/safety science and risk assessment, a plenty of published technical articles with FT/ET techniques, which are associated with OHSSs and their work-sites, and concern many different fields (like engineering, computer science, transportation, chemistry, medicine, biology, etc.)
- These articles address concepts, tools, technologies, and methodologies that have been developed and practiced in such areas as planning, design, development, quality control and maintenance, in association with occupational risk assessment.

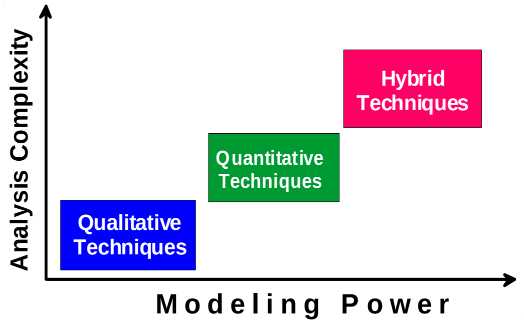


Fig. 6. The relation of modeling-power and analysis-complexity for QN/QL/HB classes

- FT/ET techniques are classified into three main categories, including qualitative, quantitative and hybrid techniques. This categorization is not unique, but it is simple and useful for RA, and has been used in the scientific literature.
- In quantitative techniques, the risk can be estimated and expressed by a mathematical equation, under the help of real accidents' data recorded in a work site, while qualitative techniques are based mainly on analytical estimation processes and safety-managers' ability; a hybrid technique mixes in a single framework both a qualitative and quantitative method.
- An alternative risk-evaluation process could be implemented by the simultaneous application and the jointly evaluation of a stochastic model and the

deterministic approach of FTs/ETs (i.e. achieving a STODET quantified risk-evaluation)

6. Conclusions and future work

6.1. General conclusions

Using the analysis described before and its main results as well, the following general conclusions can be made:

- The usage of FT/ET techniques referred to occupational safety science is not considerably expanded, and all the knowledge about FT/ET has not been fully shared among the various scientific fields, so we believe that the scientific community faces with the challenge to duplicate and transfer the commonalities from one field to another.
- In fact, the development of an integrated risk assessment scheme, which will combine a well-considered selection of widespread techniques (including FT/ET techniques), would enable companies to achieve efficient results on RA.
- If we rank the QN/QL/HB classes of FT-ET techniques, according to modeling power and analysis complexity, the result will be similar to Fig. 6. Qualitative FT/ET techniques can model the least details whereas hybrid FT/ET techniques the most. A major problem is that the analysis complexity and effort to perform it, increases as the modeling power increases.

6.2. Future work

In order to enhance FT/ET application in OHSS's risk assessment, we are planning, in a forthcoming work, the application of the alternative risk-evaluation concept in companies of various activity sectors (like transportations, car-industry, chemical-industry, wood-industry etc.) by using statistical data of occupational accidents of enormous databases covering a period of adequate years.

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