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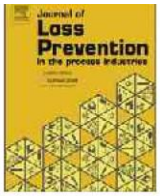

Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000-2009

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ABSTRACT

The objective of this work is to determine and study. analyze and elaborate. classify and categorize the main risk analysis and risk-assessment method s and techniques by reviewing the scientific literature. The paper consists of two parts: a) the investigation. presentation and elaboration of the main riskassessment methodologies and b) the statistical analysis. classification. and comparative study of the corresponding scientific papers published by six representative scientific journals of Elsevier B.V. covering the decade 2000-2009. The scientific literature reviewing showed that the risk analysis and assessment techniques are classified into three main categories: (a) the qualitative. (b) the quantitative. and (c) the hybrid techniques (qualitative-quantitative. semi-quantitative). The qualitative techniques are based both on analytical estimation processes. and on the safety managers-engineers ability. According to quantitative techniques. the risk can be considered as a quantity. which can be estimated and expressed by a mathematical relation. under the help of real accidents' data recorded in a work site. The hybrid techniques. present a great complexity due to their ad hoc character that prevents a wide spreading. The statistical analysis shows that the quantitative methods present the highest relative frequency (65.63%) while the qualitative a lower one (27.68%). Furthermore the hybrid methods remain constantly at a very low level (6.70%) during the entire processing period.

1. Introduction

Public interest in the field of risk analysis 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. Managers of health care, the environment, and physical infrastructure systems all incorporate risk analysis in their decision-making process. Moreover the omnipresent adaptations of risk analysis by many disciplines, along with its deployment by industry and government agencies in decision-making, have led to an unprecedented development of theory, methodology, and practical tools (Haimes, 2009).

Risk has been considered as the chance that someone or something that is valuated will be adversely affected by the hazard (Woodruff, 2005) while "hazard" is any unsafe condition or potential source of an undesirable event with potential for harm or damage (Reniers, Dullaert, Ale, & Soudan, 2005). Moreover, risk has been defined as a measure under uncertainty of the severity of a hazard (Hej & Kroger, 2002), or a measure of the probability and severity of adverse effects (Haimes, 2009). In general, "danger" should be defined as an attribute of substances or processes, which may potentially cause harm (Hej & Kroger, 2002).

A complex human-machine system is seen as being composed of humans, of machines, and of the interaction between them, which could properly be described by a system model. The role of a system model is essential in thinking about how systems can malfunction, or in other words in thinking about accidents. A fundamental distinction is whether accidents are due to specific malfunctions or "error mechanisms", or whether they are due to unfortunate coincidences. Over the years, the efforts to explain and predict accidents have involved a number of stereotypical ways of accounting for how events may take place (Hollnagel, 2004, 2006; Hollnagel, Woods, & Leveson, 2006; Qureshi, 2007).

Furthermore, 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, Aken, & Schouten, 2008) and constitutes a needful tool for the safety policy of a company. The *diversity* in risk analysis procedures is such that there are many appropriate techniques for any circumstance and the choice has become more a matter of taste (Reniers et al., 2005; Rouvroye & *van* den Bliek, 2002). We can consider the risk as a quantity, which can be measured and expressed by a mathematical relation, under the help of real accidents' data (Marhavilas & Koulouriotis, 2007, 2008; Marhavilas, Koulouriotis, & Voulgaridou, 2009).

The *objective* of this work is to determine and study, classify and categorize, analyze and *overview,* the main risk analysis and assessment (RAA) methods and techniques by reviewing the scientific literature. The paper consists of two parts: a) the presentation of the main risk-assessment methodologies and b) the statistical analysis, classification, and elaboration of the corresponding scientific papers published by Elsevier B'v. covering the last decade.

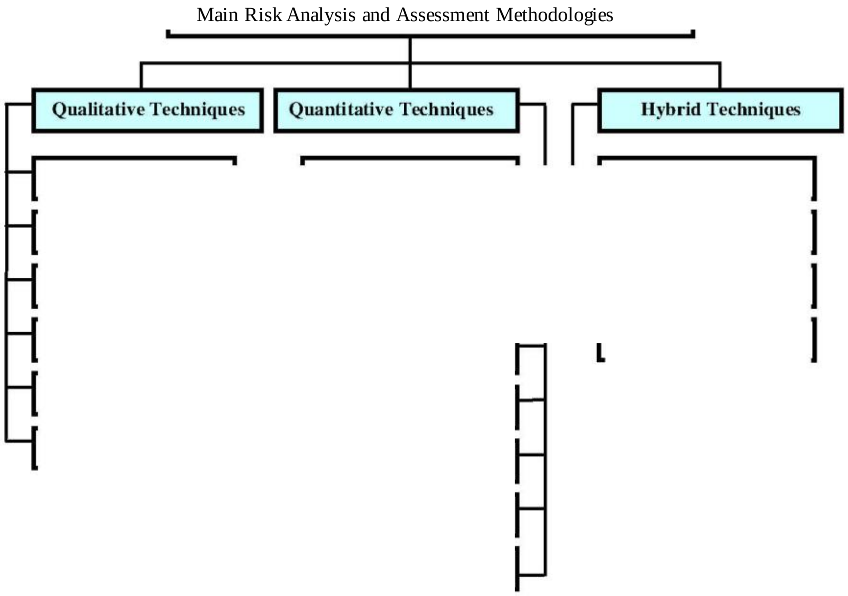
2. An overview of risk analysis and assessment techniques

The procedure of reviewing the scientific literature, revealed a plethora of published technical articles on safety, and risk analysis referred to many different fields, like engineering, medicine, chemistry, biology, agronomics, etc. These articles address concepts, tools, technologies, and methodologies that *have* been developed and practiced in such areas as planning, design, development, system integration, prototyping, and construction of physical infrastructure; in reliability, quality control, and maintenance. Furthermore, our reviewing shows that the risk analysis and assessment (RAA) techniques are classified into three main categories: (a) the qualitative, (b) the quantitative, and (c) the hybrid techniques (qualitative-quantitative, semi-quantitative). The qualitative techniques are based both on analytical estimation processes, and on the safety managers-engineers ability. According to quantitative techniques, the risk can be considered as a quantity, which can be estimated and expressed by a mathematical relation, under the help of real accidents' data recorded in a work site. The hybrid techniques, present a great complexity due to their ad hoc character that prevents a wide spreading. Fig. 1 illustrates the classification of the main risk analysis and assessment methodologies. Below, we present an *overview* of them having in mind this classification.

2.1. Qualitative techniques

a) *Checklists:* Checklist analysis is a systematic evaluation against pre-established criteria in the form of one or more checklists, which are enumeration of questions about operation, organization, maintenance and other areas of installation safety concern and represent the simplest method used for hazard identification. A brief summary of its characteristics is as follows: (i) It is a systematic approach built on the historical knowledge included in checklist questions, (ii) It is applicable to any *activity* or system, including equipment issues and human factors issues, (iii) It is generally performed by an individual trained to understand the checklist questions, or sometimes by a small group, *(iv)* It is based mostly on inter*views,* documentation *reviews,* and field inspections, *(v)*هط It generates qualitative lists of conformance and non-conformance determinations with recommendations for correcting non-conformances, *(vi)* The quality of evaluation is determined primarily by the experience of people creating the checklists and the training of the checklist users, *(vii)* It is used for highlevel or detailed analysis, including root cause analysis, *(viii)* It is used most often to guide boarding teams through inspection of critical *vessel* systems, (ix) It is also used as a supplement to or integral part of another method, especially what -if-analysis, to address specific requirements. Although checklist analysis is highly *effective* in identifying various system hazards, this technique has two key limitations: (a) The structure of checklist analysis relies exclusively on the knowledge built into the checklists to identify potential problems. If the checklist does not address a key issue, the analysis is likely to overlook potentially important weaknesses. (b) Traditionally *provides* only qualitative information. Most checklist *reviews* produce only qualitative results, with no quantitative estimates of riskrelated characteristics. This simplistic approach offers great value for minimal investment, but it can answer more complicated risk-related questions only if some degree of quantification is added, possibly with a relative ranking/risk

c)



indexing approach (Arvanitogeorgos, 1999; Ayyub, 2003; Harms-Ringdahl, 2001; Marhavilas et al., 2009; Reniers et al., 2005; http://www.oshatrain.org).

d) *What-if-analysis:* It is an approach that (1) uses broad, loosely structured questioning to postulate potential upsets that may result in accidents or system performance problems and (2) determines what things can go wrong and judges the consequences of those situations occurring (Ayyub, 2003; Doerr, 1991; Reniers et al., 2005). The main characteristics of the technique are briefly summarized as follows:
   - It is a systematic, but loosely structured, assessment, relying on a team of experts to generate a comprehensive *review* and to ensure that appropriate safeguards are in place.
   - Typically is performed by one or more teams with *diverse* backgrounds and experience that participate in group *review* meetings of documentation and field inspections.
   - It is applicable to any *activity* or system.
   - It is used as a high-level or detailed risk-assessment technique.
   - It generates qualitative descriptions of potential problems, in the form of questions and responses, as well as lists of recommendations for preventing problems.
   - The quality of the evaluation depends on the quality of the documentation, the training of the *review* team leader, and the experience of the *review* teams.
   - It is generally applicable for almost *every* type of risk-assessment application, especially those dominated by relatively simple failure scenarios.
   - Occasionally it is used alone, but most often is used to supplement other, more structured techniques (especially checklist analysis).

The procedure for performing a what-if-analysis consists of the following *seven* steps:

- We specify and clearly define the boundaries for which risk-related information is needed.
- We specify the problems of interest that the analysis will address (safety problems, environmental issues, economic impacts, etc.).
- We subdivide the subject into its major elements (e.g. locations on the waterway, tasks, or subsystems), so that the analysis will begin at this level.
- We generate "what-if' questions for each element of the *activity* or system.
- We respond to each of the "what-if' questions and develop recommendations for improvements *wherever* the risk of potential problems seems uncomfortable or unnecessary.
- We further subdivide the elements of the *activity* or system, if it is necessary or more detailed analysis is desired. The section of some elements into successively finer levels of resolution until further subdivision will (1) provide no more valuable information or (2) exceed the organization's control or influence to make improvements. Generally, the goal is to minimize the level of resolution necessary for a risk assessment.
- We use the results in decision-making. So we evaluate recommendations from the analysis and implement those that will bring more benefits than they will cost in the life cycle of the *activity* or system.

c) *Safety audits:* They are procedures by which operational safety programs of an installation, a process or a plant are inspected. They identify equipment conditions or operating procedures that could lead to a casualty or result in property damage or environmental impacts (Ayyub, 2003). An auditor or an audit team *reviews* critical features to *verify* the implementation of appropriate design criteria, operating conditions and procedures, safety measures and related risk-management programs. The result of an audit is a report that *provides* corporate management with an *overview* of the level of performance for various safety aspects of operations. Reporting results should make reasonable recommendations and suggestions about safety procedure improvements and safety awareness of operating personnel (Harms-Ringdahl, 2001; Reniers et al., 2005).

d) *Task Analysis (TA):* This process analyzes the way that people perform the tasks in their work environment and how these tasks are refined into subtasks and describes how the operators interact both with the system itself and with other personnel in that system. It can be used to create a detailed picture of human involvement using all the information necessary for an analysis in an adequate degree of details (Brauchler & Landau, 1998; *Doytchev* & Szwillus, 2008; Kirwan, 1994; Kontogiannis, 2003; Landau, Rohmert, & Brauchler, 1998). Task analysis *involves* the study of *activities* and communications undertaken by operators and their teams in order to *achieve* a system goal. The result of a task analysis is a Task Model. The task analysis process usually *involves* three phases: (i) collection of data about human interventions and system demands, (ii) representation of those data in a comprehensible format or graph, and (iii) comparison between system demands and operator capabilities. The primary *objective* of task analysis is to ensure compatibility between system demands and operator capabilities, and if necessary, to alter those demands so that the task is adapted to the person. A widely used form of task analysis is the hierarchical task analysis (HTA). Through its hierarchical approach it *provides* a well-structured *overview* of the work processes *even* in realistically sized examples. HTA is an easy to use method of gathering and organizing information about human *activities* and human interaction, and enables the analyst to find safety-critical tasks. It is time-consuming in case of complex tasks and requires the cooperation of experts from the application domain, knowledgeable about the task operation conditions. Other analysis techniques are the Tabular Task Analysis, Timeline Analysis, Operator Action Event Trees, the GOMS-methods (Goals, Operators, Methods, and Selection Rules), Critical Action and Decision Evaluation Technique etc (Brauchler & Landau, 1998; Landau et al., 1998).

e) *The Sequentially Timed Event Plotting (STEP) technique:* It *provides* a valuable *overview* of the timing and sequence of events/actions that contributed to the accident, or in other words, a reconstruction of the harm process by plotting the sequence of *events* that contributed to the accident. The main concepts in STEP are the initiation of the accident through an *event* or change that disrupted the technical system, the agents which intervene to control the system and the elementary *"event* building blocks". The analysts construct an STEP worksheet which charts the evolution of *events* and system interventions (on the horizontal axis) performed by the agents (on the vertical axis). Subsequently, they identify the main *events/* actions that contributed to the accident and construct their *"event* building blocks" which contain the following information: a) the time at which the *event* started, b) the duration of the *event,* c) the agent which caused the *event,* d) the description of the *event,* and e) the name of the source which offered this information. In the second stage, the *events* are interconnected with arrows. All *events* should *have* incoming and outgoing arrows which show "precede" and "follow" relationships between *events.* Converging arrows show dependencies between *events* while divergent arrows show the impact on following *events* (Hendrick & Benner, 1987; Kontogiannis, Leopoulos, & Marmaras, 2000).

f) *The HAZOP method (Hazard and Operability study):* It is a formalized methodology to identify and document hazards through imaginative thinking. It *involves* a *very* systematic examination of design documents that describe the installation or the facility under investigation. The study is performed by a multidisciplinary team, analytically examining design intent *deviations.* The HAZOP analysis technique uses a systematic process to (1) identify possible *deviations* from normal operations and (2) ensure that appropriate safeguards are in place to help prevent accidents. The basic principle of HAZOP study is that hazards arise in a plant due to *deviations* from normal *behavior.* In HAZOP study, process piping and instrument diagrams (PIDs) are examined systematically by a group of experts (HAZOP team), and the abnormal causes and *adverse* consequences for all possible *deviations* from normal operation that could arise are found for *every* section of the plant. Thus, the potential problems in the process plant are identified. The HAZOP team is a multidisciplinary team of experts who *have extensive* knowledge on design, operation, and maintenance of the process plants. Generally, a team of six members consisting of team leader, process engineer, operation representative, safety representative, control system engineer, and maintenance engineer is recommended for the study. The HAZOP team members try to imagine ways in which hazards and operating problems might arise in a process plant. To *cover* all the possible malfunctions in the plant, the HAZOP study team members use a set of 'guide words' for generating the process variable *devi*ations to be considered in the HAZOP study. The sets of guide words that are often used are NONE, MORE OF, LESS OF, PART OF, and MORE THAN. When these guide words are applied to the process variables in each line or unit of the plant, we get the corresponding process variable deviation to be considered in the HAZOP study. A list of guide words with their meaning and the parameters where they can be applied is presented in Table 1. The guide words and process variables should be combined in such a way that they lead to meaningful process variable *devi*ations. Hence, all guide words cannot be applied to all process variables. For example, when the process variable under consideration is temperature, only the guide words MORE OF and LESS OF lead to meaningful process variable *deviations.* The sequence of typical HAZOP study is shown in Fig. 2. The proper planning and management of HAZOP study is one of the crucial factors for better effectiveness and good reliability of the results. The HAZOP study can be planned and managed properly only when duration of each *activity* and for complete study is known (Ayyub, 2003: Baysari, Mclntosh, & Wilson, 2008: HarmsRingdahl, 2001: Hong, Lee, Shin, Nam, & Kong, 2009: Khan & Abbasi, 1997: Labovsky, Svandova, Markos, & [elernensky, 2007: Reniers et al., 2005: Yang & Yang, 2005). The main characteristics of the technique are briefly summarized as follows:

- It is a systematic, highly structured assessment relying on HAZOP guide words to generate a comprehensive *review* and ensure that appropriate safeguards against accidents are in place
- It is typically performed by a multidisciplinary team
- It is applicable to any system or procedure
- It is used most as a system-level risk-assessment technique
- It generates primarily qualitative results, although some basic quantification is possible

Table 1
The list of guide words and their meaning (Khan & Abbasi. 1997).

Guide words	Meaning
No/None	Complete negation to design intention
More	**Quantitative increase**
Less	Quantitative decrease
Part of	Only part of intention is fulfilled
As well as	In addition to design intention. something else occurs
Reverse	Logical opposition of design intention occurs
Other than	Complete substitution

3. Quantitative techniques

g) *The proportional risk-assessment(PRAT) technique:* This technique (Ayyub, 2003: Fine & Kinney, 1971: Marhavilas & Koulouriotis, 2007, 2008) uses a proportional formula for calculating the quantified risk due to hazard. The risk is calculated considering the potential consequences of an accident, the exposure factor and the probability factor. More specifically a quantitative calculation of the risk, can be given with the following proportional relation (Marhavilas & Koulouriotis, 2008):

$$R = P-5-F$$

where: *R:* the Risk: *P:* the Probability Factor: S: the *Severity* of Harm Factor: *F:* the Frequency (or the Exposure) Factor.

The *above* relation *provides* a logical system for safety management to set priorities for attention to hazardous situations. The *validity* of these priorities or these decisions is *obv*iously a function of the *validity* of the estimates of the parameters *P,* Sand *F,* and these estimates, apparently *very* simple, require the collection of information, the *visit* of the workplaces and the discussion with the workers about their *activities* (Reniers et al., 2005). The participation of the workers is thus essential as they are the only persons to know exactly how the work is actually performed. Each factor in the previous equation, takes values in the scale of 1-10 (Marhavilas & Koulouriotis, 2008: their tables 1, 2, 3), so that the quantity R can be expressed in the scale of 1-1000. We can use Table 2 to associate the gradation of the risk value R with the urgency level of required actions.

h) *The decision matrix risk-assessment (DMRA) technique:* It is a systematic approach for estimating risks, which is consisting of measuring and categorizing risks on an informed judgment basis as to both probability and consequence and as to relative importance (Ayyub, 2003: Henselwood & Phillips, 2006: Marhavilas & Koulouriotis, 2008: Haimes, 2009: Marhavilas, Kou lou riotis, & Mitrakas, submitted for publication: Reniers et al., 2005: Woodruff, 2005). The combination of a consequence/severity and likelihood range, *gives* us an estimate of risk (or a risk ranking). More specifically, the product of *severity (S)* and likelihood *(P) provides* a measure of risk *(R)* which is expressed by the relation:

$$R = S\cdot p$$

Once the hazards *have* been identified, the question of assigning *severity* and *probability* ratings must be addressed. Eventually, the technique is consummated by the construction of the risk matrix (in Table 3-a) and the decision-making table (in Table 3-b). The new developed DMRA technique has two key advantages: a) It differentiates relative risks to facilitate decision-making. b) It *improves* the consistency and basis of decision. *Moreover,* it is a quantitative (due to risk measuring) and also a graphical method which can create liability issues and help the risk managers to prioritize and manage key risks (Marhavilas & Koulouriotis, 2008).

i) *Quantitative* risk *measures of societal* risk: The societal risk associated with operation of given complex technical system e)

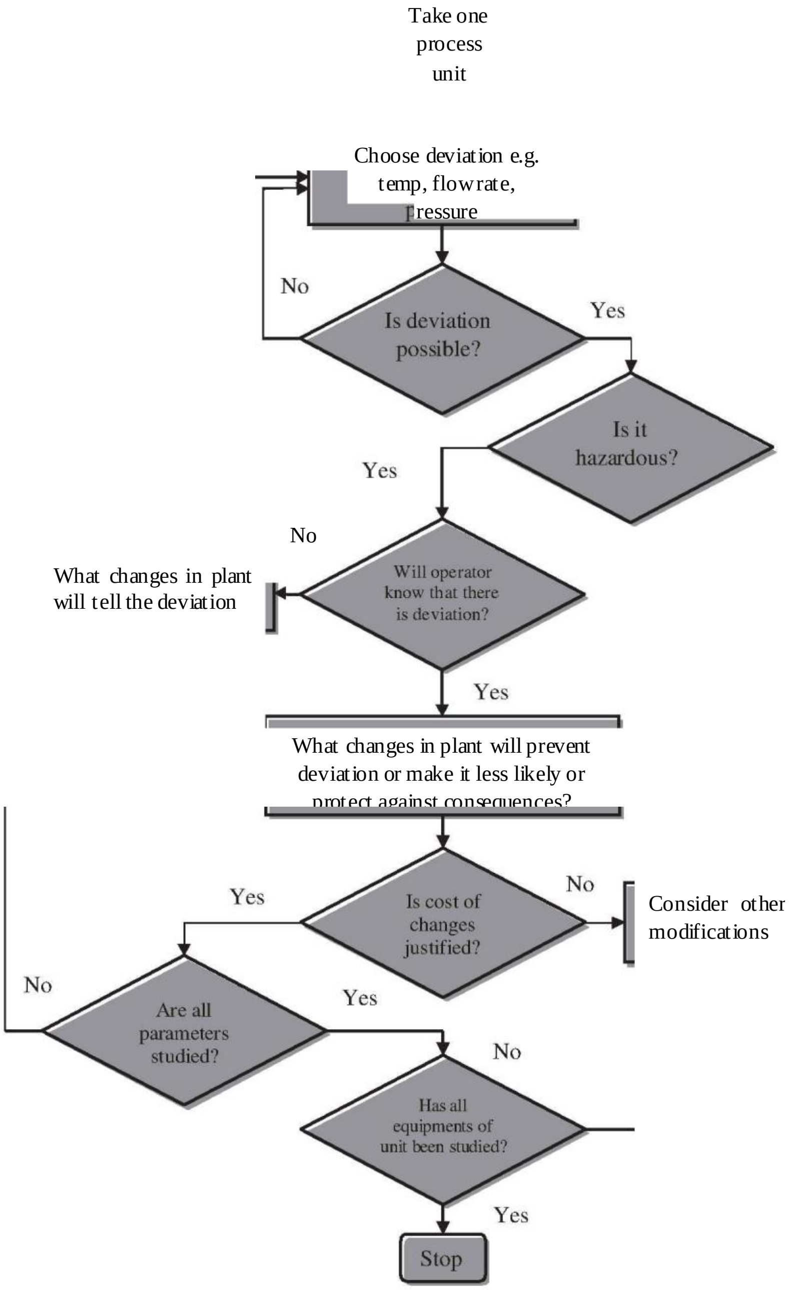


Fig. 2. Procedure of HAZOP study (Khan & Abbasi. 1997).

is evaluated (Kosmowski, 2002,2006) on the basis of a set of the triples:

$$R = \{\langle S_k, F_k, N_k \rangle\}$$

Table 2
Gradation of the risk value in association with the urgency level of required actions (Marhavilas & Koulouriotis, *2008).*

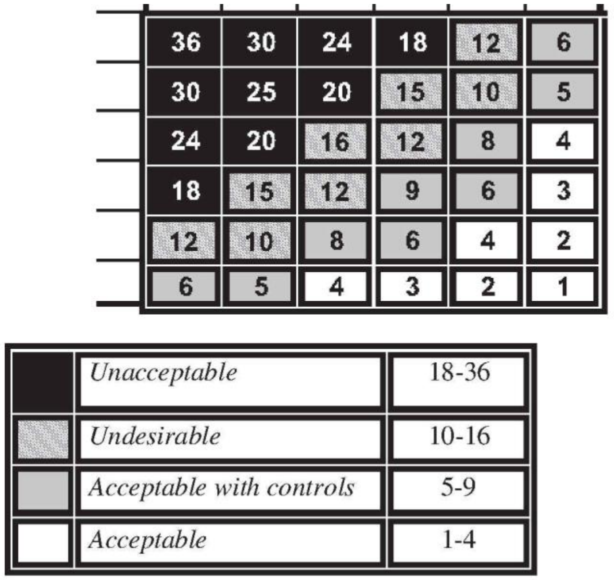
Risk Value *(R)*	Urgency level of required actions
700-1000	Immediate action
500-700	Required Action earlier than 1 day
300-500	Required Action earlier than 1 month
200-300	Required Action earlier than 1 year
<200	Immediate action is not necessary but it is required the event surveillance

where S_k is k-th accident scenario (usually representing an accident category) defined in the determined modeling process, h is the frequency of this scenario (evaluated as probability per time unit, usually one year), and N_k denotes the consequences of k-th scenario, i.e. potential losses (the number of injuries and fatalities) or financial losses. On the basis ofthe *above* relation the F-N *curve* (CCOF: complementary cumulative distribution function) is to be drawn. Fig. 3 illustrates an example of such curve in double logarithmic co-ordinates to be compared with criteria lines: 0 (lower line) and G (upper line). The social risk for a given technical system is accepted when F-N *curve* is below the criterion line 0 (a defined function with regard to societal preferences) for all N. If the F-N *curve* is situated between criteria lines 0 and G, then the ALARP (as low as reasonably practicable) principle should be applied to indicate the ways to reduce risk. Iffor any N the F-N *curve* is *above*

Table J
The decision matrix risk-assessment technique: (a) The risk matrix. (b) The decisionmaking table (Marhavilas & Koulouriotis, 2008).

Hazard probability ratings (P) f)

1



36	30	24	18	12	6
30	25	20	15	10	5
24	20	16	12	8	4
18	15	12	9	6	3
12	10	8	6	4	2
6	5	4	3	2	1

■	*Unacceptable*	18-36
▨	*Undesirable*	10-16
▒	*Acceptable with controls*	5-9
□	*Acceptable*	1-4

the upper criteria line G, the risk is intolerable and the system must re-designed (e.g, functionally and structurally modified) to reduce risk as required. A measure of societal risk can be the *average* rate of death evaluated according to the formula:

$$R = \sum_k f_k N_k$$

where: f_k is the frequency of k-th accident scenario [a 1]: and N_k is the number of fatalities resulting from k-th scenario.

j) *The QRA (Quantitative Risk-Assessment) tool*. The QRA tool has been developed for the external safety of industrial plants with a dust explosion hazard. This tool *provides* a consistent basis to analyze the individual and societal risk, it consists of a combination of sub models, and an *overview* is presented in Fig. 4. First the scenarios and their frequencies are defined. The individual risk is defined as the probability (frequency) of lethality for an unprotected person in the vicinity of a hazardous location. The societal risk takes the actual *envi*ronment into account. For example, an industrial plant is *divided* into two groups of modules, defined by their size, shape, and constructional properties. Then the relevant explosion scenarios are determined, together with their frequency of occurrence. These include scenarios in which one module participates, as well as domino scenarios. The frequency is partly based on casuistry. The QRA tool offers the possibility to define four types of objects: unprotected people, cars, domestic houses and office buildings, each with their own protection level against the different explosion effects. The development of the dust explosion and the process of venting and the launch of module parts are predicted for each scenario.

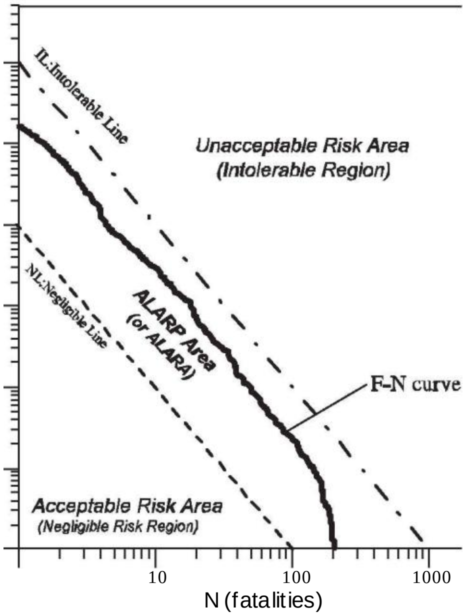


Fig. J. Examples of the F-N curve and criteria functions for societal risk.

As a result the individual risk is independent of the contributions from window failure due to blast effects. The flame jet is only relevant if the height of its origin is situated less than 5 m *above* the unprotected person. Debris throwing and bulk outflow are always relevant for the individual risk. The results are input for explosion effect calculations, followed by a prediction of the consequences for people. The consequences and the scenario frequency are then combined to the individual and societal risk, which can be compared to the relevant regulations (Van der Voort et al., 2007).

k) *Quantitative assessment of domino scenarios (QADS)*. The domino effect is assumed as an accident in which a primary *event* propagates to nearby equipment, triggering one or more secondary *events* resulting in overall consequences more *severe* than those of the primary *event*. Furthermore, an accident is usually considered as a "domino *event"* only if its overall *severity* is higher or at least comparable to that of the primary accidental scenario, while domino accidental scenarios result from the escalation of a primary accidental *event*. The escalation is usually caused by the damage of at least one equipment item, due to the physical effects of the primary *event*. Four elements may be considered to characterize a domino event: (i) A primary accidental scenario, which triggers the domino effect. (ii) A propagation effect following the primary *event*, due to the effect of escalation *vectors* caused by the primary *event* on secondary targets. (iii) One or more secondary accidental scenarios, involving the same or different plant units, causing the propagation of the primary *event*. *(iv)* An escalation of the consequences ofthe primary *event*, due to the effect of the secondary scenarios. The quantitative assessment of domino accidents requires the identification, the frequency evaluation and the consequence assessment of all the credible domino scenarios, including all the different combinations of secondary *events* that may be originated by each primary *event*. The identification of the credible domino scenarios should be based on escalation criteria addressing the possible damage of equipment due to the physical effects generated in the primary scenarios. In the approach to the frequency assessment of domino scenarios, the damage probability of g)

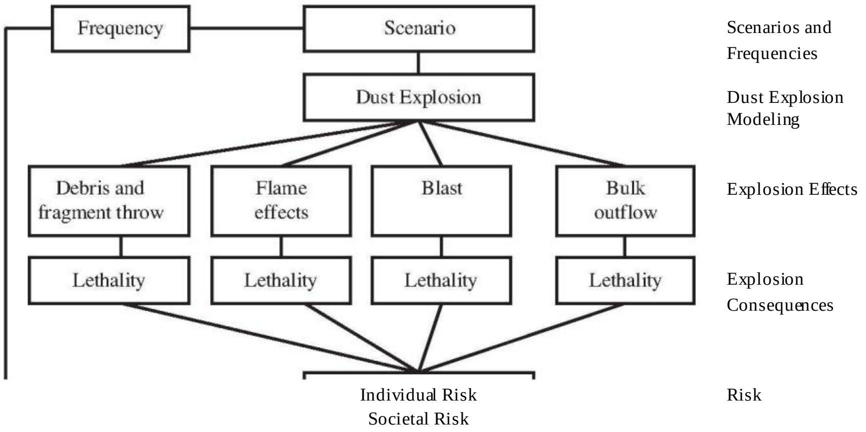


Fig. 4. An overview ofthe QRA tool is presented (van der Voort et al., *2007)*.

a unit due to a given primary event may be considered independent on the possible contemporary damage of other units. Thus, if *n* possible target units are present, a single primary event may cause a maximum of *n* different secondary events, each having an overall probability to take place equal to $P_{d,i'}$ However, each secondary event may take place contemporary to other secondary events. A single domino scenario may thus be defined as an event involving the contemporary damage of k units resulting in k secondary events, with k comprised between 1 and *n*. If each of the *n* secondary units is labeled by a numerical indicator comprised between 1 and *n*, a domino scenario may thus be indicated as a vector J~ = [r1' ... , n] whose elements are the indexes of the secondary units involved in the event. Since k < *n*, in general more than one domino scenario may involve k units. Therefore, the subscript m of *vector]* indicates that the single domino scenario is the mth combination of k secondary events. The number of domino scenarios involving k different secondary events may be calculated by the following expression:

$$S_k = \frac{n!}{(n-k)!k!}$$

The total number of different domino scenarios that may be generated by the primary event, *Sd*, may be calculated as follows:

$$S_d = \sum_{k=l}^{n} S_k = 2^n - 1$$

The probability of a single domino scenario involving the contemporary damage of k units resulting in k secondary events, identified by the vector J~, may be evaluated as follows:

$$p^{(k,m)} = \prod_{1=1}^{n} [1 - P_{d,i} + 0(i,J\sim)(2 \cdot P_{d,i} - 1)]$$

where the function *(j(i,J~)* equals 1 if the ith event belongs to the mth combination, 0 if not. The last equation is the algebraic expression obtained from the union of the probabilities of the k events belonging to the mth combination, calculated considering as independent the secondary events. The expected frequency of the mth domino scenario involving k contemporary events, *Ir:* may thus be calculated as

$$f_d^{(k,m)} = JJ \cdot P_d^{(k,m)}$$

where *fp* is the expected frequency of the primary event that triggers the escalation (Cozzani, Antonioni, & Spadoni, 2006).

I) *The (REA (Clinical* Risk *and Error Analysis) method.* CREA is a methodological approach for quantitative risk analysis, consisting of five steps (see Fig. 5) according to the work of Trucco and Cavallin (2006) and based on techniques which are well-established in industry, and have been adapted for the medical domain. CREA allows the analyst to join data which have been collected through direct observation of processes or interviews to clinical operators to statistical data reported in literature. The risk assessment for CREA method is condensed to the following: For each activity *k*; the probability $P(EM_{ik})$ of occurrence of the EMi-th error mode (EM) and the severity index $D(EM_{ik})$ of the associated harm have to be calculated on the basis of available data and the experts' judgment; their product represents the Risk Index $R(EM_{ik})$ for each EM, as shown in the classical equation:

$$R(EM_{ik}) = P(EM_{ik}) \times D(EM_{ik})$$

For each EM, only its occurrence probability related to the whole process in known, but in fact the same EM could happen in several tasks in one or more process activities. Thus, the experts estimate the likelihood to have a particular EM within the various activities ofthe process *(Yik)*, making it possible to calculate the probability of

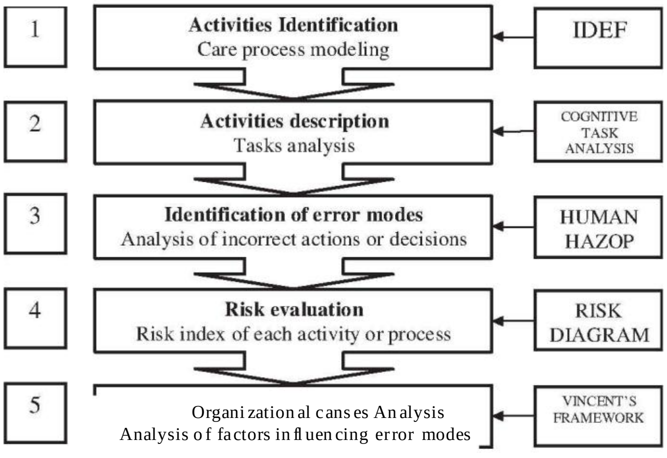


Fig. 5. Fundamental steps and tools of CREA (Trucco & Cavallin, *2006)*.

the error mode **i** which occurred in the *activity* k by multiplying the probability of occurrence of EM **i** for the estimated likelihood, as follows:

$$P(EM_{ik}) = Y_{ik} \times [P(EM_i)]_{AVERAGE}$$

As far as the *severity* index $D(EM_{ik})$ is concerned, it is calculated as the linear combination of the conditional probabilities X_{ijk} of the *severity* class j, weighted with a coefficient M_j, that grows with the *severity* of the harm.

$$D(EM_{ik}) = \sum_{j=A}^{E} (M_j \cdot X_{ijk})$$

The values of coefficient M_j could be adjusted on the basis of the risk perception of the team which is conducting the analysis. The estimates of probabilities of occurrence of EMs, the likelihood of *severity* classes and the Risk Index of each *activity* can be presented in Tables. The Risk Index of each *activity* k *(ACTk)* is given by the sum of the risk indexes of each EM detected in the same *activity*, as follows:

$$R(\mathrm{ACT}_k) = \sum R(\mathrm{EM}_{ik})$$

Each error mode of *every activity* is mapped in risk diagrams, in that three iso-risk *curves* allow four risk control areas to be identified: emergency ($R > 0.05$), urgency ($0.01 < R < 0.05$), planning ($0.0050 < R < 0.01$) and monitoring ($R < 0.005$). Risk mapping can also be done on several aggregation levels. For example, in the drug therapy management process, the error modes are presented in Table 4, while the coefficients M_j, in Table 5, according to the work of Trucco and Cavallin (2006).

m) *The PEA (Predictive, Epistemic Approach) method.* This procedure is based on the so-called predictive, epistemic approach to risk assessment. It *provides* formal means for combining hard data and subjective information and allows forecasting the abnormal (accidental) actions (AA) in the form of mathematical models, which quantify epistemic (state-of-knowledge) uncertainties in characteristics of the actions. The epistemic models allow a rough, knowledge-based estimation of probabilities of damage from abnormal actions. These models are considered to be the first step toward preventing (reducing) losses associated with damage from abnormal actions. The damage can be assessed by either deterministic or probabilistic structural analysis. The prevailing practice of modeling abnormal (accidental) actions is representing them by fixed values (*conservative* percentiles of action characteristics called the characteristic and design values) which are usually specified in structural design codes. Outside the regulatory area of the codes, attempts were undertaken to specify AAs in terms of probability distributions (p.d.'s) assigned in the framework of a classical statistical approach (CSA) which dominates the structural reliability analysis. The application of the fixed values and p.d. specified in line with CSA to a mechanical damage assessment is vulnerable to criticism. A fundamentally different approach to forecasting AAs consists in a numerical simulation of physical phenomena involving AAs. So the forecasting of abnormal actions in the framework of the predictive, epistemic approach is *achieved* by a stochastic simulation of accident courses (scenarios) involving AA(s) or, in short, a stochastic accident simulation (SAS). This simulation will *serve* as a means of propagating epistemic uncertainty. The AAs forecasting should be considered a part of a broader problem of a quantitative risk analysis (QRA) and carried out using knowledge-based methods of QRA. They allow using a wider spectrum of *diverse* knowledge related to AAs than the methods provided by CSA. The problem considered is how to answer the question "what is the frequency (annual probability, probability per year of operation, etc.) of exceeding a given magnitude m of an abnormal action" or, in brief, "what is the value of the product $Fr(AA) \times P(m|AA)$", where $Fr(AA)$ is the frequency of imposition of the AA (random *event* AA) and $P(m|AA)$ is the conditional probability of exceeding m given AA. An answer to this question depends on an interpretation of $F(AA)$ and $P(m|AA)$. Specifying the frequency $Fr(AA)$ and p.d. $P(m|AA)$ solely on the basis ofthe data gained from occurrences of AAs will more often than not be impossible. Data on AAs are usually sparse or irrelevant to a particular situation of exposure of a structure to AAs (exposure situation) or, what is not uncommon, unavailable at all. This situation may be alleviated by mixing hard data (relevant experience data) with engineering judgment (subjective information expressed as expert opinions, judgments of analysts and analyst groups, etc.). A methodological framework for such a mixing is provided by a predictive, epistemic approach to QRA (PEA). This approach uses the concept of probability as the "engineer's measure of uncertainty" or "degree of belief'. In *view* of forecasting AAs, PEA may be defined as a way of interpreting and specifying the frequency $Fr(AA)$ and p.d. $P(m|AA)$. PEA is focused on a future occurrence of observable *events*, like AA and "exceeding m given AA", and not on true, although unobservable values of $Fr(AA)$ and $P(m|AA)$. In PEA, there exists only one type of uncertainty, namely, an epistemic uncertainty in (the engineer's degree of

Table 4
Error modes in the drug therapy management process (Trucco & Cavallin, 2006).

Error mode (EM) Code	Description
EM1	Wrong patient
EM2	Inadequate monitoring after administration
EM3	Wrong dose (overdose or underdose)
EM4	Wrong dosage form
EM5	Wrong administration frequency
EM6	Wrong drug preparation
EM7	Order misunderstanding
EM8	Unauthorized drug
EM9	Different drug preparation or administration
EM10	Omitted dose
EM11	Wrong time
EM12	Extra dose
EM13	Deteriorated drug error
EM14	Drug-drug interaction or drug allergies
EM15	Wrong route
EM16	Wrong administration technique
EM17	Wrong rate

Table 5
The severity class and related weights (Trucco & Cavallin, 2006).

Class of severity	Description	Weight M_j
A-no consequences	No harm or increase of patient **monitoring**	$M_A = 0.1$
B-minor harm	Temporary harm to patient. whit additional therapeutic intervention or prolonged hospitalization inside one month	$ME = 0.3$
C-medium harm	Temporary harm to patient (temporary disability) or prolonged hospitalization over one month	$M_c = 0.5$
D-serious harm	Permanently harm to patent (permanently disability). life-threatening harm or near death event	$M_D = 0.7$
E-death	Death of patient	$M_E = 0.9$

belief concerning) a future occurrence of AA and "exceeding m given AA" (Vaidogas, 2006). In line with PEA, the final result of forecasting an AA (Abnormal Action) can be expressed by an action model defined as

$$Fr(x) = Fr(AA)(l - Fx(xlIT_{x}))$$

where *x* is the *vector* of AA characteristics, X is the random *vector* with a distribution function (d.f.) $F_{x}(xl1f_{x})$ which models an epistemic uncertainty in *x, Fr(AA)* is the frequency expressing the epistemic uncertainty related to a future occurrence of AA. The d.f $F_{x}(xl1f_{x})$ expresses epistemic uncertainty in the *event* X <= *x* ("is less component wise"). Thus, the value *Fr(x)* quantifies epistemic uncertainty in the frequency of exceeding at least one component of *x. Fr(x)* by its form is a generalization of a hazard *curve.* If the direct data on components of X is sparse or absent, both *Fr(AA)* and $Fx(xl1f_{x})$ can in some cases be assigned indirectly by a SAS which can generate samples of AA characteristics and yield an estimate of *Fr(AA).* The d.f $F_{x}(xl1f_{x})$ can be fitted to the generated samples. Such a SAS can be used for a propagation of epistemic uncertainties and relate stochastic models of the physical phenomena preceding AA to epistemic uncertainties in characteristics of AA (Vaidogas, 2006).

n) *The weighted* risk *analysis (WRA):* In order to balance safety measures with aspects, such as environmental, quality, and economical aspects, a weighted risk analysis methodology is used. The weighted risk analysis is a tool comparing different risks, such as investments, economical losses and the loss of human *lives,* in one-dimension (e.g. money), since both investments and risks could be expressed solely in money (Suddle, 2009). When a risk analysis is performed, not only technical aspects but also economical, environmental, comfort related, political, psychological and societal acceptance are aspects that play an important role. In some cases or scenarios with great consequences, weighing factors for all risk dimensions are used in order to make them comparable to each other and to relate them to the measures that must be taken for possible risk reduction. It is therefore, recommendable to compare and to integrate different decision-making elements, such as political, social, psychological, environmental, and quality risks or benefits, in a "one-dimensional" weighted risk R_{w}, e.g. in terms of money, as following (Suddle, 2009: Suddle & Waarts, 2003):

$$R_{w} = LajLRij \quad \underset{j=l}{} \; \underset{i=l}{}$$

in which R_{w} is the weighted risk (cost unit per year): (lj is the (monetary) value per considered loss (cost unit). It has to be noted that the weighted risk R_{w} may consist of cost unities, which can be financial, but not necessarily. The weighted risk R_{w} can easily be extended into multiple decision-making elements, depending on the origin of the decision-maker. The previous formula can be specified into particular risk components:

$$R_{w} = al \, L_{i=1} \, \mathrm{Rhuman,i} + a2 \, L_{j=l} \, \mathrm{ReconomicJ} + a3 \, L_{k=l} \, \mathrm{Renvironment,k}$$

$$+ \, a4 \, L_{1=1} \, \mathrm{Rquality,l} + \ldots$$

in which 111 is the (monetary) value per fatality or injury (cost unit): (12 is the (monetary) value per environmental risk (cost unit): (13 is the (monetary) value per economical risk (cost unit) (mostly (13 = 1), (14 is the (monetary) value per quality risk (cost unit), and so on. If these non-safety-related aspects are quantified in the proposed weighted risk (analysis), and thus in one (monetary) dimension, safety measures can be balanced and optimized in respect of decision-making, shown as follows:

$$\text{M} \quad (\quad C() \quad \text{"""} \; R_{wj}$$

$$\underset{i=l}{\text{Hl l Ifll Sf :}} \, (1 + r)J \qquad \text{tot} = 0 \; y + \sim \text{---}.$$

in which (tot is the total costs (money): *(o(y)* is the investment in a safety measure (money): y is the decision parameter: *j* is the number of the year and r is the real rate of interest. The *above* equation *provides* an overall mathematical-economic decision problem for balancing safety measures for all kinds of aspects by expressing both positive/negative risks and benefits of a project. The components of the weighted risk can only be computed quantitatively, if the monetary value per considered risk (lj is determined. Some of these values can be found in literature. It should be noted that these values are depending on local circumstances, which *themselves* depending on cultural and political aspects of the local policy.

3.1. Hybrid techniques

0) *Human Error Analysis Techniques (HEAT)* or *Human Factor Event Analysis (HFEA):* Human errors *have* become widely recognized as a major contributory cause of serious accidents/incidents in a wide range of industries. The systematic consideration of human error in the design, operation, and maintenance of highly complex systems can lead to *improved* safety and more efficient operation (Attwood, Khan, & Veitch, 2006a,b:

Baysari et ai, 2008: Hollywell, 1996: Kontogiannis, 1999: Kontogiannis & Malakis, 2009). Work place design, safety culture, in addition to training, competence, task complexity, stress, etc. constitute a group of factors that influence operators' *behavior.* These factors are called Performance Shaping Factors (PSF) (Kim &jung, 2003), concern all work-related areas that exert certain influence on the operators performance, they are used in HEAT techniques (Kirwan, 1994), and "can be cause of some failures in other complex industrial systems" (Bellamy, Geyer, & Wilkinson, 2008: Cilingir & Mackhieh, 1998). *Doytchev* and Szwillus (2008), and Kirwan (1994) *have* listed different human error analysis techniques, including ATHEANA (A Technique for Human Error Analysis), CREAM (Cognitive Reliability and Error Analysis Method), HEART (Human Error Analysis and Reduction Technique), HEIST (Human Error Identification in System Tools), THERP (Technique for Human Error Rate Prediction) and others. The goal of these techniques is to determine the reasons for human error occurrence, the factors that influence human performance, and how likely the errors are to occur (Zarboutis & Marmaras, 2007). *Moreover,* a commonly utilized tool for investigating human contributions to accidents under a widespread evaluation scheme is the HFACS (Human Factors Analysis and Classification System) method which quantitatively characterizes the role of human errors (Celik & Cebi, 2009). Li, Shu-dong, and Xiang-rui (2003) *have* studied some mathematical tools for incorporating human factors (HF) in system reliability analyses. The overall method, called "HF *event* analysis" (HFEA) relied on two analytic methods (i) "technique for human error rate prediction" (THERP), which provided a human *event* tree model, and (ii) "human cognitive reliability" (HCR), which determined human errors during the diagnosis stage of an accident. Balkey and Phillips (1993) *have* proposed a practical approach to quantifying human error within the accident process. A mathematical relationship was proposed to model the likelihood *(P)* of occurrence of a human error *event,* as follows:

$$P(\text{human\_error}) \quad 1 - \left[\left(\frac{1.}{\#\text{options}}\right) \times \text{feedback} \times \text{adjuster} \times \text{redundancy}\right]$$

The variables in the equation are expected to affect the likelihood *(P)* of human error according to the following comments:

- *#Options:* as the choices faced by an individual increase, so does the opportunity for, and likelihood of, error.
- *Feedback:* visual feedback (e.g. the ability to actually see an action performed) will reduce the likelihood of human error.
- *Adjusters (external or internal):* these *cover* the environment experienced by the operator - including temperature, humidity, clothing, mental and physical capabilities, and training.
- *Redundancy:* this is defined as a real-time repeat of the *investigation* of whether a human error is occurring.

p) *Fault-tree analysis (FTA):* It is a deductive technique focusing on one particular accident *event* and providing a method for determining causes of that *event.* In other words FfA is an analysis technique that visually models how logical relationships between equipment failures, human errors, and external *events* can combine to cause specific accidents. Fault trees 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 that may intensify technical failures. The gates of the fault trees can be used to represent several ways in which machine and human failures combine 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* (Ayyub, 2003: Haimes, 2009: Harms-Ringdahl, 2001: Hong et al., 2009: Kontogiannis et al., 2000: Reniers et al., 2005: Vesely, Goldberg, Roberts, & Haasl, 1981: Yuhua & Datao, 2005). Below it is presented a summary of the graphics most commonly used to construct a fault tree.

  - *Top event and intermediate events:* The rectangle is used to represent the TOP *event* and any intermediate fault *events* in a fault tree. The TOP *event* is the accident that is being analyzed. Intermediate *events* are system states or occurrences that somehow contribute to the accident.
  - *Basic events:* The circle is used to represent basic *events* in a fault tree. It is the lowest level of resolution in the fault tree.
  - *Undeveloped events:* The diamond is used to represent human errors and *events* that are not further developed in the fault tree.
  - *AND gates:* The *event* in the rectangle is the output *event* of the AND gate below the rectangle. The output *event* associated with this gate exists only if all of the input *events* exist simultaneously.
  - *OR gates:* The *event* in the rectangle is the output *event* of the OR gate below the rectangle. The output *event* associated with this gate exists if at least one of the input *events* exists.
  - *Inhibit gates:* The *event* in the rectangle is the output *event* of the INHIBIT gate below the rectangle. This gate is a special case of the AND gate. The output *event* associated with this gate exists only if the input *event* exists and if the qualifying condition (the inhibiting condition shown in the *oval)* is satisfied.
  - *Transfer symbols:* Transfer symbols are used to indicate that the fault tree continues on a different page.

Procedure for Fault-Tree Analysis: The procedure for performing a fault-tree analysis consists of the following eight steps:

- *Define the system of interest.* Specify and clearly define the boundaries and initial conditions of the system for which failure information is needed.
- *Define the TOP event for the analysis.* Specify the problem of interest that the analysis will address. This may be a specific quality problem, shutdown, safety issue, etc.
- *Define the treetop structure.* Determine the *events* and conditions (i.e. intermediate *events)* that most directly lead to the TOP *event.*
- *Explore each branch in successive levels of detail.* Determine the *events* and conditions that most directly lead to each intermediate *event.* Repeat the process at each successive level of the tree until the fault-tree model is *complete.*
- *Solve the fault tree for the combinations of events contributing to the TOP event.* Examine the fault-tree model to identify all the possible combinations of *events* and conditions that can cause the TOP *event* of interest. A combination of *events* and conditions sufficient and necessary to cause the TOP *event* is called a *minimal cut set.* For example, a minimal cut set for *over*pressurizing a tank might *have* two *events:* (1) pressure controller fails and (2) relief *valve* fails.
- *Identify important dependent failure potentials and adjust the model appropriately.* Study the fault-tree model and the list of minimal cut sets to identify potentially important dependencies among *events.* Dependencies are single occurrences that may cause multiple *events* or conditions to occur at the same time. This step is qualitative common cause failure analysis.
- *Perform quantitative analysis.* Use statistical characterizations regarding the failure and repair of specific *events* and conditions in the fault-tree model to predict future performance for the system.
- *Use the results in* decision-making. Use results of the analysis to identify the most significant vulnerabilities in the system and to make *effective* recommendations for reducing the risks associated with those vulnerabilities.

For example a *vessel's* hydraulic steering system (Fig. 6a) will fail if both hydraulic pumps fail to operate. The TOP *event* for the analysis is "both pumps transfer off', and the treetop structure is illustrated in Fig. 6b.

q) *The ETA method (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 & 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 subevents. 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 h)

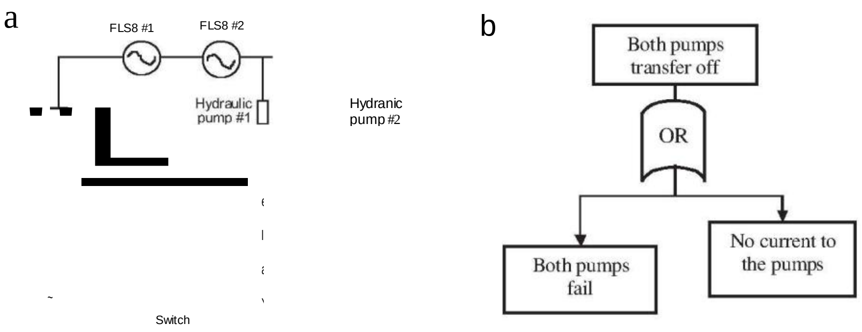


Fig. 6. (a) A drawing ofa vessel's hydraulic steering system. (b) The treetop structure produced by the application ofFTA.

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 ETA technique is applicable not only to design, construction, and operation stages, but also to the change of operation and the analysis of accident causes. The main characteristics ofthe technique are briefly summarized as follows:

- It models the range of possible accidents resulting from an initiating event.
- 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
- It is an analysis technique that generates the following:
  - o Qualitative descriptions ofpotential problems as combinations of events producing various types of problems from initiating events
  - o Quantitative estimates of event frequencies or likelihoods and relative importance of various failure sequences and contributing events
  - o Lists of recommendations for reducing risks
  - o Quantitative evaluations of recommendation effectiveness

r) *The RBM Method (Risk-based Maintenance).* This is a comprehensive hybrid (quantitative/qualitative) technique for risk based maintenance and can be applied to all types of assets irrespective of their characteristics. The quantitative description of risk is affected by the quality of the consequence study and the accuracy of the estimates of the probability of failure. The methodology of RBM is broken down into three main modules: (i) risk determination, which consists of risk identification and estimation, (ii) risk evaluation, which consists of risk aversion and risk acceptance analysis, and (iii) maintenance planning considering risk factors (Khan & Haddara, 2003).

Module I: risk estimation. This module comprises four steps, which are logically linked as shown in Fig. 7.

Step I.1: Failure scenario development. A failure scenario is a description of a series of events which may lead to a system failure. It may contain a single event or a combination of sequential events. Usually a system failure occurs as a result of interacting sequence of events. The expectation of a scenario does not mean it will indeed occur, but that there is a reasonable probability that it would occur. A failure scenario is the basis of the risk study; it tells us what may happen so that we can devise ways and means of preventing or minimizing the possibility of its occurrence. Such scenarios are generated based on the operational characteristics of the system; physical conditions under which operation occur; geometry of the system, and safety arrangements, etc.

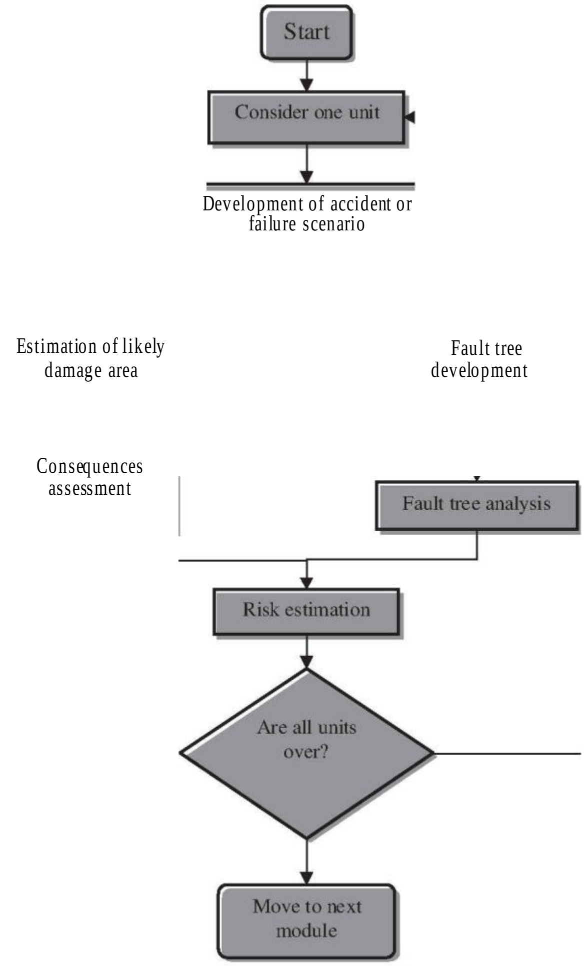


Fig. 7. Description ofthe risk-estimation model according to RBM technique (Khan & Haddara, *2003).*

Table 6
Quantification scheme for system performance function (Khan & Haddara, 2003).

Class	Description	Function (operation)
	Very important for system operation Failure would cause system to stop functioning	8-10
1 1	Important for good operation Failure would cause impaired performance and adverse consequences	6-8
II I	Required for good operation Failure may affect the performance and may lead to subsequent failure of the system	4-6
IV	Optional for good performance Failure may not affect the performance immediately but prolonged failure may cause system to fail	2-4
V	Optional for operation Failure may not affect the system's performance	0-2

Step /.2: *Consequence assessment.* The objective here is to prioritize equipment and their components on the basis of their contribution to a system failure. Consequence analysis involves assessment of likely consequences if a failure scenario does materialize. Initially, consequences are quantified in terms of damage radii (the radius of the area in which the damage would readily occur), damage to property (shattering of window panes, caving of buildings), and toxic effects (chronic/ acute toxicity, mortality). The calculated damage radii are used to *assess* the effect on human health, and environmental and production losses. The total consequence assessment is a combination of four major categories:

2.a) *System perfomzance loss:* Factor *A* accounts for the system's performance loss due to component/unit failure. This is estimated semi-qualitatively based on the expert's opinion. In the work of Khan and Haddara (2003), it is suggested using the following relation for determining the value of this parameter: *Ai = function (perfomzance),* where details of the function are given in Table 6.

2.b) *Financial loss:* Factor *B* accounts for the damage to the property or assets and may be estimated for each accident scenario using the following relations:

i)

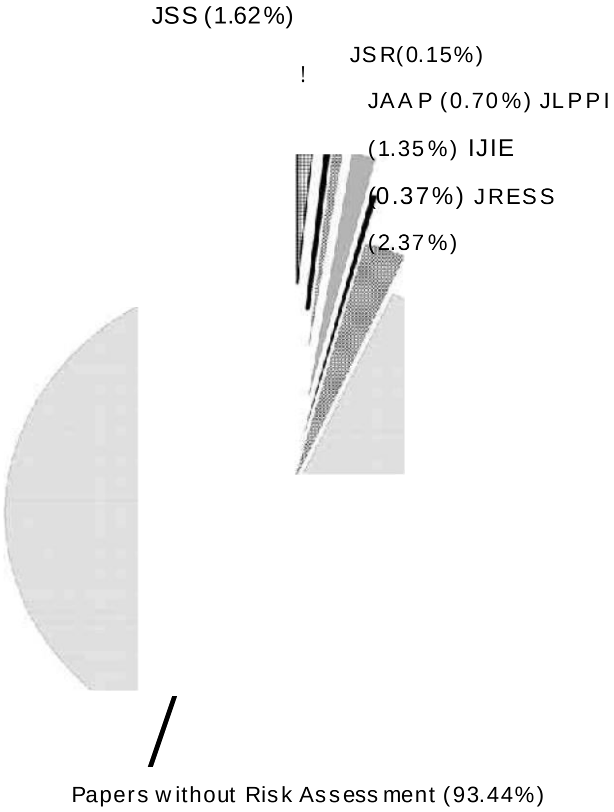


Fig. 8. It is presented the distribution of the relative occurrence-frequencies *f; = n;/N.* concerning papers including RAA techniques. as a result of six scientific journals reviewing. covering the period of 2000-2009.

$$B_i \quad (AR_k\,(AD)_i/UFL$$

$$B = \sum_{i=1,n} B_i$$

where **i** denotes the number of events (i.e. fire, explosion, toxic release, etc.). The UFL in the first equation signifies the level of an unacceptable loss. This value is subjective and may change from case to case as per an organization's criterion (Khan & Haddara,

Table 7
It presents for the period 2000-2009. the statistical results of six scientific journals investigation. concerning papers with as main aim the risk analysis and assessment (RAA) techniques.

Normalized per journal frequency of occurrence (j; " = n;/N;) [%]	Relative frequency of occurrence (j; = n;/N) [%]	Number of papers with risk-assessment techniques (Absolute frequency of occurrence n;)	Relative frequency (F;=N;/N) [%]	Number of investigated papers (Absolute frequency N;)	Journal
(F)=(D)j(B)	(E)=(D)jN	(D)	(C)=(B)jN	(B)	(A)
13.02	1.62	100	12.46	768	Safety science (JSS)
1.37	0.15	9	10.68	658	Journal of Safety Research (JSR)
3.05	0.70	43	22.90	1411	Accident Analysis and Prevention (JAAP)
9.31	1.35	83	14.47	892	Journal of Loss Prevention in the Process Industries (JLPPl)
2.65	0.37	23	14.08	868	International Journal of Industrial Ergonomics (lJIE)
9.32	2.37	146	25.41	1566	Reliability Engineering & System Safety (JRESS)
	6.56	404	100.00	6163	Total

Annotations: Total absolute frequency (i.e. the total number of investigated papers): $N = 6163$; Total absolute frequency of occurrence (i.e. the total number of papers with risk-assessment techniques): $n = 404$; Total relative frequency of occurrence: $f = 0.0656$ (6.56%).

2003) use for UFL the value of 1000). AR: The area under the damage radius (rrr'): AD: The asset density in the vicinity of the *event* (up till ~ 500 m radius) ($/m^2).

2.c) Human health loss: A fatality factor is estimated for each accident scenario using the following equations:

POI =POI· PDFI

(i = (AR)['(POI);/UFR (=

L (i

i= 1,n

where UFR denotes an unacceptable fatality rate. The suggested value for UFR is 10 3 (subjective value and may change from case to case).

The PDFl defines the population distribution factor, which reflects heterogeneity ofthe population distribution. If the population is uniformly distributed in the region of study (~500 m radius), the factor is assigned a value of 1: if the population is localized and away from the point of accident the lowest value 0.2 is assigned. PD!: The population density in the vicinity of the *event* (up till ~500 m radius) (personsrrrr')

2.d) Environment and/or ecological loss: The factor D signifies damage to the ecosystem, which can be estimated as:

D, = (AR)iX(IM);/UDA

D= *LDi*

i= 1,n

where UDA indicates a level for the unacceptable damaging area, the suggested value for this parameter is 1000 m^2 (subjective value and may change from case to case): 1M denotes importance factor. 1M is unity if the damage radius is higher than the distance between an accident and the location of the ecosystem. This parameter is quantified by Khan & Haddara (2003) (see their figure 4).

Finally, the factors A, B, C and 0 are combined together to yield the factor Con (consequence assessment factor)

Con = $[0.25A^2 + 0.25B^2 +$ 0.25(2 + 0.25 D2 r5

Step I.3: *Probabilistic failure analysis*. Probabilistic failure analysis is conducted using fault-tree analysis (FTA). The use of FTA, together with components' failure data and human reliability data, enables the determination of the frequency of occurrence of an accident.

Step f.4: Risk *estimation.* The results of the consequence and the probabilistic failure analyses are then used to estimate the risk that may result from the failure of each unit.

Module II: risk evaluation. The evaluation algorithm comprises two steps as detailed below:

Step fI.1. Setting up the acceptance criteria. In this step, we identify the specific risk acceptance criteria to be used. Different acceptance risk criteria are available in the literature.

Step II2. Risk *comparison against acceptance criteria*. In this step, we apply the acceptance criteria to the estimated risk for each unit in the system. Units whose estimated risk exceeds the acceptance criteria are identified. These are the units that should *have* an *improved* maintenance plan.

Module III: maintenance planning. Units whose level of estimated risk exceeds the acceptance criteria are studied in detail with the *objective* of reducing the level of risk through a better maintenance plan.

Step III.1. Estimation of optimal maintenance duration. The individual failure causes are studied to determine which one affects the probability of failure adversely. A *reverse* fault analysis is carried out to determine the required value of the probability of failure of the root *event.* A maintenance plan is then completed.

Step III.2. Re-estimation and re-evaluation of risk. The last step in this methodology aims at verifying that the maintenance plan developed produces acceptable total risk level for the system.

4. Statistical analysis and results of the scientific literature reviewing

The second *objective* of the work was the statistical analysis, classification, and comparative study of the scientific papers with as main aim the risk analysis and assessment (RAA) techniques. This *objective* was *achieved* by the investigation of six represen*tative* scientific journals published by Elsevier B'V. during the last decade. So, we exhaustively searched the journals (a) Safety Science OSS), (b) journal of Loss Prevention in the Process Industries OLPPI), (c) Accident Analysis and Prevention OAAP), (d) journal of Safety Research OSR), (e) International journal of Industrial Ergonomics (IJIE), and (f) Reliability Engineering and System Safety ORESS), covering the period 2000-2009.

More specifically, we studied and investigated all the published papers of the *above* referred journals, gathering a total number of 6163 papers. The reviewing of the scientific literature (i) revealed a plethora of 404 published technical articles including risk analysis and assessment (RAA) techniques concerning many different fields, like engineering, medicine, chemistry, biology, agronomics, etc. and (ii) showed that the risk analysis and assessment techniques are classified into three main categories the qualitative, the quantita*tive* and the hybrid techniques (qualitative-quantitative, semiquantitative). These articles address concepts, tools, technologies, and methodologies that *have* been developed and practiced in such areas as planning, design, development, system integration, prototyping, and construction of physical infrastructure: in reliability, quality control, and maintenance.

In the Appendix (Table A) we depict the *above* referred 404 selected papers, taking into account the basic classification of Fig. 1, and using *seven* columns e.g. (A) the number (or numerical code) of the paper, (B) the paper's citation information, (C) the name of the risk analysis or/and assessment technique, (D) the type of the main methodology, (E) the kind ofthe paper's data or material, (F) the field of application, and (G) the source OSS, jSR, jAAP, jLPPI, IjIE, jRESS).

Table 7 illustrates the statistical results of the investigation including the following: (a) the absolute frequency N_i i.e. the number of investigated papers per journal (JSS:768, jSR:658, jAAP:1411, jLPPI:892, IjIE:868, jRESS:1566), (b) the relative frequency *t,* = *N;/N* OSS: 12.46%, jSR: 10.68%, jAAP:22.90%, jLPPI:14.47%, IjIE:14.08%,jRESS:25.41%), (c) the absolute frequency of occurrence n, i.e. the number of papers with risk-assessment techniques OSS:100, jSR:9, jAAP:43, jLPPI:83, IjIE:23, jRESS:146), (d) the relative frequency of occurrence *f; = n;jN* OSS:1.62%, jSR:0.15%, jAAP:0.70%, jLPPI:1.35%, IjIE:0.37%, jRESS:2.37%), and (e) the normalized (per journal) frequency of occurrence f;' = *n;jN*$_i$ which has been used in order to weigh up the contribution of each journal (JSS:13.02%, jSR:1.37%, jAAP:3.05%, jLPPI:9.31%, IjIE:2.65%, jRESS:9.32%).

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