Trends, problems and outlook in process industry risk assessment and aspects of personal and process safety management

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1. Introduction

Process industry brings economic activity and provides us with unique materials. While mankind grows in numbers, needs are at the increase and while natural resources become more scarce, process industry is even more needed to provide for energy and energy carriers, fertilizers, plastics, fibres, coatings, pharmaceuticals to name a few, and even clean water. At the down side there is an always looming risk of accident, loss of containment of hazardous substances and the ensuing hazards of explosions, fires and toxic spread. This creates a background threat to workers and when risks have effect outside plants to the general population. Since for several reasons industry favours locations near crossways of trade and traffic and thus vicinity to population is inevitable, risk assessment has in many places become a routine based on legislation. Risk assessment as an instrument to describe and delimit the risk of chemical process operations was introduced to the community of Loss Prevention in the process industry in the mid-seventies. Much has been written about it since that time and considerable investments made in developing methodology, release and dispersion models, as well as ways to predict damage. Many data have been collected and much has been said about interpretation of results. The latter has been an infinite source of quarrels. Meanwhile, the use of risk assessment has become rather widespread and more decision making depends on it. Not only installations bound to a certain location, but also transportation routes have been object of risk analysis and assessment. Yet, the methodology produces results which in a number of aspects are still unsatisfactory. To mention an aspect the variance of outcomes of an analysis for example is high and can cover in some cases two orders of magnitude in risk defined as the product of expected event frequency and likely damage (Pasman et al., 2008, 2009).

Apart from having doubts about the magnitude of remaining risk, there is the question why despite the large body of experience still major accidents happen. In process industry progress in maintaining safety has been impressive. Statistic figures on personal safety of workers have fallen over 40 years in a steady rate. Yet, from time to time, high loss process incidents keep on occurring. This paper will start off presenting a statistical study on petrochemical accidents over a long period of evidence underpinning the need of developing and sufficiently strengthening control barriers to prevent catastrophic consequences to people or environment resulting from accidental releases of hydrocarbons. It will present some results extracted from a data base on the main categories of causes. It will then pay attention to human performance with respect to safety. Human decisions and acts in management, design, construction, and operation of plant have a large influence on safety. Qualitative and quantitative assessments should cover the human/machine interface, operating and emergency procedures, and training. Unfortunately, human performance factors do not always find systematically its way as input into facility design, development of operating procedures, or operator training. Also underlying economic and organizational processes have large influence as recently described by Knegtering and Pasman (2009). Cost pressure, aging, work force turnover and failing safety management play an important role and have an adverse effect on culture. This weakens the resilience of an organization.

The paper will continue describing what is meant with risk assessment, where it is used for and why and what trends can be seen. It will briefly summarise experiences in various countries. It will then try to analyse the underlying problems as there are the subjectivity in hazard identification, oversimplification in release models, assumptions in environmental conditions (weather, terrain), the large uncertainties in technical failure mechanisms and failure rates, and the deficiencies in consequence modelling and in view of the above about organization and Human Factor the effects of failures of safety management system. It will try to formulate how to go ahead.

2. Accidents in the oil industry

Investigating and analyzing the origins and consequences of accidents over a long period in a given industrial sector, in connection with proper statistical evaluation, can provide lessons on how to improve assessment and management of risk. In fact, historical analysis leads to the identification of the most probable scenarios (e.g. release, fire, explosion etc.) including consequences, as well as to the identification of the most frequent immediate or direct and underlying or root causes. Where safety improvement based on accident analysis is mainly addressed via quantification of lagging indicators as lost time injury frequency, the statistical approach can also be useful in identifying key indicators which on an industry wide basis better resolve the nature of incidents. Accidents that are considered in this section are taken from the TNO FACTS Database (TNO), which includes accident data from a number of countries starting from the beginning of the twentieth century. We focused our attention on the downstream oil industry sector for which accidents, connected to both personal and process safety, represent an area of significant concerns. By the way to put things in perspective, some measures evidence that in 2004 oil and gas workers were six times more likely to die from a fall than from an explosion/burn (OGP, 2005). We analyzed a time period starting from the early 1930s to 2008, during which 1209 events are identified. Distribution of accidents according to time, by natural decades, is depicted in Figure 1, showing a jump followed by a slower increasing trend in the last four decades after much power and chemical industry became oil based.

The distribution is to be attributed both to the improvement of accident information availability and to the increase of oil product consumption and corresponding development of the downstream oil industry.

Considering in detail the last three decades, (see Fig. 2) accident trend from statistical viewpoint is not a monotonic one, but evidences upswing and drop, which contrarily to other industrial sectors cannot be correlated to production rate (expressed as million barrel per day). Traditional lagging indicators (i.e. measures of outcomes and occurrences) are determined for a work unit. They include lost time accident frequency (e.g. eq. 1), total accident frequency index (e.g. eq. 2), fatal accident frequency index (e.g. eq. 3); high potential incident frequency; worker compensation expressed as percentage of payroll; property damage costs; loss of hydrocarbon containment; etc. They can provide historical trends in safety performance for a certain location or work unit useful for highlighting appropriate opportunities and priorities for safety improvement.

$$LTI = \frac{Number\ of\ hours\ absent\ from\ work}{Number\ of\ worked\ hours} 10^6 \tag{1}$$

$$FI = \frac{Number\ of\ total\ accidents}{Number\ of\ worked\ hours} 10^6 \tag{2}$$

$$FAFR = \frac{Number\ of\ fatalities}{Number\ of\ worked\ hours} 10^8 \tag{3}$$

Leading indicators on the other hand try to detect trends in potential 'precursors' and in safety culture. For a further overview and definitions, see CCPS, 2008. These indicators on the basis of hours worked will not be pursued here; instead we shall develop a picture for the oil downstream industrial sector as a whole. It is interesting to analyze statistics on the severity of recorded accidents, again going decades back to the middle of the twentieth century, based on total number of fatalities and total number of injured people in the sector.

From Fig. 3, it can be observed that in the last three decades, the number of fatality evidences shows a decreasing trend, while the number of injured people increases continuously from the fifties onward reaching a maximum by the end of the 20th century. It seems that in this sector the most effective actions in preventing casualties result in less fatal accidents, while the general improvement in process industrial practice and automation has lower effect on injuries.

The classification of each accident was done elaborating a structured scheme based on the approach of EU MARS (Major Accident Reporting System) reports and considering three macro-categories, namely Organization, Plant/process and Environment. Under the headline Plant/process are grouped the possible causative factors directly connected to hardware and inherent characteristics of the process (see Fig. 4). The area Organization collects causative factors related to human factors at different levels and to the safety management system and safety culture (see Fig. 5). Under the headline Environment were included natural events, domino effects, items related to work place lay-out, machine safety, ergonomics and other environmental conditions. According to this framework, starting from the direct cause of the accident, it is possible to analyze the accident histories deeper (provided that adequate data are available) in order to identify two/three underlying causes in a sort of causal logic chain that, for example links a direct cause under Plant/process to more distant causes within the heading Organization.

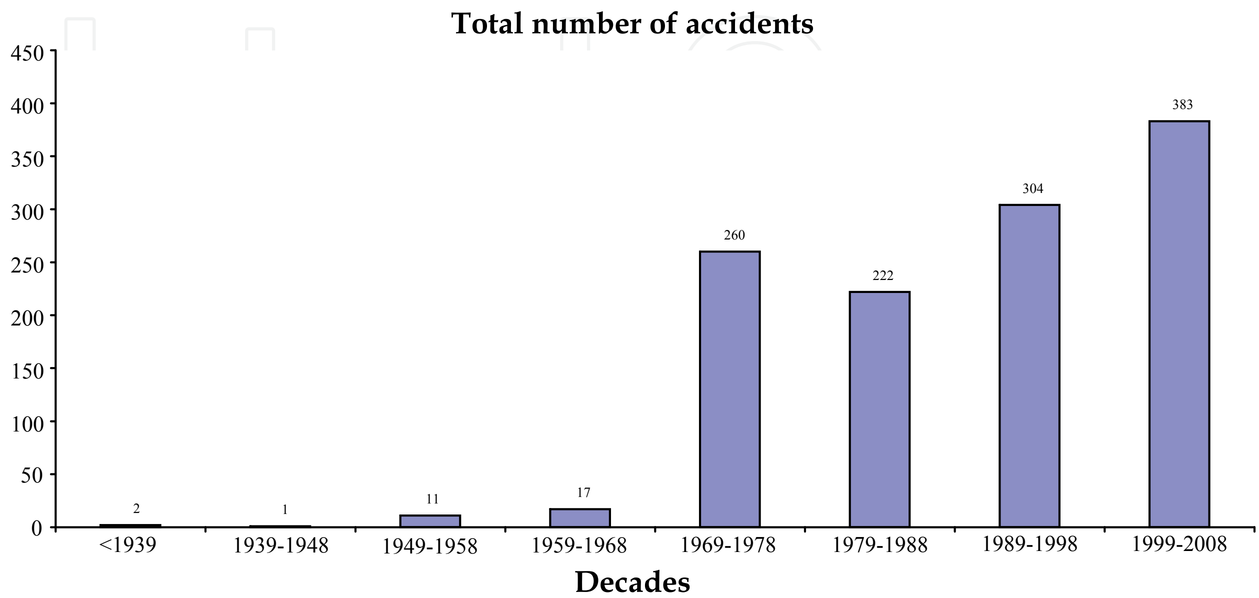


Fig. 1. Global total number of accidents in the downstream oil industry per decade recorded in the TNO FACTS data base.

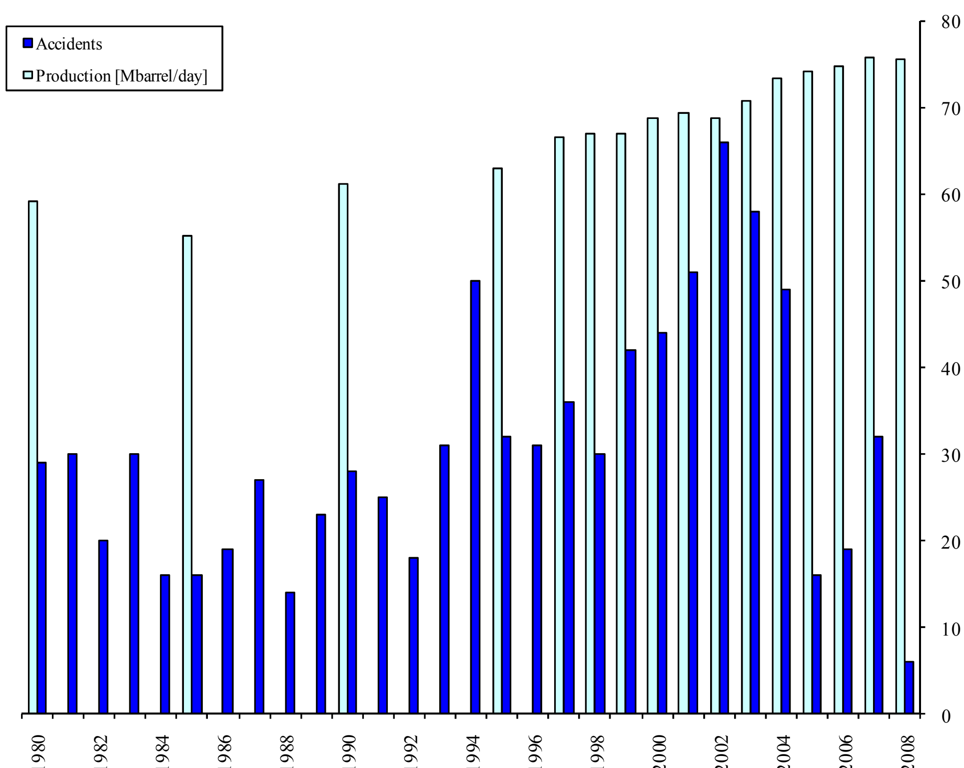
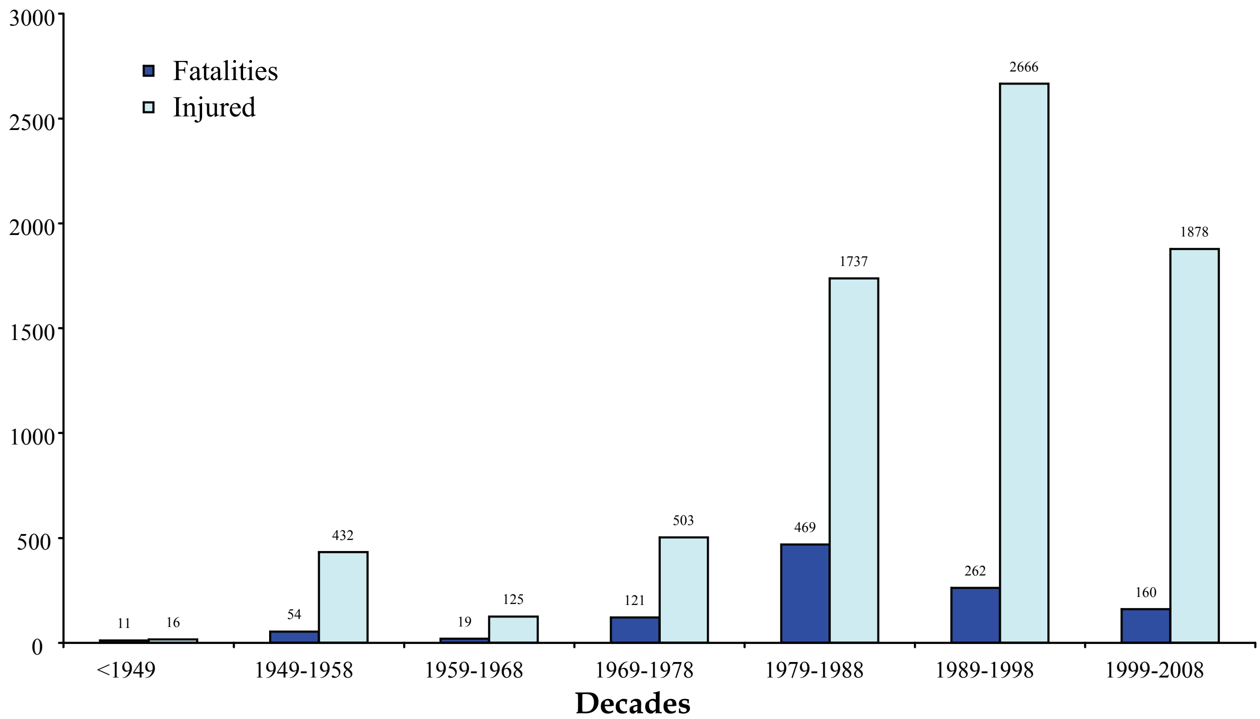


Fig. 2. Oil production over the last few decades and number of accidents.



Number of fatalities and injured people

Fig. 3. Casualties (fatalities and injured persons) per decade found in Database FACTS recorded industrial accidents.

The distribution of the entries among the three main categories evidences that in the downstream oil industry Plant/process cause accounts for 64.8 % of total accidents, Organization for 28.8% and, at last, Environment for the remaining 6.4 %.

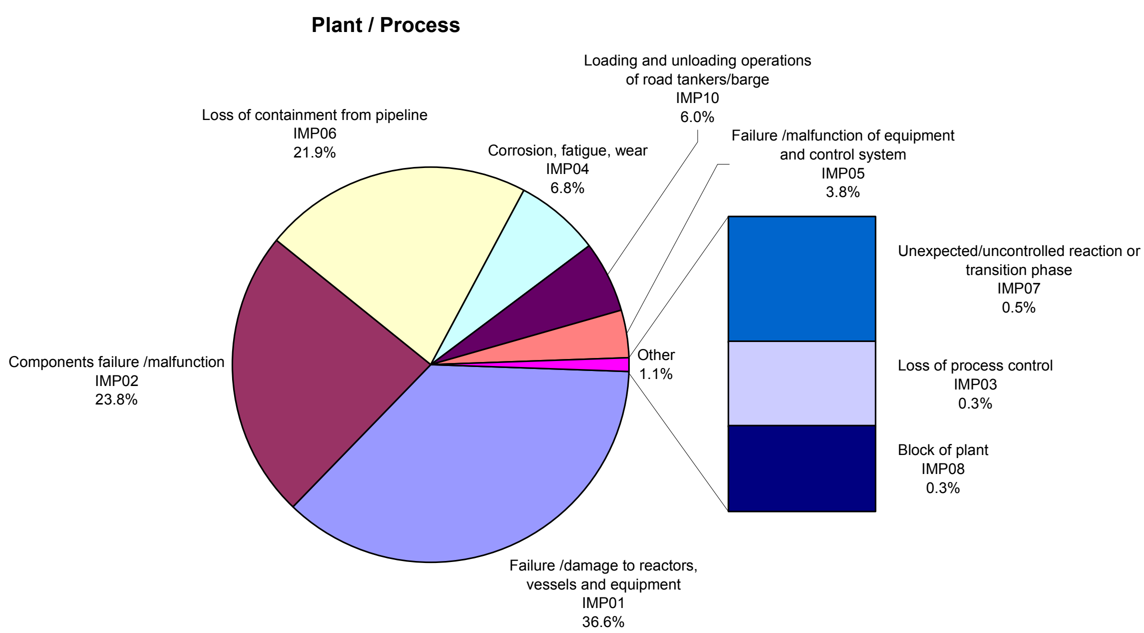


Fig. 4. Distribution of accident causes within the category Plant/process

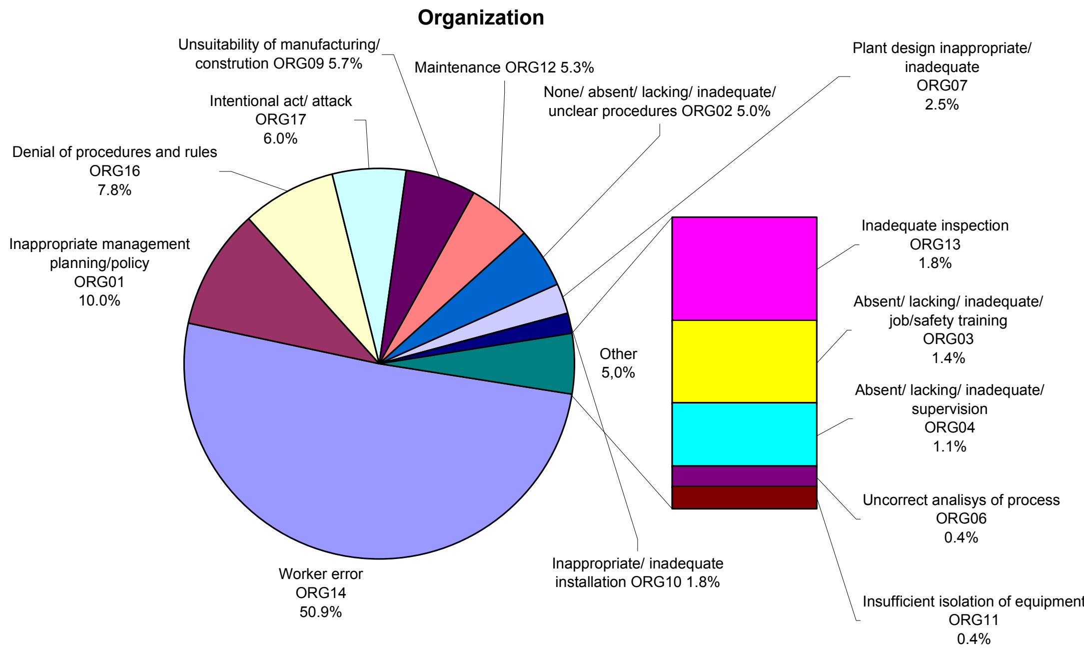


Fig. 5. Distribution of accident causes within the category Organization.

The distribution of the main direct causes is depicted in Figures 4 and 5, respectively for Plant/process and Organization, corresponding to the two items that globally cover more 93.6 % of the accidents. Under each heading three sub-steps were identified as possible underlying cause (recalling the complete classification scheme), allowing evidence to possible deficiencies in the safety management system or in the safety culture of the company.

Dealing with the category Organization (see Fig. 5), it appears that more than 50 % of the accidents can be connected to a form of human error: the analysis shows worker error (unsafe act) to be a significant direct cause as well as a root cause during design stage, operation, and management of the plants, the so-called latent failures. Remarkably, accident analysis as mentioned before revealed that both immediate and root causes are often interacting in parallel and/or in series among multiple, interdependent elements in the complex, high hazard context of a refinery. This has already been concluded in general by Professor James Reason in his many publications, e.g. Reason, 1997 and embodied in his so-called Swiss Cheese concept. It does not help to make risk assessment an easy job!

Accidents can be divided into classes according to the number of fatalities per accident. Although information is not available for all accidents that occurred, it can be assumed that the sample taken here is statistically significant. Data on accidents with fatalities can then be elaborated as suggested by Oggero et al., 2007 obtaining curves in a way similar to societal risk f/N. Calculated is the (relative) probability of occurrence of an accident class exceeding a given number of fatalities, normalized by the total number of accidents involving at least one fatality observed in the sector over a certain period. The cumulative probability data are plotted as a function of the given number of deaths of each class:

$$P_{(x \geq N)} = F_j = \frac{\sum_{i=j}^{n} \nu_i}{\sum_{i=1}^{n} \nu_i} \tag{4}$$

where: N is the lower limit number of deaths in a class (x -axis);
i is class number;
$P_{(x \geq N)} = F_j$ is the probability of an accident class j in which the number of deaths will be $\geq N$ (y-axis);
n is the total number of classes;
ν_i is the number of accident entries for a given class i.

Figure 6 shows the cumulative probability of accidents with N or more fatalities as a function of N, in the downstream oil industry, obtained on the basis of all selected worldwide accidents and plotted on a log-log axis diagram.

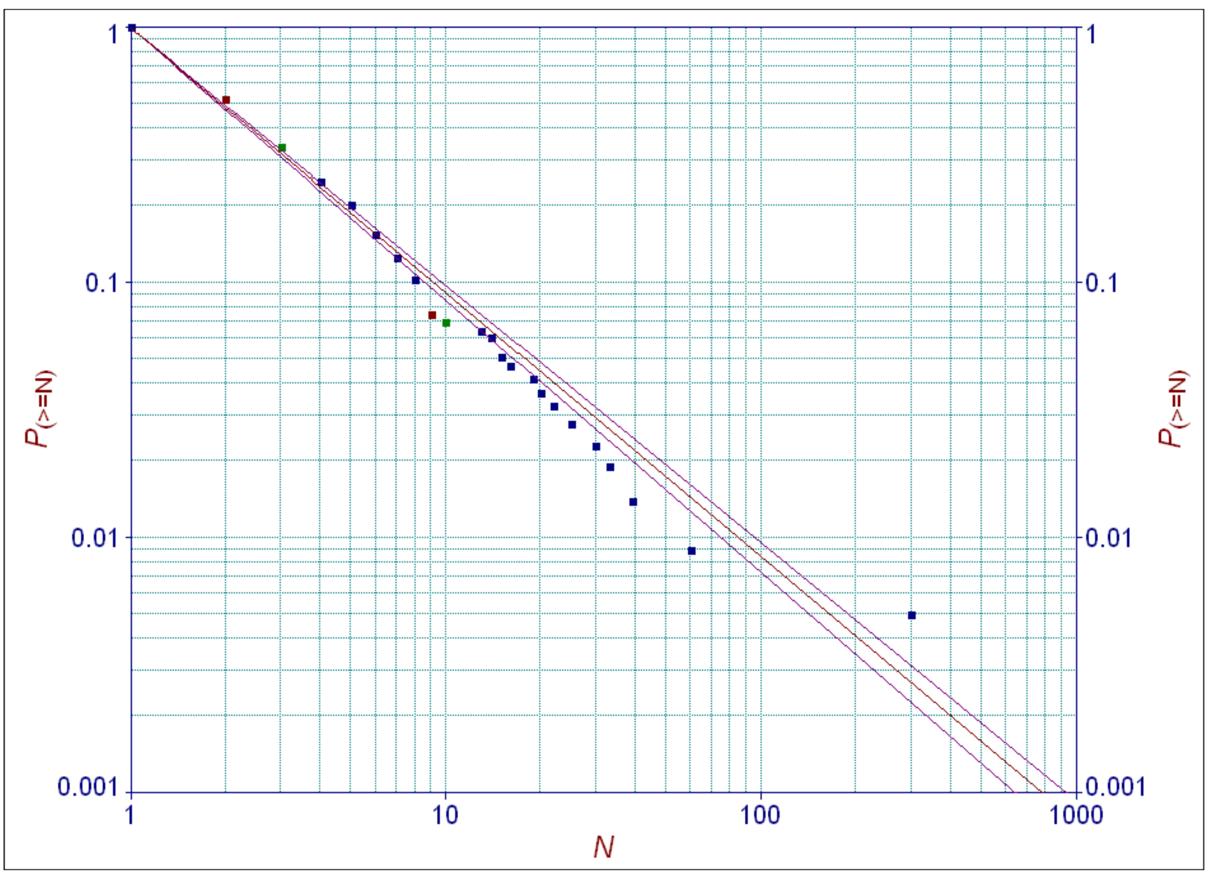


Fig. 6. Cumulative probability of an accident with N or more fatalities as a function of N for all accidents with fatalities in the downstream oil industry (TNO database FACTS entries over the time period 1938-2008).

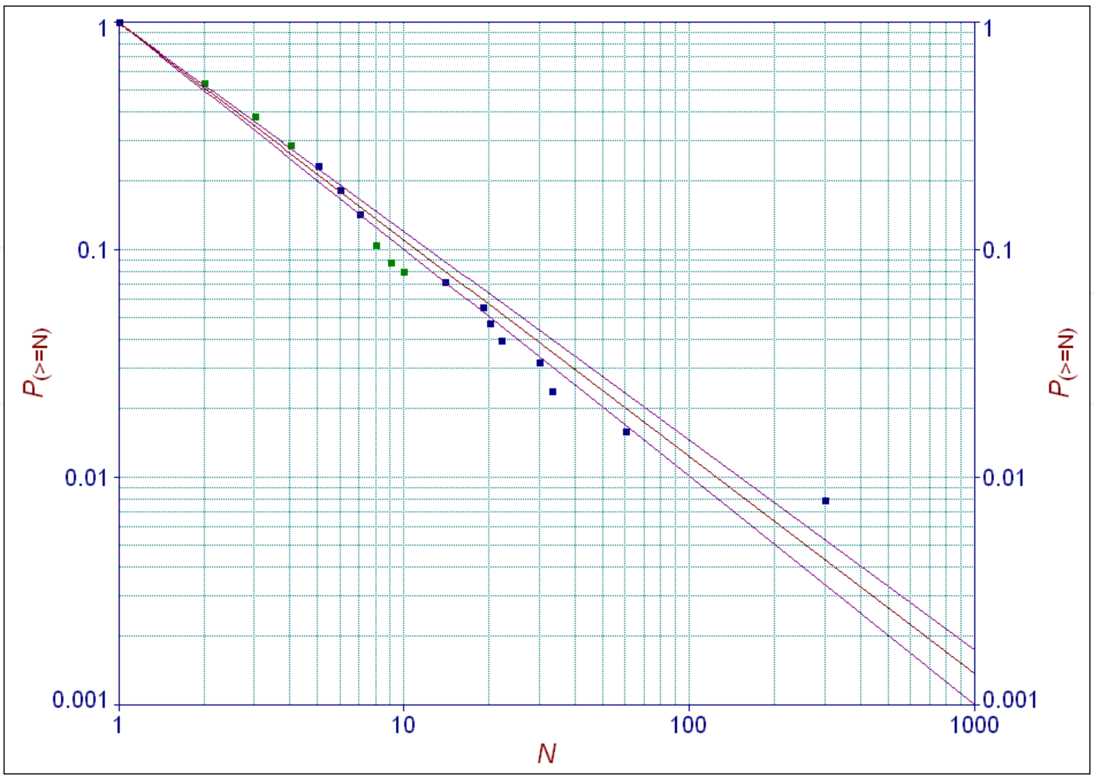


Fig. 7. Cumulative probability of an accident with *N* or more fatalities as a function of *N* for all accidents with fatalities in the downstream oil industry, within the category Plant/process (TNO Database FACTS entries over the time period 1938-2008).

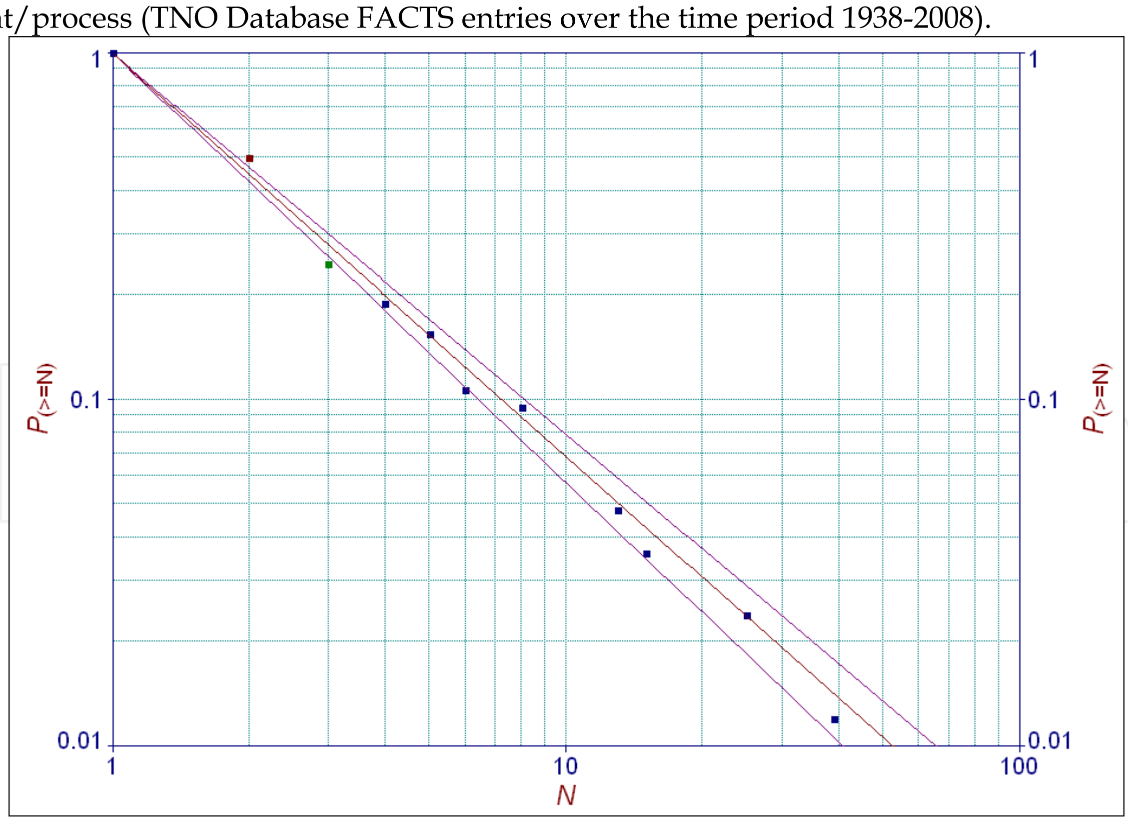


Fig. 8. Cumulative probability of an accident with *N* or more fatalities as a function of *N* for all accidents with fatalities in the downstream oil industry, within the category Organization (TNO Database FACTS entries over the time period 1938-2008).

As shown in the same figure, the best-fit provides a $P=N^b$ curve type, with 95% confidence limits, (r^2 = 0.995) yielding b = -1.037. This finding means that the probability of an accident involving ten or more deaths is about 11 times higher than the one of an accident involving 100 or more deaths. By selecting entries in the two items accounting for nearly all fatalities (Plant/process and Organization), we obtained the trends respectively shown in Figure 7 and 8.

According to this elaboration, based on the concept of cumulative probability of fatal accidents, it can be argued that the consequences in terms of human harm of an oil refinery accident are likely to be more severe, when the accident is primarily connected to a cause in the category Plant/process, rather than in the category Organization.

It is interesting applying the same approach to a specific major hazard activity within the oil industry, namely storage. The statistical elaboration over the same time period allowed obtaining the graph depicted in Fig. 9. The best-fit yields a value b=-0.835, indicating that the consequence of an accidents connected to storage activity is significantly higher than the average for all downstream oil activities. This may have to do with the relative large quantities of hazardous material involved in storage accidents.

It is amply recognized that the ultimate goal of industrial accident analysis is the generation of lessons learned in order to avoid accident recurrence; however, events having the potential of inducing hazardous situations though not materializing after all – the so-called near misses-, can also contribute to the corporate learning and memory (ESReDA, 2001). The challenge of improving the organizational memory and the need for a new look at the sort of injury and accident data that are collected, was already highlighted by Kletz (1993). Problems in actually analyzing case histories have been described by Pasman (2009). In this context shall be mentioned that examination of statistics and causes of minor injuries, hazardous situations and in particular of near-misses can prove even more challenging but also more fruitful with respect to extraction of experience because it is based on an higher frequency of occurrence (see also Körvers et al., 2010). In fact, injury and fatality statistics tend to reflect the quality of the organization in managing personal safety hazards, while near misses point more effectively to process safety hazards.

For the purpose of learning lessons we developed a *Near-miss reporting system (NMRS),* suitable to trace back near-misses to possible deficiencies within the company under examination, including both human and organizational factors. As case-study, this framework was applied to categorize events directly collected in-the-field, over eight years observation, in a major downstream oil company.

According to this approach, the immediate cause classification of near-misses was identified as schematically shown in Fig. 10. The distribution over the categories is roughly similar to the distribution observed earlier in accident causes.

Fig. 9. Cumulative probability of an accident with N or more fatalities as a function of N for all accidents with fatalities, related to storage activity in the downstream oil industry (TNO Database FACTS entries over the time period 1938-2008).

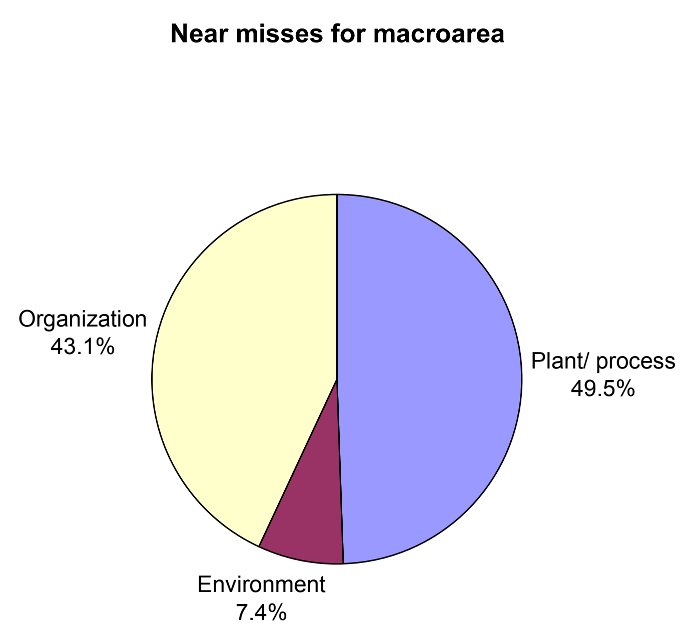


Fig. 10. Near miss classification within the NMRS framework, recorded over an 8-year period in a downstream oil company.

Further analysis can maximize the benefits of a near miss reporting system. Among them, we can mention (CCPS, 2008):

- the utilization of process safety near misses in connection with process safety lagging indicators to build up a process safety performance Heinrich pyramid;
- the evaluation of process safety near misses considering the potential as well as the actual consequences of the event;
- the establishment of ties between the near miss data and the deficient management system, so as to drive system improvement from near miss as well as from actual incidents.

As shown in Fig. 11, an effort was made to identify top ranking direct causes of near-misses over a prolonged period: the knowledge of how frequently these categories are involved in potential accidents can help in improving safety performance. In addition, for every near-miss it is important to conduct a complete root cause analysis while keeping in mind the question why that cause could be present. Component failure or malfunction appeared to be the top cause. However, it must be underlined that the near-miss reporting system evidenced again in several events a combination of root causes.

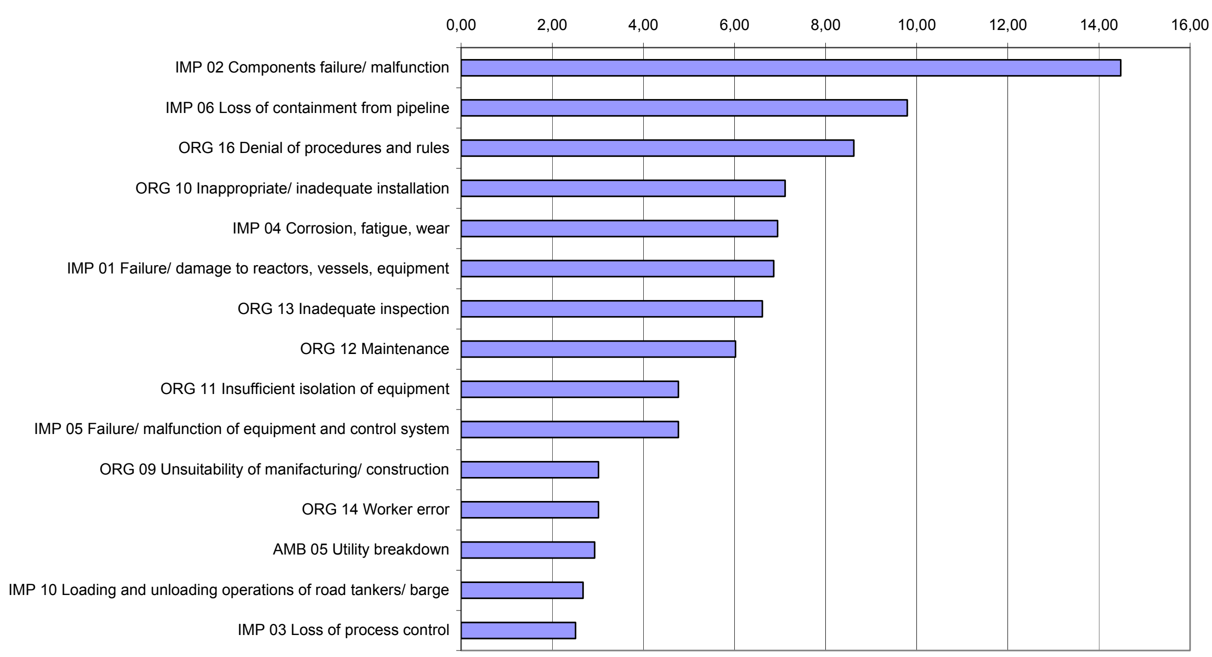


Fig. 11. Top fifteen immediate causes of near-misses (percentage of the entire number of entries) recorded in a downstream oil company over an eight-year period.

3. Some considerations on the human factor

The investigation on many high profile accidents across the process industry, confirmed by the statistical analysis previously outlined, concludes that different human failures can be identified as prominent amongst the root causes. Many of these can be ascribed to poor safety culture, or an inadequate safety management system. Safety culture is hard to precisely define although its absence can be sensed easily observing details in the execution of work. In the Culture Ladder training programme developed by Van der Graaf, Hudson et al. for Shell E&P, available at the website of the Energy Institute in London, the various stages of culture development are each characterized by a few pithy words (see Van der Graaf et al., 2002 and Hudson et al., 2004). In case leadership is serious about safety the organization will follow. The boss' seriousness about safety is in fact what determines the safety attitude of the worker (Zohar,1980 and 2000).

Human failures were categorised by HSE in the UK as either unintentional (error) or intentional by breaking of the rules (violation): the importance of its definition is connected to possible risk reduction by proper intervention. Generally speaking, the factors influencing accident frequency can be divided into following categories:

- technical factors: low automation, multi-product industries, discontinuous operating cycles, and non-standardized production affect safety negatively, since they require a higher interaction between man and devices. On the other hand, a reduction in individual exposure to severe hazards was reported in case of the introduction of mechanized machinery and equipment in the mining (Asogwa, 1988) and the logging industry (Laflamme, 1988).
- economical factors, e.g., the general economic climate (Saari, 1982), the unemployment rate, labour and social-insurance legislation, (Blank, 1996);
- organization of the work, e.g., management system and performance monitoring, work practice, oversight, communication structure, etc.;
- environmental conditions: about half of the general industrial accidents in Italy are related to conditions at the work place and they could be prevented by rather simple lay-out and protection measures, but in small companies their realization becomes extremely difficult, or even unfeasible because of operating, economic and/or space constraints (Fabiano et al., 2004);
- human factors, both individual and inter-individual, e.g., workload, experience and training, competencies, fatigue, etc.

Petrochemical and process industries experienced in the last two decades a substantial level of change in both terms of production globalization and in the way the business is structured. Current market conditions often make it necessary to apply outsourcing to remain competitive, particularly utilizing external and precarious human resources. In fact, in the last 20 years there has been a significant growth of workers in casual, part-time, subcontract or franchised arrangements, virtually in all OECD countries. Investigation of a possible relationship between personal and process accidents/near miss and temporary work was recently performed, adopting a questionnaire survey, for the definition of peculiar risk factors and for setting priorities to improve safety standards in this context. Data from the structured questionnaire were coded and entered into a database for subsequent multivariate analysis of variance (ANOVA).

The independent variables, whose effects on the number of injuries and their severity were evaluated, included: worker age, job position, training period, on-site experience, temporary contract life, perceived accident cause. Significant results can be usefully analysed by adopting response surface methodology (RSM). An applicative example related to personal safety is depicted in graphical form in Figs. 12 and 13.

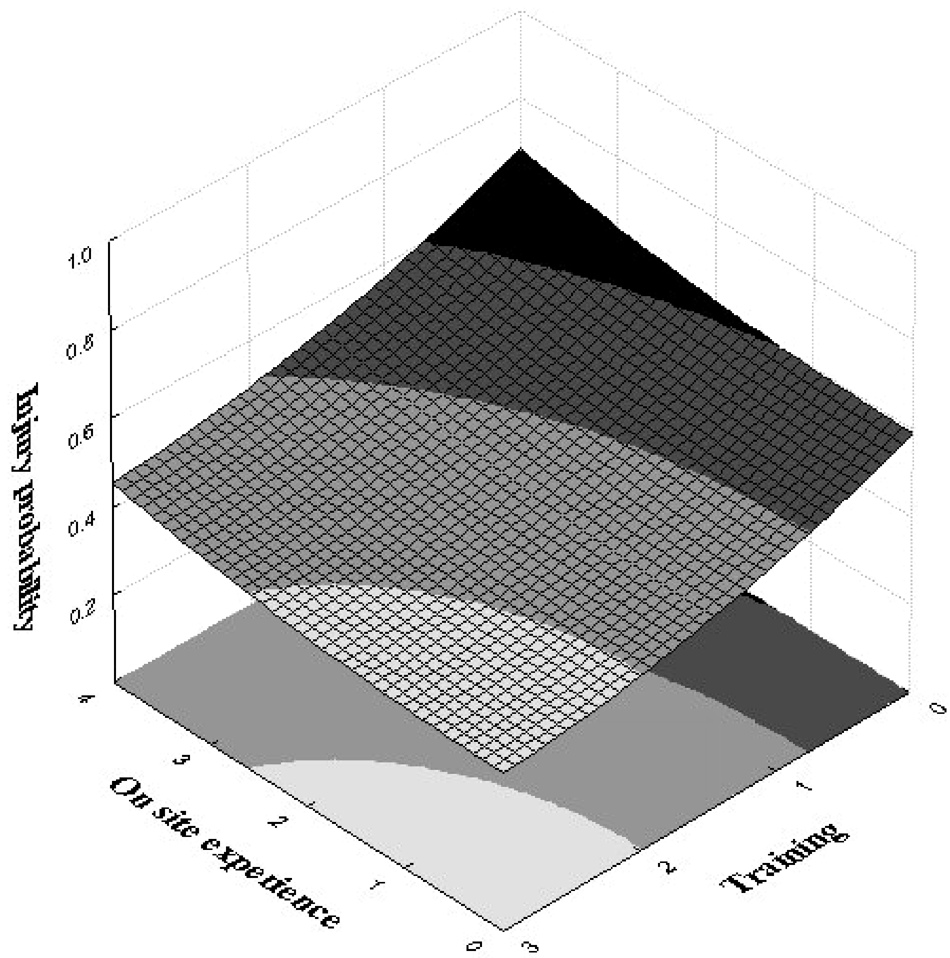


Fig. 12. Response surface for injury probability, as a function of training and on-site experience (Legend: a=less than 7 days; b=7-30 days; c=31-60 days; d=61-90 days; e=more than 90 days; r=less than 3 hours; s=3-5 hours; t=6-7 hours; u=more than 7 hours). (Fabiano et al., 2008).

The significant interaction of the independent variables indicates that an increase of the training period (professional training and job tutoring) greatly reduces injury probability. Notwithstanding efforts by many consultants to train personnel, there is no substitute for a period spent within a process company to gain experience. It must be noted that safety programs include training as a part of the risk management process. However, implementation of rules followed-up by training may often not sufficiently reduce unsafe practices, as safety rules are often seen to apply only in certain situations and as being impossible to follow in the many exceptional situations which are seen to be the reality of the shop floor situation (Hale, 1990). Complacency, not seeing a risk or masculine pride not to fear a hazard plays also a role.

Equally, it seems that staying of the worker on the same job site involves an increase of experience and knowledge of one's duties, reducing the probability of an accident. In other words, even if employees are unaware initially of occupational risk, they can often acquire on-the-job experience. A key aspect is that, as reported by Asogwa (1988), an adaptation period is required for workers to perform adequately in new work assignments and a changed environment, while under conditions of pressure and intensified production (like those that usually correspond to the utilization of temporary workers) this training period is being reduced or eliminated. It must be underlined that the type of human failure influences the choice of the most effective intervention for their reduction. In fact, for violations or mistakes further training of operators may be most appropriate whereas for errors by skilled operators, improvement of the work environment or design of the man-machine interface is more likely to be effective (Ellis and Holt, 2009).

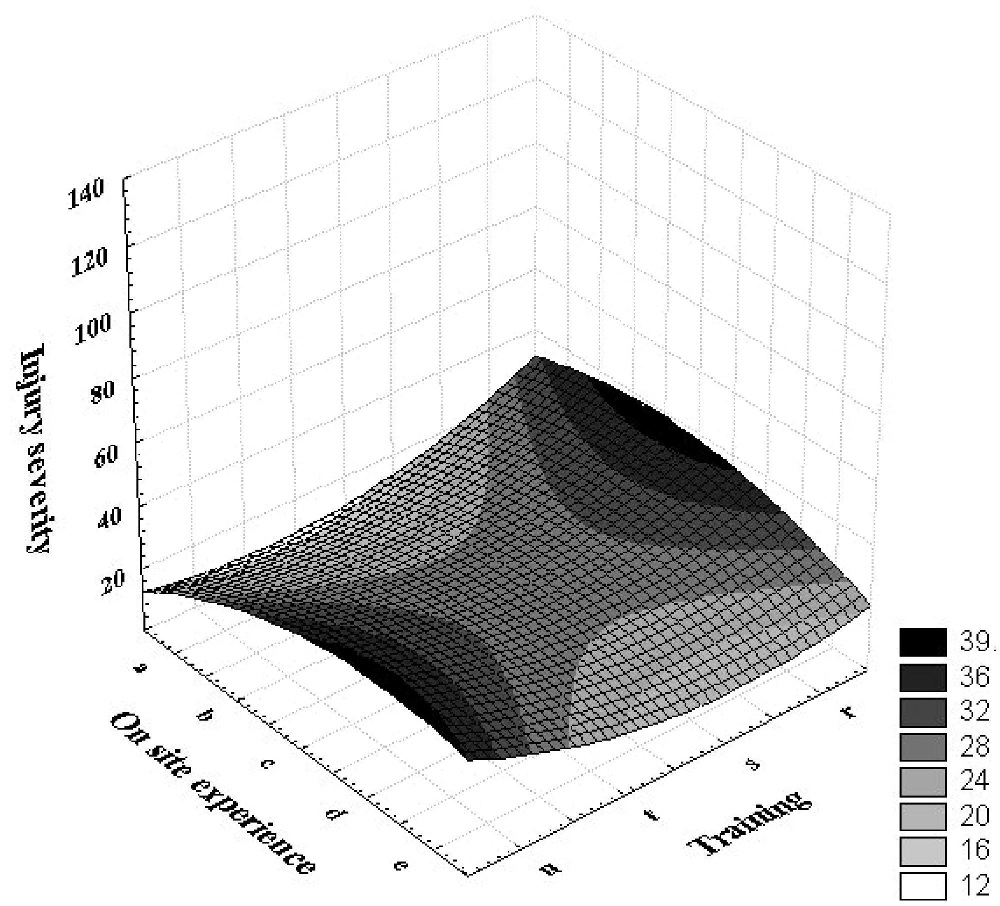


Fig. 13. Response surface plot of injury severity, as a function of training and on-site experience (Legend: a=less than 7 days; b=7-30 days; c=31-60 days; d=61-90 days; e=more than 90 days; r=less than 3 hours; s=3-5 hours; t=6-7 hours; u=more than 7 hours) (Fabiano et al., 2008).

In conclusion, remembering that "to err is human", human error must always be part of an effective training to shape a safety habit and must be considered in writing policy/procedures, so as to achieve maximum understanding and acceptance. It therefore also seems crucial to take human error into account when assessing risk.

A key factor in QRA according to flammable release scenarios is connected to the selection of the ignition probability. The commonly applied approach based on correlating the ignition probability to the mass release rate may lead to unrealistic and very conservative estimates in many common plant situations. On the basis of a recent review by the Energy Institute (2006), a comparison among ignition probabilities assigned by various models to selected scenarios is presented in Table 3.
It shows that the DNV method gives ignition probabilities from 20 to 30 times lower than the WS Atkins method, with the only exception of hot work ignition. Cox, Lees and Ang method, based on mass release rate, yields higher values than the other models, with the exception of scenario "heavy equipment, short contact time".

The afore mentioned is all but the effect of human error and of safety management system failures. Not only do these effects have an upward pushing effect on risk values but they contribute also significantly to the spread in results. On top of that comes that the effects cannot be measured simply.
Summarising: choices, complexity, available computing time, limited knowledge and experience will contribute all to unavoidable spread. It will be clear that in case of land use planning or licensing the disagreement in model outcomes will cause much debate and friction amongst planners from both private and public parties. As to be expected there will be different interests hence providing fertile grounds for lawyers, while competent authorities under pressure become uncertain and will try to delay decision or eliminate the risk source and with that the activity.

7. Future increase of demand and possible improvement

Requirements tend to become more stringent. People will not tolerate risks 'in their backyard', but will foster on the other hand the economic activity process industry will bring. Quality of life of the European is much dependent on economic activity, while safety has a high priority. However, cities and traffic nodes expand also in the direction of established industry and the above mentioned group risk criterion cannot always be met. In view of the ever increasing scarcity of land this will happen in future more frequently. The latest Dutch legislation on public (external) safety requires an advice of the emergency response organisation (fire brigade). Since towns often expand in the direction of industrial sites, in case of license renewal this becomes a more general problem. On the basis of the advice the group risk requirement can be waived. The demand for advice is quite a burden on the fire brigades which traditionally had not the capability and knowledge level to perform risk analysis. At the same time as an emergency response organisation their mission is saving life. This will not only be that of casualties in the general public but also with respect to plant workers. Since the mayor of the city is responsible for a (regional) plan for disaster management, there is even more interest in prediction of injuries (number, nature, degree) than in only fatalities as in present risk analysis. Although probit data for injury by fire are available, those on injury by toxics and blast barely exist.
Analysis of emergency response effectiveness is already needed for providing facilities in the area to exploit available capacity optimal. Emergency response is time sensitive though. A disaster develops usually progressively, so the effectiveness of the response operation depends on the time of arrival, deployment of emergency responders etc. relative to the

evolution of the scenario. Moreover the development of the threat in time and space determines the possibilities of self-rescue and evacuation. Hence analysis for emergency response unlike the present scenarios for a risk analysis would have to be developed with time functions while one would also be interested in the close-in scenario rather than in the far-field. As a risk analysis for a plant can encompass many tens to hundreds of scenarios it is pretty obvious that for *scenario analysis* a selection has to be made. However what criterion can be used to make the selection: A certain frequency of occurrence level? Another question to be answered is what shall be done if the capacity of the emergency forces, even on a regional basis, will not suffice? Will there be a dialogue with the plant owner to implement additional risk reducing measures at the source? In an early stage of land use planning adaptations are still possible but in already established situations there is less space for manoeuvre. Anyhow, time resolved answers for close-in to the source will increase the models performance requirement.

There is also a tendency to go to fixed routes in which transportation of hazardous substances is channelled, with the idea that the risks over the trajectory can be analysed and better controlled. As a result some identified real vulnerable spots of e.g. higher collision probability or larger population density can be removed. In addition where necessary on e.g. certain parts of highway emergency response stations can be installed (Fabiano, 2005). This will require investments in safety and the question how safe is safe enough will of course be asked again.

To get rid of spread in risk analysis results by prescribing (by law) the use of one particular model, in one particular version with a particular set of model options (SAFETI-NL), Uijt de Haag, 2007 is from a juridical point of view favourable but scientifically unsatisfactory. User influence on the results is this way minimised, but the reality content becomes questionable. It prevents QRA to be used where it should contribute most namely for making operations safer because influence of additional protective measures and of management quality is not included. This holds too for human error of which we have seen the significance. Adaptation to non-standard conditions and to hazardous materials with properties that differ strongly from common ones is in principle not possible. The approach may therefore discourage incentives to improve. Instead use shall be made of better knowledge, progress in IT and computer technology.

Much has already been written about uncertainty in risk analysis. Paté-Cornell, 1996 presented an overview. Main division is in aleatory uncertainty by variability of a known quantity as a result of randomness, and epistemic uncertainty which stems from lack of knowledge on e.g. mechanisms. The first can be treated by objective, classical statistics, the second only by a Bayesian approach of probability as belief (subjectivity) and can include beside classical statistical information other evidence such as expert opinion. Aggregation of the latter in to a distribution is a challenge; there are many hooks and eyes. The classical treatment provides the use of *confidence intervals* (the selection of which is the only subjective element), but most analysts suffice to produce a mean and unfortunately do not bother with confidence intervals. Reliability engineering methods to determine failure rates from observed failure times and the corresponding confidence interval are standard (see Red Book, Coloured Books, 2005). The use of the interval is emphasized in Modarres, 2006.

The physical release models of the hazardous materials are embedded in a software program. For a reliable and reproducible answer the program shall be transparent, verifiable and robust. It means it shall be more than just a black-box. Insight in model assumptions and limitations, which inputs and equations are used where etc. shall be easily obtained. Verifiable means sources of input values shall be traceable, as also the choices made and the reasons why. Robustness has to do with reproducibility. The outcome shall not be dependent on the team performing the calculation. Reliability of software forms a sector of science in itself. In the early '90-ties there has been an EU initiative by the CEC Model Evaluation Group in the field of industrial safety. For heavy gas dispersion this started with a comparison by Brighton, Mercer et al., 1994 of computer codes for instantaneous releases, which earlier had been validated against experiments. Differences in prediction ranged between a factor 3-5. This was followed by the development of an evaluation protocol (Duijm, 1997) and a survey of test data sets and resulted in project SMEDIS (Scientific Model Evaluation of Dense Gas Dispersion Models) lead by HSE, U.K. The protocol distinguished a number of steps of which the main are: assessment of the model with respect to the physics describing the phenomena including aerosols, terrain features – slopes, valleys- and obstacles, verification of its translation in algorithms in the software in the code and validation of the results against test data sets. An example applied on the model PHAST is given in DNV, 2002.

Recently HSE, UK and NFPA in US together assigned Health and Safety Laboratory in UK to apply the SMEDIS protocol on specific LNG dispersion models, see NFPA59A, 2009. For the same reason as in risk calculations spread in model outcomes of LNG vapour dispersion will result in discussion on the size of the exclusion zone around LNG terminal facilities. With the newer developments in CFD and the refinement and improved flexibility of codes the protocol should be applied more extensively to release models in general. It must be remarked that notwithstanding the development and improvement of CFD explosion models, predictions from theses codes in complex offshore and onshore facility geometries appear to lie within a factor of 2 of the experimental data (Bull, 2004). Improving and refining human body response models to damaging threats are also needed.

New activities in risk assessments are both methodological and in application. Methodological is beside the improvements already mentioned above, the introduction of Bayesian approach in statistics. Scenario identification and overview of cause-consequence chain possibilities was already facilitated much by applying the bow tie structure of a combined fault and event tree tied together at the critical event node (ARAMIS project). Also showing the preventive and protective barriers in such directed graph diagrams appears to be very helpful. However, Bayesian Belief Networks can bring larger freedom and flexibility to depict scenario structure while retaining quantification. In case chance and deterministic nodes of a belief net are extended with decision and value nodes to an Influence Diagram it can develop into a self-contained decision making tool.

As already mentioned the Health and Safety Excutive in the UK, (see H.S.E., 2010) develops an effort to improve data on failure rates of on-shore process equipment the way they did before for off-shore installation components. Other initiatives such as the one by the Center for Chemical Process Safety in the US are collecting industry contributions based on their experience. Although these data will be proprietary spin-off has to be expected.

Human factor influences have been object of much study but to make the available information practical applicable for risk assessments for process industry requires further effort. Operator error probabilities have been studied in depth in connection with nuclear safety. Most known for prediction of human performance reliability is THERP, Technique for Human Error Rate Prediction, see Swain and Guttmann, 1983 and Dougherty and Fragola, 1988. The European Process Safety Centre has coordinated the European Union PRISM project about which reports have been presented at the 11th International Symposium on Loss Prevention and Safety Promotion in Prague in 2004. Management has a strong influence on frequency of human error in operation and maintenance, but it is virtually impossible to model. Latent failures and conditions such as wrong design, wrong planning decisions, time and cost pressure, and extreme climatic conditions are even more difficult to account for. It makes sense that usually for risk analysis best practice conditions for failure rates are assumed and effects of human factors in operation are disregarded wherever possible. Yet some modelling attempts have been published. The ARAMIS project has given the influence of quality of organisation and the Human factor a great deal of attention. In the first place Guldenmund et al., 2006 developed an auditing technique to assess the quality of safety barriers in a plant. Underlying are models for the plant's safety management system (SMS), the barrier, and what they called 'recursivity'. Seven SMS 'delivery systems' are distinguished. Barriers have a broader notion than just protection layers. 11 Different types of barriers are distinguished. 'Recursivity', freely interpreted, refers to the cultural phenomenon that values and attitude of the top percolate down through the organization and reflect in the reliability of the barriers. Given the conceptual structure the auditing is on itself straight forward and all the delivery systems rated on 5-point scale producing a nominal value between 0 and 1. As a last step the audit results are quantified to an *M*-index for each barrier type, which is the effect of actual management performance normalized on top performance, hence *M* ranges between 1 and 0. The 11 barrier types are weighted by their influence on the barriers and summed over the seven delivery systems according to the following formula:

$$M_k = 1 - \sum_{i=1}^{7} (1 - D_i) B_{i,k} \tag{5}$$

where D_i corresponds to the ratings of the seven delivery systems and $B_{i,k}$ is a matrix consisting of barrier types (*k* = 1, 2, . . ., 11) distinguished by delivery system influence (*i* = 1, 2, . . ., 7) and containing the weights. The *M*-value is applied as a correction factor and is assumed to have an exponential effect, hence is multiplied with the negative of the 10-based logarithm of the design probability of failure on demand of an equipment component, *PFD*:

$$PFD_{actual} = 10^{-[-\log(PFD)M]} \tag{6}$$

If management performs ideally $M = 1$ and PFD_{actual} is *PFD*, if management is in total neglect $M = 0$ and $PFD_{actual} = 1$. Subsequently, Duijm and Goossens, 2006 derived weight factors for the 7 management 'delivery systems' on the 11 types of barriers. Design values for reliability are a departure point. For most barriers even the worst management will not reduce reliability to zero, while for some barriers reliability may go to zero also under excellent management as a result of design and conditions. The approach allows this result to occur. As already mentioned above the effect on reliability is assumed to be exponential, which is a matter to be further considered. Other approaches assume a linear relation. For a first set of values of weight factors, use was made of databases. The nuclear industry NARA database (Kirwan et al., 2004) was used to estimate the effect of error producing conditions on behavioural barriers. In addition the PRIMA tool (Hurst et al., 1996) developed in work for UK HSE in early 90s to account for the effect of management quality determined by auditing on hardware failure rates. The latter regarded only pipe work failures in process plant. It further involved applying Bayes' theorem to relate cause and management influence to the accident rate as shown in Eq. (7). The probability of failure A given a deficiency in management delivery system *i* of weight B_i is $P(A/B_i)$, while this probability given absence of a deficiency is $P(A/\neg B_i)$, so that the quotient of the two yields M_i the management influence. According to Bayes' theorem holds:

$$P\left(A \mid B_i\right) = \frac{P\left(B_i \mid A\right)P(A)}{P(B_i)} \tag{7}$$

And therefore, because $P(\neg B_i) = 1 - P(B_i)$, the quotient can be obtained as:

$$\frac{P(A \mid B_i)}{P(A \mid \neg B_i)} = \frac{P\left(B_i \mid A\right)}{1 - P\left(B_i \mid A\right)} \frac{1 - P(B_i)}{P(B_i)} \tag{8}$$

Another attempt has been by Hochheimer et al., 2006 in which the human factor contribution in all components over the entire life cycle of a plant was identified and by different questionnaires safety management procedures, management quality and safety culture were rated. It is clear that these approaches need further development to become practical.

To present results of risk analysis more convincingly and more refined improved Information Technology offers new possibilities. Wiersma et al., 2007 showed e.g. how with colours group risk results as function of cell location can be shown on a map output of a GIS (Geographical Information System) in which population density is embedded. The technique will help to find solutions in case at certain spots acceptance criteria cannot be met and population density, hazardous substance transport or storage has to be reduced or distance to the risk source be enlarged.

Sustainable society and reduction of carbon dioxide emissions will bring a shift in the type of fuels, or perhaps better worded, energy carriers used. The fraction of less carbon containing fuels such as natural gas and hydrogen will grow at the cost of the traditional ones such as gasoline. Both methane and hydrogen, although representing extremes in their gas explosion properties, the first as the least reactive and the last as the most, will be comparable in risk of explosion and fire when it comes to large scale storage and distribution plants. Storage of these fuels at large scale has to be under pressure or liquefied when it becomes really massive. Apart from paying attention to security and guarding against risks by acts with bad intent QRA will need to be carried out for land use planning and licensing of facilities. For LNG there is a need of larger scale tests to study the phenomena at release, Koopman and Ermak, 2007. This was confirmed by various contributors to 2nd AIChE/CSChE LNG Topical Conference, "Answering Safe-Siting Questions for LNG Import Terminals" during the 8th World Congress on Chemical Engineering in Montreal, Canada in August 2009. On the various aspects of evaporation by a spill on water, the dispersion of cloud and the thermal effects of a burning cloud there exist considerable uncertainties. Hydrogen is a potential energy carrier replacing gasoline and serving as a fuel for fuel cells. It can be stored under pressure, as a cryogen or absorbed on e.g. a metal substrate. For the time being the pressurized mode is most practicable. Large scale distribution and use will introduce risks with this highly flammable material which has properties differing considerably from hydrocarbons. Various organizations such as the International Energy Agency and the European HySafe in the 6th Framework Program sponsored risk assessment studies. In 2009 results were presented at the Third International Conference on Hydrogen Safety took place in Ajaccio, Corsica France. Another aspect of sustainability is removal of carbon dioxide from flue gases and sequestration, CCS or carbon capture and storage. Carbon dioxide above concentrations of a few percent is toxic; it induces first drowsiness and unconsciousness, while above 10% depending on exposure time it will be lethal. Sequestration in cavities in the underground on land introduces the risk of spills in transport, during compressing operation and from the well. Because it is a heavy gas, dispersion has to be modelled if the release can be close to inhabited areas or traffic nodes. Low wind speed and sloping terrain will make that a cloud at higher concentration can travel considerable distance before being diluted. A complication is the release at pressures above critical, because under expansion part of the carbon-dioxide will solidify and sublimate again once at atmospheric conditions.

Finally, improvement can be made in decision making processes on the basis of risk assessments. For this distinction has to be made between decision making for public safety and in case of optimum investment strategy from a cost-benefit point a view in business, see also Pasman et al., 2009 and Prem et al., 2010.

8. Conclusions and Recommendation

A data base study on the downstream oil process industry revealed that the total number of accidents in the world on average is still on the increase. The annual fluctuations are large. Further decreases the number of fatalities but the number of injured persons grows. An analysis was made of the main cause categories used in the EU MARS reporting system: Process/plant, Organization and Environment which decreased in contribution in this order. It was further tried to delve deeper into the cause-consequence chains. The largest contributor to Process/plant is failing integrity of reactors, vessels and equipment, whereas for Organization it appears that 50% is due to worker error. It was tried to find out which category produced relatively the highest fraction of fatalities. In that respect the number in the category Process/plant is slightly higher than in Organization. By analyzing near misses over a prolonged period the top fifteen root causes in an oil company were found. Top of the list was component failure.

Subsequently, human factor was further analyzed and it was found that more intense training and experience on the job had a reducing effect on the number of injuries sustained. When considering process risks it is essential not to neglect human error.

History shows a growing use of risk assessment applied to process industry. There is however also growing criticism with respect to the large spread in results when different teams do an assessment on a same object. This is due for a large part to differences in details of scenario generation, incompleteness and inaccuracies in models (source terms, dispersion models) and data (failure rates and ignition probabilities). For legal use in land use planning and licensing standardization is a way out but for making a plant safer or for emergency planning realism is more important.

Concluding it can be stated that we shall not give up reducing uncertainty in risk analysis. Most difficult but most important will be scenario development to include sufficient detail realism on human error, management quality, possible escalation and domino effects. New modelling techniques such as Bayesian Networks may help. Consequence models can be improved. CFD refinement is there now. There are a number of tools to scrutinise existing models better. The idea of SMEDIS can be extended over a wider range of models. Further (field) tests can help to fill knowledge gaps. Effort on human body response shall be increased. The scientific community should make a plea to top management and governments that much resource is wasted in fighting each other over fuzzy analysis results if investment in further knowledge development stays behind. ETPIS (http://www.industrialsafety-tp.org) is a platform to carry this message to the European Commission in Brussels.

Next is the problem of the formulation of criteria for decision making, which shows a national diversity in Europe with respect to public safety, which hampers comparison and a more uniform regulation. A European Working Group on Land Use Planning tries to improve the situation.

Finally, it was tried to give a perspective of promising developments in methodology and of applications required by the change in energy sources for reasons of sustainability. Cooperative efforts on e.g. a European scale are highly needed to give relief to the larger demands in a more complex and economically striving society which puts a high value to overall safety and security.

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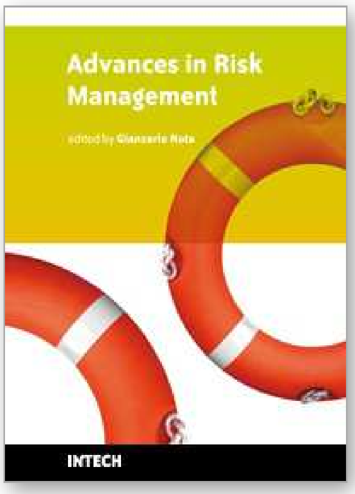

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Risk management is an important part of governance sciences and has applications in several domains ranging from enterprise risk management to environmental surveillance. The ideas and approaches described in the book deal with general aspects of risk management as well as the peculiarities arising from given application domains. With contributions from researchers and practitioners in different fields, Advances in Risk Management will provide you with valuable insights into the evolution of models, methodologies and technologies necessary for an effective implementation of risk management systems.

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