Trends, problems and outlook in risk assessments: Are we making progress?

Hans J. Pasman, the Netherlands
hjpasman@gmail.com
Bruno Fabiano– DICheP University of Genoa, Italy
brown@unige.it

Process industry brings economic activity and provides us with unique materials. Inherent to it are risks of loss of containment of hazardous substances and the ensuing risks of explosions, fires and toxic spread. 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. The paper will review the state of the art and will call for improvements.

1. The advance of application of risk analysis

With the development of amongst others crude-oil based petrochemical industry in the late ’60-ties of last century large-scale chemical plants were built in areas with easy access to sea and inland waterways, mostly harbours, to enable transportation of feed stock and products and to find people to run the plants.

After several catastrophic accidents, mostly explosions, but also fires and spread of toxic clouds safety concerns arose, which with rising prosperity and consciousness of people over time grew. Risk analysis as a methodology to describe and delimit the risk of chemical process operations was introduced in the mid-seventies to the then newly founded community of Loss Prevention in the process industry. The methodology borrowed from the nuclear industry, was seen by some as a panacea but initially stirred up endless discussions and controversy based on misunderstandings on contents of concepts and differences in definitions. Also, from the start there was an apparent dichotomy *qualitative* versus *quantitative*. In 1980 ‘human factor’ became an issue and with good reason many did not believe this could ever be quantified. Moreover a qualitative search for the hazards in a hazard identification step is indeed half the work. The HAZOP method to that end became immensely popular. Quantification is afflicted with uncertainties and where failure of components is stochastic, the determination of risk as a product of damage and likelihood requires a probabilistic approach. Some argued that in safety, where human life may be at stake, once a possibility of mishap was identified, an improvement to the process should be made or an additional safety measure installed. On the other hand a large quantity of stored chemical as existed on quite some places after the scale-up of the industry in the ’60-ties, forms an undeniable hazard potential. The protection of the public at large requires therefore safety distances to such risk source, which can extend to far outside the plant’s premises despite all safety measures taken. So, quantification of possible effects is a minimum requirement.

However, over the years economic activity and habitation development needed more space, everywhere. As long as space is not a scarce item safety distances work. Risk quantification can take into account preferential directional effects and weigh the chances of occurrence. This enables assessment of the risk versus the benefit of use of land. No wonder that in densely populated industrial areas as in The Netherlands risk analysis as a tool for land use planning and licensing of plant became so widespread.

Quantification of effects had to be done anyhow, so in the second half of the’80-ties quite some countries initiated research projects to experimentally investigate and model so-called source terms: one- and two-phase outflow of pressurised or cryogenic liquid substances, evaporation of jets and pools formed on different substrates (water, soil), rain-out, dispersion of cold, dense clouds in time and space under different atmospheric conditions. Also radiation intensity of different kinds of fires (jet fire, pool fire, flashing flame, flame ball) was measured and modelled, vapour cloud explosions simulated and boiling liquid expanding vapour explosions (BLEVE) from a bursting tank with pressurised liquid heated by e.g. external fire investigated. The Research Directorate of the European Union got involved and the Europeans could do some cooperative work on gas dispersion and vapour cloud explosion that had body compared also with the field tests sponsored by the Department of Energy in the United States. In the early ’80-ties TNO assigned by the Dutch government, composed the series of ‘Coloured Books’, latest edition 2005, and developed the software package EFFECTS (TNO, 2007). Damage expressed as fraction of exposed people killed or extent of damage to structures given a threat intensity level was collected in probit relations.

Meanwhile at various places computerised risk analysis had been developed making use of the physical data and models. Most known became the commercial package of DNV SAFETI. Risk outcome is first of all the probability per year of an (unprotected) person being killed when permanently exposed on a certain location relative to the risk source - *individual risk*, or as a measure of societal disruption the number of people living locally which will be instantaneously killed – *group risk*. In a number of countries quantitative criteria to assess risk figure outcomes were developed for land use planning and also for licensing. Cozzani et al., 2006 describes a comparative case study. In general a probabilistic approach results in use of less land for safety zoning than fixed effect distances and hence is more economic.

After the tragic Bhopal disaster in 1984 and later the Piper-Alpha oil rig calamity in the North Sea in 1988 process safety got a boost all over the world and risk analysis got applied more generally. Beside the communities sticking to a qualitative approach by conviction, people using QRA discovering drawbacks and weaknesses uttered criticism. Analysis reports to convince competent authority to issue a licence were often actually drafted by consultants and after obtaining the license not used anymore in the company to improve safety, although continuing improvement is a cornerstone of the safety management system. Uncertainty in the methods and controversy between analysts undermined trust. In people’s perception low probability is overshadowed by potential large effects. We shall now first consider some recent developments in the methodology before we shall analyse weaknesses and failures of QRA closer.

2. Recent improvements of the state of the art

Hazard & Operability study, HAZOP (Crawley, 2000) and related methods such as ‘What, if’ had proven their merit since the early ’70-ties. Going through a plant’s Piping and Instrumentation Diagram by section and answering in a multidisciplinary team continually the same guide word questions is time consuming and tiring and may miss the overall top down view. However it identifies hazardous situations and initiating events, and hence provides triggers for improvement, but not a conceptual structure.

In the middle of the ’90-ties in the United States Layer of Protection Analysis, LOPA, (CCPS, 2001) was introduced to the process safety community as a simplified risk assessment tool. It became in a short time very popular in industry. This was also because it fitted perfectly together with the new standard IEC 61511 specifying levels of reliability of Safety Instrumented Systems (Safety Integrity Levels) for reducing various categories of risk to a tolerable value. LOPA is examining the functioning of safety measures in a process section given an initiating event which progressively would upset the system. A layer is defined as a subsystem (sensor, processor, actuator) counteracting the process deviation and trying to get the process back in a safe state. Once a layer fails the next will come in action. Given an installation the team performing the HAZOP and identifying the most probable and serious initiating events can carry out subsequently one or more LOPAs also involving the operating crew, to check the adequacy of present safety measures or ones additionally to be installed. Carrying out a LOPA is less simple than it looks, since common cause failures of the layers shall be excluded. Depending amongst others on the degree of hazard of the substances involved a target frequency of final tolerable unreliability can be specified. As the defined layers are independent, overall failure frequency can be easily found by multiplying the supposedly known (!) unreliability values of subsequent layers. One can go a step further and draw an event tree with at each branch the damage produced given previous layers failed. Making use of a risk matrix and defining a target line of consequence-frequency combinations permits rather simply, given the data are available, to set-up a cost-benefit assessment and helps to answer the question how safe is safe enough, Pasman et al., 2004.

In 2002, after the Toulouse ammonium nitrate explosion, an EU-project was initiated led by Salvi and Debray, 2006 called ARAMIS, Accidental Risk Assessment Methodology for IndustrieS with the purpose to shake up the bed and have a new start. The advantage of the method is the very systematic way it is set up and is developing scenarios. ARAMIS offers structured hazard identification for process installations by introducing the concept of the ‘bow-tie’: a combined Fault tree (90^o clockwise rotated) and Event tree with the critical event in the connecting centre. In the bowtie safety measures are shown as barriers. ARAMIS contains example trees and suggested pipe, tank and other failure figures. Identification can be further elaborated by the Belgian software PLANOP, 2005. ARAMIS also considers quality of management and its impact on the overall safety, although quantification has to further develop. It splits risk in three components: intensity of the damaging phenomenon, frequency of occurrence and vulnerability of the environment. The first two combine in severity. This enables one to consider for an installation various locations without having to repeat the whole calculation, but only the location specific part. By applying a Geographical Information System (GIS) results can be presented for concrete areas and the 'hot' spots immediately show up. Damage is covering various categories of people, e.g. workers, locals, by-passers and people in public places, and further categories of structures and environment. Aggregation of the results is via indexes of severity and vulnerability in which various contributions weighed by a factor are accumulated. The 195 weighing factors have been determined in a multi-national, questionnaire based multi-criteria exercise. Disadvantages are – again – the lack of data on e.g. management effectiveness and the amount of effort needed for the analysis. The latter is due to the refinement. The project did not develop any new consequence models but relies on existing ones. So far, few results on concrete cases have been published, hence it is difficult to judge how much gain the method can bring.

3. Negative experiences: Spread in QRA outcomes

In the early '90-ties the reliability of risk calculation results was tested by an EU benchmark exercise having a number of groups analysing risks of the same ammonia plant, Amendola et al., 1992. The spread in outcomes appeared to become an Achilles heel of risk analysis; in Figures 1a and b results are shown of the dispersion calculation and individual risk as a function of distance. The risk figures are in principle averaged over the affected surface area, but some models did not have the capability to calculate that value and only produced the centreline value. In EU project ASSURANCE, Lauridsen et al., 2002 a similar exercise has been performed on an ammonia storage plant with loading/unloading operations. Although spread in results had improved, the root problems of spread had not been solved. Individual risk contours differed by at least a factor 3 in radius, which expressed in area is very large; group risk differed over 2 orders of magnitude. In Table 1 the relative importance of various contributing sources of uncertainty are summarised.

The largest contribution to uncertainty is the variety in the definition of the scenarios. Project ARAMIS tries to cure that situation. Failure frequencies are a known bottleneck from the beginning of risk analysis. The bulk of the data in data banks such as that of

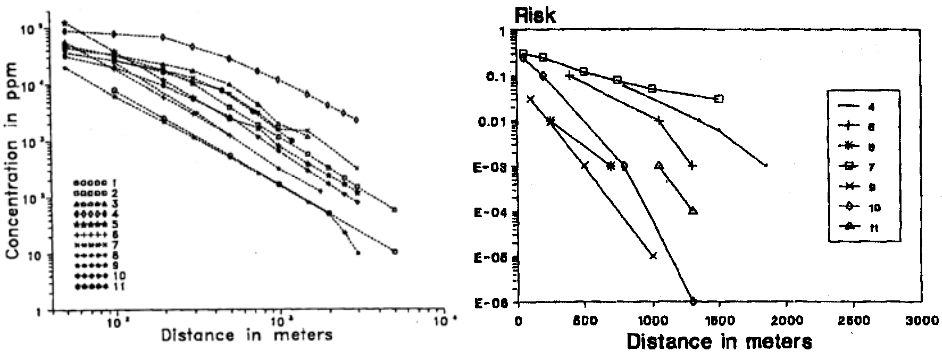

Figure 1a and b: EU benchmark exercise to investigate uncertainty limits in risk assessment. Left: Application of various gas dispersion models on a liquid ammonia release scenario. Plotted is the calculated ammonia concentration as a function of distance 15 minutes after the release. Right: Calculated individual risk as a function of distance (Amendola et al., 1992).

Table 1. Qualitative assessment of the importance of various factors to the uncertainty in the calculated risk (the more stars the more important): project ASSURANCE, Lauridsen et al, 2002.

Factor	Importance
Differences in the qualitative analysis	**
Factors relating to frequency assessment:	
Frequency assessments of pipeline failures	***
Frequency assessments of loading arm failures	****
Frequency assessments of pressurised tank failures	****
Frequency assessments of cryogenic tank failures	***
Factors relating to consequence assessment:	
Definition of the scenario	*****
Modelling of release rate from long pipeline	***
Modelling of release rate from short pipeline	*
Release time (i.e. operator or shut-down system reaction time)	***
Choice of light, neutral or heavy gas model for dispersion	****
Differences in dispersion calculation codes	***
"Analyst conservatism" or judgment	***

CCPS and OREDA are proprietary. The Purple Book (Coloured Books, 2005) offers a basic set though. A third category causing spread is consequence modelling (release rates, evaporation, dispersion and the probit damage models). In the previous CISAP-2 conference Ditali et al., 2006 have shown examples of how outcomes of pure physical models of release, vaporisation and dispersion can differ with at least a factor 2. In Table 2 because of reasons of space a small part of their results as typical example is reproduced while results of a next version of TNO EFFECTS 5.5 are added, not making the overall picture better. Damage probit parameters are also object of much discussion.

Table 2. Hazardous substance loss of containment effect calculations with various models. Some example outcomes from Ditali et al., 2006 with results added of TNO EFFECTS 5.5 (TNO, 2007)

Release case	**Variable calculated**	**EFFECTS4**	**PHAST**	**GASP**	**EFFECTS 5.5**
Toluene confined pool	Max evap. rate, kg/s	0.21	0.15	0.11	0.21
Toluene unconf. pool	Max evap. rate, kg/s	3.5	1.2	1.1	3.5
	Max. pool area, m^2	2005	995	1042	2000
LNG on water	Max evap. rate, kg/s	166	273-197	147-32	Avg 169.5
	Max. pool area, m^2	387	1451-1520	804-1256	385
		STERAD	**PHAST**	**Int-HSE**	**EFFECTS 5.5**
2-Phase jet fire	Surface Emissive Power, kW/m^2	230	151	184	81
		DISPGAS	**PHAST**		**EFFECTS 5.5**
Dispersion dense gas (10 wgt% H_2S)	Vertical max. dist. 100 ppm H_2S, m	625	275		367 (1695)
	Hor. max. dist. 100 ppm H_2S, m	150	205		372

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.

4. Future increase of demand

Requirements will become more stringent. People will not tolerate risks, 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 is quite a burden on the fire brigades which traditionally have 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 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. However, data barely exist.

Analysis of emergency response effectiveness is already needed for providing facilities in the area to exploit available capacity optimal. However emergency response is time sensitive. A disaster develops usually progressively, so the effectiveness of the response operation depends on the time of arrival, deployment 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. As a result some identified, real vulnerable spots can be removed and in addition where necessary on e.g. certain parts of highway emergency response stations be installed. This will again require investment and the question how safe is safe enough will for sure come. With the new threat of terrorist attack this becomes more urgent. New fuels/energy carriers such as LNG and hydrogen do not make it any easier. For LNG there is a need of larger scale tests, Koopman and Ermak, 2007. For hydrogen the EU is active with the HYSAFE programme.

5. How to further improve the methodology

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 scientifically unsatisfactory. User influence on the results is this way minimised, but the reality content remains questionable. The approach may further discourage incentives to improve. Instead use shall be made of better knowledge, progress in IT and computer technology. The latter should not only be used to present results more convincingly but also more refined. 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 in which population density is embedded. The technique will help to find solutions in case criteria cannot be met and population density, hazardous substance transport or storage has to be reduced or larger distance to be kept.

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) and already described clearly by Buffham et al., 1971. The use of the interval is emphasized in the book of Modarres, 2006.

Models 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 is given in DNV, 2002. With the newer developments in CFD and the refinement and improved flexibility of codes as for example in FLACS (Dharmavaram, 2007) this should be picked up again. Improving and refining human body response models to damaging threats is much needed.

6. Conclusions and Recommendation

Concluding it can be stated that we shall not give up reducing uncertainty in risk analysis. 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 to Brussels.

7. References

Amendola A., Contini S. and Ziomas I., 1992, J Hazardous Materials, *29*, 347-363.

Brighton P.W.M..., Mercer et al., 1994, “Comparison of heavy gas dispersion models for instantaneous releases”, Journal of Hazardous Materials, *36*, 193-208.

Buffham B.A., Freshwater D.C., Lees, F.P., 1971, IChemE Symp Series **No.34**, 87-98.

Coloured Books, 2005, PGS 1– 4, http://www.vrom.nl/pagina.html?id=20725.

TNO, 2007, http://www.tno.nl ; Search for EFFECTS.

CCPS, 2001, Layer of Protection Analysis, Guideline AIChE, N.Y., ISBN 0-8169-0811-7.

Cozzani V., Bandini R., Basta C., Christou M.D., 2006, Application of land-use planning criteria for the control of major accident hazards, J. Haz Mats, *A136*, 170-180.

Crawley F., Preston M. and Tyler B., 2000, HAZOP, IChemE, ISBN 0 85295 427 1.

Dharmavaram S. and Hanna S.R., CFD Modelling, 12th Symp Loss Prev, Edinburgh, U.K., 22-24 May.

Ditali et al., 2006, Consequence models assessment, Chem Eng Trans 9, p. 177-184.

DNV, 2002, Search for SMEDIS report, via http://www.dnv.com/search/index.asp

DNV SAFETI, http://www.dnv.be/consulting/safetyhealthenvironment/software/safeti.asp.

Duijm N.J., Carissimo, B., Mercer, A., Bartholome C., Giesbrecht H., 1997, Development & test of eval. protocol for heavy gas disp. models, J. Haz. Mats, *56*, 273-285.

Koopman R.P. and Ermak D.L., 2007, Review LNG, J. Haz. Mats, *140*, 412-428

Lauridsen K. et al., ASSURANCE project, www.risoe.dk/rispubl/sys/syspdf/ris-r-1344.pdf.

Modarres, M., 2006, "Risk Analysis in Engineering", Taylor & Francis.

Pasman H.J., Trieling W.B., Schupp B.A., Lemkowitz, S.M., 2004, Some Recent Developments in Proc Saf Tools- Part I. LOPA, CISAP-1, Chem. Eng. Trans, Vol.5, 1-6.

Paté-Cornell M.E., 1996, Uncertainties in RA, Rel. Eng and System Safety *54*, 95-I 1 I.

PLANOP, 2005, http://www.planop.be/.

Salvi O. and Debray B., 2006, A global view on ARAMIS, J Haz Mats, *130*, 187-199.

Uit de Haag P., 2007, QRAs for Dutch installations, 12th Symp Loss Prev, Edinburgh, U.K., 22-24 May.

Wiersma T, Boot H. and Gooijer L., Societal Risk on a Map, 12th Symp Loss Prev, Edinburgh, U.K., 22-24 May.