Safety, Reliability and Risk Analysis: Beyond the Horizon – Steenbergen et al. (Eds)
© 2014 Taylor & Francis Group, London, ISBN 978-1-138-00123-7

Better science does not make decisions easier

Ben J.M. Ale
Emeritus Professor, TU Delft, The Netherlands

ABSTRACT: Forty years of development in the science and technology of estimating and quantifying risk, of understanding of human behaviour and human rationale has made decision makers more informed. We are in a much better position now, than forty years ago in estimating probabilities, consequences, and damages, and in estimating and dealing with the associated uncertainties in an organised way. This did not take away the fundamental questions about the acceptability of activities bearing risk. It did not take away the differences between people and groups of people and it did not take away that these decisions are difficult.

1 INTRODUCTION

In 2003, now 10 years ago, I said in a lecture for the ESREL 2003 conference: "a bonus based on sales or throughput has the effect of rewarding taking risk" (Ale, 2003).

Never could I have imagined then that the financial industry would provide proof even more than the chemical industry ever had and that the world would be plunged into a financial crisis by bonus driven sales of mortgages that could not be paid back and financial products that have all the characteristics of a pyramid game. That does not mean that the financial crisis could not have been expected and therefore was and is anything but a "Black Swan". But that is for later. For now let us look at where we stood at the beginning of my almost forty years in the risk business and where we stand today.

Four states of competence of a person can be distinguished as is often attributed to Maslow: Conscious incompetence; Conscious competence; Unconscious incompetence; Unconscious competence. These states have been rephrased by Secretary of State Ronald Rumsfeld as states of general knowledge using the terms known unknown, known known, unknown unknown and unknown known. I would add a fifth state: the no more known. In the forty years I spent in risk analysis and risk management we have gone through all these stages and now, our knowledge and our science can be in any of these stages as we will see below. There is nothing really wrong with any of the first four stages, although it may be more comfortable if we knew everything and were aware of all our knowledge. But such is the state of human mind. More worrying is that acquired knowledge is disappearing. Knowledge that is not obsolete and irrelevant, but still is necessary to keep our systems going and risk under control.

There has been a time without internet and without tablets or personal computers. A time when information travelled slowly, accidents became known only to a limited number of people and often long after the event. Where conferences such as these were the medium to exchange this information and papers were typed on typewriters. Forty years ago, a number of nasty accidents, explosions in the United Kingdom and in the Netherlands, BLEVEs in the United States and ammonia accidents in South Africa and Mexico, which killed tens of people and damaged large areas, gave rise to the feeling that something needed to be done. The material damage was beyond anybody's expectation. We started to wonder what we could do and how, to reduce the impact of these accidents. Apparently there was more to building a chemical factory than classical chemical and physical engineering, to take a successful lab experiment and make the setup big.

There was not much public outcry yet. Yes there were the public enquiries and local action groups. But all was still localised and small. But it was soon recognised that the chemical industry could follow the Nuclear Power industry, where the debate on the acceptability was already hot. So the efforts to contain the risks were as much aimed at self-preservation of the industry as at protection of the environment and the population.

We did not know much about potential effects of explosions and toxic clouds. In fact, unconfined vapour cloud explosions should not happen, they were physically impossible. There also was only little statistical data on failures of equipment, and these were often in reports by of for governmental agencies and therefore not widely accessible, such as data on the failure frequency of pressure vessels (Philips & Warwick, 1969; Smith & Warwick, 1974).

Thus we were in the stage that we knew we did not know enough and that any attempt to get to grips with these events, either by technology or by policy should be preceded by acquiring additional knowledge and skills. The European Federation of Chemical Engineers, who had a Working Party on Loss Prevention started the Loss Prevention and Safety Promotion Symposia, the first of which was held in 1974 in Delft, The Netherlands. The search for methods to assess hazards, consequences, failure probabilities and risks was a European and often co-operative effort. This does not mean that industry, authorities and population agreed on the path to follow. The latter has been discussed in many papers, so I let that subject rest.

Luckily the nuclear power industry had faced similar problems and the Nuclear Regulatory Commission of the US issued the reactor safety study (Rasmussen, 1975), which gave the pathway to develop a similar analysis scheme for the chemical industry.

2 DAMAGE ESTIMATION

In the search for knowledge and methods we embarked on the first step, which was to design methods to estimate the potential damage. The estimation of damage started with simple correlations such as Vic Marshalls (1977), estimate of 1 death per tonne of exploding hydrocarbon and 0.5 death per tonne of toxic. These are still being updated (Garol et al, 2001). But soon the efforts of Norman Eissenberg et al (1975) of the US coast guard found their way to Europe. The vulnerability model was the first comprehensive methodology book for chemical hazards, be it on sea, which also had computer programmes associated with them. These were all in Fortran and not or not readily available, but at least there was already something. This convinced the Dutch authorities that an organised methodology was possible.

Two lines of research were set up by the Minsitry of the Environment. One to establish whether one could get results that were useable in decision making especially in the Netherlands, and one to establish, formulate and document methods to estimate consequences.

The COVO study was to investigate whether meaningful results could be obtained from a calculation of risk. This study resulted in a report (Cremer and Warner, 1981), which was later printed as a book and a long discussion between the authorities and the industry. This discussion had components of science and technology, especially regarding the estimation of the initial frequencies and the behaviour of dense vapour clouds. It also had components of policy, because after every stakeholder, including industry, having done their best efforts to get to a realistic estimate of the risk, the results for the disaster potential of these six industrial activities was already high, when compared for instance with the risks of floods in the Netherlands. Obviously industry did not like this to be common knowledge and the societal risk results have been kept a secret for some 5 years or so, by which time the calculation of risks and the publication of the results had been made obligatory.

At the same time efforts were underway to document the methodology to be used in the Netherlands. These efforts resulted in the now familiar coloured book series. The yellow book describing methods to calculate effects, the red book describing methods for calculating probabilities and the green book describing methods for calculating damage (CPR14, 1979; CPR12, 1985; CPR16, 2005; Ale & Uitdehaag, 1999).

The yellow book was the first to see the light. After the initial refusal of industry to share their knowledge with the authorities, the book was issued by the ministry of labour in 1978. There were many deficiencies in this first attempt. Since the authorities announced that they would use the yellow book in the future as their method to assess the potential effects of an installation and use the results in permitting, the industry realized that a common effort would lead to much better methods and better methods were also in their advantage. The red and green books came much later, after a computer based system for quantified risk analysis for use in the Netherlands—and the rest of the world as it turned out to be—was developed.

3 COMPUTER PROGRAMMES

The yellow book came with supplementary preprogrammed memory cards for the HP65 hand held calculator, but with these the steps of the calculation could only be done one at the time and a complete risk analysis took ages. Therefore it was decided to have a computer based system built that could do the calculations and the bookkeeping associated with the risk analysis of a chemical plant automatically, once a description of the plant and the parameters of the calculation and the models were given. The general idea was that once this could be done, there would no longer be a need to the severe restrictions on numbers of scenario's. Without that restriction a much richer picture of the risk could be generated, that would also allow the results to be explored for potential risk reducing measures. For this purpose the minimal granularity of the program would be length of pipe of 10 m and individual vessels. In that way specific pieces of equipment could be identified as primary sources of risk, when appropriate, and suitable measures designed. This project started in 1981 and led to the first edition of SAFETI in 1984 (Technica, 1984).

The initial version already had 400000 lines of Fortran code, so a main frame computer was needed to run the programmes. In that time the development of personal computers was sufficiently advanced to release the effect calculation programmes as a separate package. This package, WHAZAN, was released in 1985 (Technica, 1985).

This program was later released as PHAST, in a project initially funded by Rohm and Haas. The programmes were subsequently further developed and integrated in a single package, when computers were sufficiently developed to handle large integrated programmes. Other consultants, such as TNO (TN, 1996), followed to release similar programmes, based on the coloured books.

4 HEAVY GAS DISPERSION

A major and unsolved problem was the behaviour of clouds denser than air. Since it were these sort of clouds that gave rise to the large explosions and the large toxic disasters it was necessary to sort out their behaviour major research efforts were aimed at understanding the behaviour of clouds heavier than air. In international consortia involving a large number of European and Amercan institutions large scale tests were conducted. (McQuaid et al, 1984). This resulted in a series of ever improving models (Witlox, 1994, Puttock et al, 1980).

These were all integrated in the so-called Universal Dispersion Model (UDM) found its way in later releases of the software (Witlox & Holt, 1999).

However, the problem of dispersion of these gases in urban areas, also known as the street canion problem, still is not adequately solved and the physics that make these clouds explode catastrophically remains equally unsolved as became clear after the Buncefield explosion (HSE, 2009).

These are areas of known unknowns. Estimates for the toxic effects of large scale releases of toxics like ammonia, chlorine or acrylonitrile remain extremely unreliable. For the effects of flammable clouds the assumption that these clouds do not explode over flat terrain has been largely replaced by the assumption that they do. It would be better to assume a probability distribution in the range no effect—explosion. This is already possible by performing a number of calculations representing a discrete distribution, but in the near future using continuous distributions will be possible.

For the remainder of the consequence calculations we are pretty much in the known known area, at least in the area's that are relevant for the risks outside the fence of the establishments.

It made sense to derive the plant related input directly from the design drawings of a plant. The project was defined in 1989, but was completely beyond the capabilities of a computer system a ministry in the Netherlands could afford. Thus this project was abandoned, to surface in another form in 2010, in an on-going experimental project by TU-Delft for SHELL, in which it is attempted to use the equipment database of a plant as direct input in a programme to construct a Bayesian Belief Net with which the risks of a plant can be evaluated, as will be discussed later.

5 PROBABILITIES

Now that a system was available for use on a daily basis, and on faster and faster computers, the problem of establishing the initial probabilities became more and more pressing. The Fault-tree handbook was issued in 1981 (Vessely et al, 1981) which documented the fault-tree methods and helped in estimating the effect of interdependencies. Data on failures however remained scarce. The Norwegian Petroleum Directorate (now: Petroleum Safety Authority) initiated the OREDA Project in 1981. The primary objective was to collect reliability data for safety equipment. The objective of OREDA was subsequently expanded to collect experience data from the operation of offshore oil & gas production facilities to improve the basic data in safety and reliability studies. The companion project assembling on shore data did not yet lead to a similar database. There are sources of data such as the AMINAL guidebook (AMINAL, 2004).

But the sources of these data are only a limited number of papers such as the one by Smith and Warwick and expert judgements in committees 25 years ago. New attempts such as described in Beerens et al (2006) and Laheij et al (2012) did not produce any better numbers.

Therefore these numbers remain uncertain and between known and unknown.

6 HUMAN PERFORMANCE

Because it soon became clear that human behaviour had a lot to do with failures of equipment and the occurrence of accidents. It also became apparent that human behaviour was heavily influenced by the management of an industry.

Attempts to estimate the probability of human error were conducted by Swain & Guttman (1983) to be followed by Reason (1990) and Dekker (2006).

The first attempts to incorporate these management effects in the risk estimation was by means of management factors on the end result (Ale et al, 1998), followed by modification factors on the base frequencies. A better understanding of the drivers of human behaviour (Reason) and the way companies are managed (Hudson) lead to more sophisticated models including performance shaping factor, delivery systems and safety barrier maintenance models (Papazoglou et al, 2003; Ale et al, 2006).

7 UNCERTAINTIES

From the beginning there was the problem of what is loosely called uncertainties. There are, as is well known different types of uncertainty, which may or may not be expressed as or translated into distributions of the values of parameters and variables around a central estimate. I will return to the more fundamental uncertainties, such as the known unknowns later. The problem with these uncertainties in the decision making process was and is, that stakeholders try to use this in their advantage. The advocates of certain technologies use the uncertainty to argue that the real risk is not as bad as the calculations show. The opposition does the opposite and uses uncertainty as an argument to show that the real risk is much worse. Therefore it was desirable from the beginning to take these uncertainties into account. In the early softwares this was done by repetitive calculations. The more common—and much less expensive—calculation methods used a limited number of scenarios. The method used in the Netherlands calculated a range of values for variables such as source strength, weather conditions and location of release, to simulate the variability of these parameters. What could not be taken into account was the uncertainty in the estimates of the base frequencies, although it was no secret that the statistical or historical foundation of the numbers was sometimes weak and sometimes the result of an afternoon negotiation between experts. In the course of time caveats and conditions that were associated with the use of these numbers and which were carefully written down in the reports were forgotten to the extent that for instance taking measures to reduce vibration was used to reduce the standard frequency of vessel failure, while the number was conditional on the absence of vibrations to begin with. The knowledge of these conditions and caveats in old reports could by now be classified as the unknown knowns, but better as the one time knowns. All the knowledge acquired, cumulated and documented in sources that are not on the internet or in the cloud, such as paper and floppy disks in formats that cannot be read on any present computer. The knowledge, the existence of which resides in the heads of pensioners or soon to be pensioned oldies, such as me, and which is already in the process of being forgotten.

That does not take away that these uncertainties can be treated as additional information influencing the estimate of the risk. A distributed parameter has a probability of being bigger or smaller that its central; estimate and even when the maximum knowledge is that the parameter is bounded between certain values and but it is in that range is unknown (and therefore its distribution over these values uniform), it can be treated inside a risk calculation, improving the estimate of the risk taking account of these uncertainties, rather than keeping them out of the calculations and just discussing them. Keeping them in the calculation has the additional advantage that the effects of "fat tail"- distributions show up in the results. Obviously using discrete calculations to cover all these ranges of values for all parameters involved is just a theoretical possibility even with todays computing power. Therefore the development of method to handle continuous distributions inside the mechanics of BBN, as was done for the first time in the CATS project was a major step forward in dealing with these uncertainties rigorously.

The unification of all these: technical failures, human behaviour and, management influences and the variability of nature became possible when the computational efforts associated with automatic generation of fault-trees and the large scale use of Bayesian Belief Nets became possible. This took away the need to work with single point estimates for the parameters and variables in the modelling, including the estimates for the frequencies. Taking the variability of the into account earlier only was possible by sheer endless repetition of the calculations. This resulted in the quantification of occupational risks (WORM) of air traffic risk (CATS) and currently the quantification of risk in chemical plants including the uncertainty in the estimates (Ale et al, 2006a, 2008, 2009). The realisation that normal accidents (Perrow, 1984) were the materialisation of a combination of extreme, rare but possible values of variables, including the variability of human behaviour led to the attempt to use distributed initial frequencies rather than point estimates. In the CATS project it proved to be possible to do so without a numerical explosion using non-parametric continuous distributions for the base frequencies. Although CATS has fallen victim to the world financial crisis, the work could be continued with support from SHELL, leading to the Platypus project. In this project a technique was developed and demonstrated to use that installation data from an installation, combine it with the models for failure of hardware, software and people-ware as mentioned before and calculate the resulting risk. In this calculation the risk posed by lack of knowledge is included in as far these are not the so-called unknown unknowns, about which later.

8 THE OMINOUS F-N CURVE

With the development of risk analysis techniques came the question about what manner of representation would be suitable in the decision making process, given that it was already accepted that just the average for Probability Times Consequence was insufficient. For events with large consequences, the probability has to decrease disproportionally, for the utility of the result to remain the same (Rowe, 1974; Bernouli, 17380; Howard, 1966; Swalm, 1966, Huber, 1990). For the release size of losses of containment the possibilities between no failure and full instantaneous failure are infinite. In order to keep any calculation to a manageable size usually a limited number of scenarios where selected for which the effect and damage calculations were performed. These scenarios were considered representative for the whole of the installation or plant under consideration. The estimated total probability of failure was then divided over these scenario's, this lead to very unstable presentations of the results, when plotted in an f-N diagram. When the frequency of the event was plotted against the number of people affected or the damage, a cloud of points resulted, the shape of which depended heavily on the initial choices of the size of the classes of incidents the scenarios stood for. Luckily Farmer (1967) already had made the FN curve an instrument for making societal risk more amenable for decision makers. Governments do not like to be inventors. Therefore the much more stable representation of societal risk in the form of a complementary cumulative distribution curve, the now familiar FN curve, was chosen. It should be noted in passing that many of the risk matrices going around are not cumulative in f (http://www.cgerisk.com/). For the use of these matrices the attribution of frequencies to the scenarios and the definition of the scenario classes can make a significant difference in the severity score, which is often preset.

9 RISK PERCEPTION

In another corner of the risk science landscape we were busy trying to understand what motivated the population in general and surrounding population in particular in their judgement of hazardous activities. This understanding was and is necessary when one wants to make decisions that are acceptable for the population or when one want to develop a general policy aimed at protecting people against undue risk. In these decisions risk is only part of the consideration, the others being among other the desirability of an activity, the stakeholders for and against, and at the bottom line, money. In the Netherlands a general policy was especially needed because free ground is scarce and there is a constant pressure on developments of housing and of industry to encroach on each other. Studies performed in the Netherlands by Vlek & Stemerding (1984) and by Stallen & Thomas (1986) confirmed the findings by Slovic et al (1987) in the US that individuals have their own internal weighting system for all sorts for criteria that play a role in their final judgement. Over the years several attempts have been made to produce a definitive list if these attributes of risk and make them part of the definition of risk, with the aim that a more positive score on the combined attributes and thus on the risk would be a predictor for the final societal verdict on the acceptability (Schoot-Uiterkamp & Vlek, 2007). But the rationalities behind the judgement on risk are just as diverse as in other decision problems and politics in the end seems to be the only method or process to resolve these issues.

Attempts have been made to rationalise risk decisions by reducing them to the economic question of how much money people are prepared to save their environment, their health and the life. The ALARA principle already has substantial characteristics of a cost benefit approach. In determining what is reasonable the benefits do not have to be expressed in monetary form. There is increased pressure to try and express all the benefits and all the costs in a single easily comparable unit: money. This moves the problem of weighing different aspects on a case by case basis towards the more general problem of determining the monetary value of various qualitative aspects of both the cost and the benefit side of the balance. The weighting process for each case than reduces to a cost-benefit balancing process (Helsloot et al, 2010). There are great advantages attributed to this approach in the context of a market economy because it makes safety from an ethical concept into a good with a price worth paying. However; there are also significant problems.

As far as the value of human life is concerned a continuous stream of efforts has been made to deduct a number. Several attempts have been made who all have their specific—ethical—drawback (Morall, 1986; Morall, 1992; Tengs et al, 1995; NN, 1995; Pikaar & Seaman, 1995).

If the earning power is used (Morall, 1986) the question arises how to deal with pensioners and the—currently—unemployed. If the number of life years lost how to deal with the question of putting the elderly or the young in specific hazardous situations. The notion of Quality Adjusted Life Years (QALY) brings the question of the handicapped or challenged against the healthy. In terms of expenditure per life-year the numbers range from 0 to 99*109 US dollar. The policy value of a human life seems to gravitate to approximately 7 million US$. This is equivalent to 200000 per life-year. In the Netherlands amounts of 80000 euro's per year or 64M for a whole life are mentioned (Helsloot, 2010). If this proves to be indeed the value of a human life-year, it does not seem to be a large amount; especially when multimillion revenues are at stake. Even more difficult is the valuation of injuries and of environmental damage. A comprehensive description is given in the ExternE report NN 1995), but even there the results are inconclusive.

There are also great difficulties in assessing the actual value of the risk reduction costs. A seemingly expensive measure such as the desulphurization of residual oil actually brought money. Many of the expenses made in safety result also in increased reliability of the production and less costs of down time and accidents. In fact in the study performed by Pikaar & Seaman (1995) for the Dutch ministry of Housing, Physical Planning and Environment it appeared that most industries did not consider it worth their while to register the costs of these measures. This is consistent with the finding of Tengs et al (1995) of the low costs of measures related to the prevention of accidents.

Additionally recent findings indicate that it is not in the interest of managers to spend money on safety and that for companies spending money on safety is uneconomical (this conference) because most of the costs of un-safety are borne not by these companies but by the victims, their family and society.

10 THE UNKNOWN UNKNOWNS

Cost benefit analysis implies that the costs and the benefits can be determined on an equal par. In many cases that is the case, with the proviso of what was said about the valuation of damages to health and life. But there are many instances where this is not possible. Here we enter the realm of the hard uncertainties, the known unknowns and the unknown unknowns.

For the known unknowns three options are open. The simplest one is to take time and money and acquire the missing knowledge. However, this may not always be possible. It may be that it takes too much time and decisions have to be taken. It may be that the costs involved are prohibitive, such as seems the case for large scale hydrocarbon mist explosions, or, and this is the most difficult case, there is no way to find out. There is only one earth, so we cannot do repeated experiments with different levels of CO_2 emissions to see whether it makes a difference and how much. We also cannot roll back time. In all the cases that we cannot acquire the known unknowns we have to live with that. If we can give a range of values, we still can do a risk analysis. But otherwise we may have to be cautious, like Columbus when he sailed west under the assumption that the earth was round and Asia was on the other side of the Atlantic. Or maybe we have to be brave and set foot on the moon. Both cases are worth careful consideration. And if the risk is put on other people than our selves it may be ethical to ask their consent, although there are scientists in the Netherlands who are of the opinion that for a larger, societal good it should be possible to force people to accept a certain risk.

Now that we have discussed the known knowns, i.e. the results of technical and scientific analysis, including the associated uncertainties, the unknown knowns i.e. knowledge that is forgotten, or known by some and not by others, and the known unknowns, what remains are the unknown unknowns. The recently popular image of the Black Swann, introduced eloquently in the book by Taleb (2007) seems an attempt to deal with these and account for the unknown unknowns in a decision making process. However, this is the ultimate form of hindsight bias. What we don't know we don't know. Sure, now we know that black swans exist, but in the context of the 17th century, two centuries before years before Darwin there was no way to know. Sure, the financial crisis seems to have come out of nowhere (and that is the main subject of Thalebs book), but spending money you do not have is risky when you think you can earn it later (but you might not) and leads to disaster when you are sure it cannot be earned back. Anybody with any understanding about the behaviour of exponential curves knows where exponential rises in share values, or exponential rises in debt ends. And that there is a subtle difference between exponential behaviour and linear growth, especially if you are a government who can print its own money. But apart from this deterministic behaviour there are probability distributions that are not Gaussian, but have fatter tails. There is even a uniform distribution where all values have even chance. The real world may be between the Gaussian and the uniform, but it remains a probabilistic world and therefore predictable. Predictable in the sense that given enough time the average will be realised and predictable in the sense that events with low probability are not impossible and therefore may occur. An event with a small probability is NOT an event that cannot happen. This is true in the small, as in the tunnel-effect on which most of our electronic devices rely, an in the large such as an 11 m tsunami hitting a nuclear power plant. Nothing in these events even remotely resembles the Black Swan, which was truly unknown. It more but not really resembles the appearance of a fire breathing dragon, for which we are warned in countless books, which did not show up in any radar image yet. It mostly resembles a die with just a larger number of faces. Sooner or later each face will come up.

11 CONCLUSION

We have come a long way since the first attempts on quantifying probabilities, effects and damage of incidents and accidents. The estimation of industrial risk has become a technology rather than a form of black art. This has been the combined result of four decades of scientific research into the behaviour of chemicals, of installations and of humans. And the development of data processing means, which also was more witchcraft than science half a century ago. This has not made risk analysis a route job for everybody. There are still many factors that are not precisely defined and need an expert eye. This does not make the results subjective, it only makes them less precise than one sometimes would wish.

The largest challenge in the process of risk management remains, and is unlikely to disappear. That is how to make decisions on risk, given the information available. These decisions are unavoidable, no matter how many stakeholders have been involved and how long the discourse has lasted. There comes a time when the choice has to be made between taking the risk or terminating the risky activity. There is no law of nature that determines what risk is acceptable and when. And there is no definitive way to determine how to value human life, health and happiness in the equation. These decisions are even harder if the uncertainties around costs and benefits are large, when organised risk analysis does not really help. When there is just not enough information to go by. Or when there remains the nagging feeling that there is something out there.

It is up to the risk management society, scientists, managers and politicians, to face these issues in an ethically justifiable fashion, where the three elements of sustainability profit, planet people are not interpreted as profit comes first and people are an expendable commodity. Article 3 of the declaration of human rights implies that we are not supposed to harm others in the pursuit of our own material gain. The decision maker decides what this statement is worth when money runs out. Science cannot make the decision. It can and should only inform the decision maker, who shlould bear in mind that:

> "A reasonable estimate of economic organization must allow for the fact that, unless industry is to be paralyzed by recurrent revolts on the part of outraged human nature, it must satisfy criteria, which are not purely economic."

A quote from W.D. Rowe (1977, p vi) who in turn cited R.H. Tawney (1926). With the growing opposition against the behavior of the financial institutions on one side and the recurring call for economic valuation of human life in risk decisions on the other, this quote may serve as a persistent warning for decision makers who are informed about the benefits, the risks and the behavior of people.

These informed decision makers are us.

REFERENCES

Ale, B.J.M., J.G. Post & L.J. Bellamy, (1998) The interface between the technical and the management model for use in quantified risk assessment, in A. Mosleh and R.A. Bari (eds) Probabilistic Safety Analysis and Management 4, Springer 1998.

Ale, B.J.M. & P.A.M. Uitdehaag, (1999) Guidelines for Quantitative Risk Analysis, (CPR18) RIVM, 1999. (The purple book).

Ale, B.J.M. (2003) Keynote Lecture: Living with Risk: a management question, in ESREL 2003, Safety and Reliability, - Bedford en van Gelder (eds), Swets en Zeitlinger, Lisse, ISBN 90 5809 551 7.

Ale, B.J.M., L.J. Bellamy, J.I.H. Oh, J.Y. Whiston, M.L. Mud, H. Baksteen, I.A. Papazoglou, A. Hale, A. Bloemhoff & J. Post, (2006) Quantifying Occupation Risk, Working on Safety, 12–15, September 2006.

Ale, B.J.M., L.J. Bellamy, R.M. Cooke, H.J. Goossens, A.R. Hale, A.L.C. Roelen & E. Smith, (2006a) Towards a causal model for air transport safety—an ongoing research project, SAFETY SCIENCE, vol. 44, no. 8, October 2006, pp. 657–673.

Ale, B.J.M., L.J. Bellamy, R. van der Boom, J. Cooper, R.M. Cooke, L.H.J. Goossens, A.R. Hale, D. Kurowicka, O. Morales, A.L.C. Roelen & J. Spouge, (2008) Development of a Causal Model for Air Transport Safety CATS: Final Report, Ministry of Transport and water management, The Hague, The Netherlands.

Ale, B.J.M., L.J. Bellamy, R. van der Boom, J. Cooper, R.M. Cooke, L.H.J. Goossens, A.R. Hale, D. Kurowicka, O. Morales, A.L.C. Roelen, J. Spouge, (2009) Further development of a Causal model for Air Transport Safety (CATS): Building the mathematical heart, Reliability Engineering & System Safety, vol. 94, no. 9, September 2009, pp. 1433–1441.

AMINAL (2004) HANDBOEK KANSCIJFERS voor het opstellen van een VEILIGHEIDSRAPPORT, GECOÖRDINEERDE VERSIE 2.0, 01/10/2004, Ministerie van de Vlaamse Gemeenschap, AMINAL—Afdeling Algemeen Milieu- en Natuurbeleid, Cel Veiligheidsrapportering.

Beerens, H.I., J.G. Post, P.A.M. Uijt de Haag, (2006) The use of generic failure frequencies in QRA: The quality and use of failure frequencies and how to bring them up-to-date, Journal of Hazardous Materials, vol. 130, no. 3, 31 March 2006, pp. 265–270.

Bernoulli, D. (1738) "Specimen Theoriae de Mensura Sortis, cited my D. Miller and M. Starr, The structure of human Decision. Englewood Cliffs, N.J. Prentic Hall, 1967.

Carol, S., J.A. Vilchez & J. Casal, A new approach to the estimation of the probable number of fatalitiesin accidental explosions CentreSafetyScience 39 (2001) 205–217.

CPR14 (1979) Methoden voor het berekenen van fysische effecten, (CPR14), Directoraat Generaal van de Arbeid, 9 maart 1979. (Third revised English edition CPR14E methods for the calculation of physical effects. 2005) (The yellow book).

CPR12 (1985) Methoden voor het bepalen en verwerken van kansen (CPR12), Directoraat Generaal van de Arbeid, 1985. (Second English edition CPR12E Methods for determining and processing probabilities, 1997) (The green book).

CPR16 (1989) Methoden voor het berekenen van Schade, (CPR16) Directoraat Generaal van de Arbeid, 1989. Last edition PSG1, 2005, Last English edition CPR16E, Methods for the calculation of damage, 1989) The red book).

Cremer and Warner (1981), Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area: A Pilot Study; Rijnmond Public Authority Springer, 1982. ISBN 9027713936, 9789027713933.

Dekker, S. (2006) A field guide to Understanding Human Error, Ashgate, Hampsihere, England, ISBN 07546-4825-7.

Eissenberg, Norman A., Cornelius J. Lynch, Roger J. Breeding (1975) Vulnerability model: a simulation system for assessing damage resulting from marine spills, U.S. Coast Guard, Office of Research and Development, 1975.

Farmer, F.R. (1967) Reactor Safety and Siting, a proposed risk-criterium, Nuclear Safety, 8 (1967) 539.

Helsloot, I., R. Pieterman, J.C. Hanekamp (2010) Risico's en Redelijkheid, Boom Juridische Uitgevers, Den Haag, ISBN 978-90-8974-243-8, p. 110.

Howard, R.A. Decision Analysis: Applied Decision Theory, Proceedings of the Forth International Conference on Operational Reasearch, vol. SSC4, no. 3, September 1968, pp. 211–219.

HSE (2009) Buncefield Explosion Mechanism Phase 1, Volumes 1 and 2, Prepared by the Steel Construction Institute for the Health and Safety Executive 2009 RR718.

Hubert, Ph, M.H. Barni & J.P. Moatti (1990) Elicitation of criteria for management of major hazards, 2nd SRA conference, April 2–3 1990, Laxenburg, Austria.

Laheij, G.M.H., Gooijer, L. & Wolting, A.G. (2012) Framework for the adjustment of failure frequencies in quantitative risk assessment methodologies, In: Proceedings of the 11th international probabilistic safety assessment and management conference and the annual European safety and reliability conference 2012 (PSAM11 ESREL 2012), Helsinki, Finland, June 2012; 2047–2055.

Marshall, V.C. (1977) How lethal are explosions and toxic escapes? The Chemical Engineer, August 1977, 573–577.

McQuaid, J., B. Roebuck & D.G. Wilde (1985), Large-Scale Field Trials on Dense Vapour Dispersion, Safety of Thermal Water Reactors, Proceedings of a Seminar on the Results of the European Communities' Indirect Action Research Programme on Safety of Thermal Water Reactors, Held in Brussels, 1–3 October 1984 1985, pp. 179–189.

Morall, J.F. (1986), A Review of the Record, Regulation, vol. 10, no. 2, 1986.

Morall III, J.J. (1992), Controlling Regulatory Costs: The Use of Regulatory Budgeting, Regulatory Management and Reform Series No. 2, OECD/GD(92)176, 1992.

NN (1995) Externe, Externalities of Energy, vol. 2, Methodology, European Commission EUR 16521 EN.

Papazoglou, I.A., L.J. Bellamy, A.R. Hale, O.N. Aneziris, B.J.M. Ale, J.G. Post & J.I.H. Oh, I-Risk: (2003) development of an integrated technical and management risk methodology for chemical installations, Journal of Loss Prevention, Journal of Loss Prevention in the Process Industries 16 (2003) 575–591.

Perrow, Charles (1984). Normal Accidents: Living with High-Risk Technologies, With a New Afterword and a Postscript on the Y2 K Problem, Princeton, New Jersey: Princeton University Press, ISBN 0-691-00412-9, 1984, 1999 (first published by Basic Books 1984).

Phillips, C.A.G. & Warwick, R.G. A survey of defects in pressure vessels built to high standards of construction and its relevance to nuclear primary circuits. UKAEA AHSB(S) R162, 1969.

Pikaar, M.J. & M.A. Seaman, (1995) A review of risk control, Report nr SVS 1994/27A, Ministry of Housing Physical Planning and Environment, The Netherlands.

Puttock, J.S., G.W. Colenbrander & D.R. Blackmore (1984) Maplin Sands Experiments 1980: Dispersion Results from Continuous Releases of Refrigerated Liquid Propane and LNG, Air Pollution Modeling and Its Application III Nato, Challenges of Modern Society Volume 5, 1984, pp. 353–373.

Rasmussen, N. (1975) WASH-1400, 'The Reactor Safety Study' US Nuclear Regulatory Commission (NRC), Washington.

Reason, J. (1990), Human Error, Cambridge University Press, ISBN 0 521 31419 4.

Rowe, W.D. (1977) An anatomy of risk, Rober E Krieger Publishing company, Florida, ISBN 0-89874-784-8.

Schoot Uiterkamp, A.J.M. & C. Vlek (2007), Practice and Outcomes of Multidisciplinary, Research for Environmental Sustainability, Journal of Social Issues, vol. 63, no. 1, 2007, pp. 175–197.

Slovic, P., Fischoff, B., Lichtenstein, S., Read, S. & Combs, B. (1978) How safe is safe enough, a psychometric study of attitudes towards technological risks and benefits, Policy Sciences, 8: 127–152, 1978.

Smith, T.A. & Warwick, R.G. The second survey of defects in pressure vessels built to high standards of construction and its relevance to nuclear primary circuits. Safety and Reliability Directorate, SRD R30, 1974.

Stallen, P.J. & A. Thomas (1986), De Beleving van Industriële Veiligheid in Rijnmond, PhD thesis, Nijmegen University, Netherlands, ISBN 90-9001422-5.

Swain, A.D. & Guttman, H.E. (1983), Handbook of Human Reliability Analysis with Emphasis on Nuclear

Power Plants Applications, NUREG/CR-1278 Sandia National Laboratories.
Swalm, R. (1966) Utility Theory—Insights into Riso Taking, Harvard Business Review, Nov–Dec 1966, pp. 132–136.
Taleb, N.N. (2007) The Black Swann, Pengui, UK, ISBN 978-0-141-03450-1.
Tawney, R.H. (1962) Religion and the rise of capitalism, Transaction publishers, 1926, ISBN-10: 0765804557, p. 284.
Technica (1984) Report on a Computer Based System for Risk Assessment of Chemical Plant using a Simplified Classical Method, London, 1984.
Technica (1985) Whazan World Bank Hazard Analysis, Technica, London, 1985.
Tengs, T.O., Miriam E. Adams, Joseph S. Pliskin, Dana Gelb Safran, Joanna E. Siegel, Milton C. Weinstein & John D. Graham (1995) Five-Hundred Life-Saving Interventions and Their Cost-Effectiveness, Risk Analysis, vol. 15, no. 3, 1995.
TNO (1996) The EFFECTS 2.1 Programme, The Fire Explosion and Dispersion Models for Accidental Releases of Hazardous Materials, TNO Apeldoorn, 1996.
Vesely, W.E., F.F. Goldberg, N.H. Roberts, D.F. Haasl (1981), Fault Tree Handbook (NUREG-0492) US NRC 1981.
Vlek, C.A.J. & Stemerding, S. (1984). Beschrijving en beoordeling van risico's verbonden aan het gebruik van gevaarlijke stoffen. [Description and evaluation of risks associated to the use of hazardous materials.] University of Groningen, NL, Departments of Environmental Science and Psychology, the summary has 81 pp. The whole study 1200 pp.
Witlox, H.W.M. (1994) The HEGADAS model for ground-level heavy-gas dispersion—I. Steady-state model, Atmospheric Environment, vol. 28, no. 18, October 1994, pp. 2917–2932.
Witlox, H.W.M. & Holt, A. (1999) A unified model for jet, heavy and passive dispersion including droplet rainout and re-evaporation., International Conference and Workshop on Modelling the Consequences of Accidental Releases of Hazardous Materials, CCPS, San Francisco, California, September 28. October 1, pp. 315–344 (1999).