Introduction of the concept of risk within safety science in The Netherlands focussing on the years 1970-1990

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Summary

Serious incidents in the 1970s and continuous growth of factories producing and/or using hazardous substances formed the basis of a quantitative approach to risk. While discussions of risk were conducted in all industrialized countries they were particularly important in The Netherlands due to space limitations and short distances between industrial plants and residential areas. This article is part of a series covering the history of the safety science discipline (Swuste et al., 2015; Gulijk et al., 2009; Swuste et al, 2010).

The concept *risk* entered the Dutch safety domain before the 1970s in relatively isolated case studies and in managing The Netherland's flood defences. Since the 1970s these cases paved the way for the development of mathematical models for quantitative risk analysis that were based on experience from nuclear power plants, the process industries and reliability engineering from operations research. 'External safety' was a focal point for these early developments: adverse effects of dangerous goods outside the factory's property boundaries. The models were documented in standardized textbooks for risk analysis in The Netherlands, the so-called 'coloured books'. These works contributed to the development of the Seveso Directive. For internal safety (taking place within property boundaries) semi-quantitative approaches were developed alongside external quantitative models.

The models for quantitative risk analysis were deemed reliable, but the acceptability of a quantified risk was another matter. Making decisions on risk relates to complex societal issues, such as ethics, stakeholder perception of risks, stakeholder involvement, and politics, all of which made the decision making process far from straightforward. Parallel with the introduction of the concept of risk in the Dutch safety science domain, the question of risk perception also became important in Dutch safety research.

The concept risk and methods for quantitative risk analysis first entered into Dutch law in environmental risk regulations. It took a while before risk was accepted by occupational safety experts, but just before the turn of the century 'occupational risk inventory and evaluation' or RI&E methods were introduced into Dutch occupational safety legislation. This finalized the paradigm shift to risk-based safety-decision making in the Dutch safety science domain. While methods for quantifying risk are now widely applied and accepted, the proper use of risk perception and risk in the political decision process are still being debated.

1. Introduction

The public debate on whether to allow LNG super tankers into Rotterdam harbour in 1975 shed light on the context in which risk enters the safety domain in The Netherlands. The proposals for LNG landing led to spectacular visions of vapour cloud explosions with the power of a atomic bomb. These exorbitant projections drove the need to ‘put some numbers’ and thus to get a better grip on the problem, thereby facilitating sensible safety decision making. The heated debate about LNG abated after the discovery of a huge natural gas field in the North of The Netherlands, but the debate about the introduction of the risk paradigm and the acceptability of risks had started. The LNG discussion took place in the background of the introduction of new industrial activities in The Netherlands that would involve huge amounts of hazardous materials. In this context, the discussion about adverse consequences for local residents provided the motive for risk research in the seventies. The limited land space in The Netherlands forced consideration of safe separation distances between the (process) industry and residential areas. This development emphasizes the central role of the Dutch risk-based approach in the discussion about safe distances between urban centres and high hazard industries. As risk-based research progressed, the definition of risk as a combination of the probability and the effects of incidents became increasingly accepted. This definition had a structuring effect on the public debate on risks, and reduced the debate to realistic proportions (Pasman, 1999). From the seventies onward risk was frequently placed on the political agenda. The scientific debate on risk as a basis for safety decision making was not restricted to the field of safety science and is still on-going (Vlek and Stallen, 1979; Health Council of The Netherlands, 1996; Health Council of The Netherlands 2008; WRR, 2008, Ministry of the Interior and Kingdom Relations, 2012). Despite that, the full implementation of the risk paradigm for safety decision making can said be completed in the late 1990’s.

This article is part of a series on historical research into the professional field of safety science. The first article in this series described the first steps in this field in the early twentieth century. The theory of accident-prone workers was developed in this period and was supported by the first statistics data on occupational accidents (Swuste et al, 2010). A second article deals with the development of safety engineering in the interwar period, with emphasis on the contribution of the American Heinrich (Gulijk et al, 2009). The third article covers the period after the Second World War until the early seventies. Then the focus remains strongly on occupational safety and broadens the analysis of accidents in the direction of task analysis and epidemiological approach (Swuste et al, 2014a). Two recent articles describe the period of emergence of safety management systems until the nuclear incident at Three Mile Island in 1979 (Swuste et al, 2014b), and from Three Mile Island till Piper Alpha (Swuste et al., 2015), both dealing with the development of occupational and process safety.

This article covers the period 1970-1990, during which the concept and definition of risk was introduced into the safety science domain. From 1970 onwards there are articles in Dutch journals discussing the assessment of risks. Gradually the attention shifts from damage and effect to damage related to probability: from damage control to risk control. Together with the concept of risk and risk perception, terms such as damage, effect and hazard were explored and defined.

In the period after 1990, the public debate about the concept of risk broadened. Therefore, 1970-1990 is an appropriate time period for this article, notwithstanding that occasionally the text reports developments that have taken place outside this period.

This article addresses the following research questions:

1. What developments were decisive for introducing the concept of risk in safety science in The Netherlands?
2. Which theories, models, and metaphors were developed in the considered period (1970-1990)?
3. What differences exist between the introduction of the concept of risk into occupational safety and into process safety?

More than previous articles in this series, this article focuses on specifically Dutch developments around the concept of risk in safety studies. In The Netherland the probabilistic approach was first introduced in flood risk, but with the introduction in chemical process safety, the concept and the analytical methods developed further and were much more widely used,. Only later was the term risk also used in the Dutch occupational safety domain. Whereas occupational safety focuses on the entire range of incidents in the workplace, process safety tends more to focus on incidents with a small probability of occurrence but with major effects, effects both inside and outside the plant premises, the latter including public and environment.

2. Materials and methods

This article is based on analysing original safety science and professional literature of the period examined. We studied publications that introduced the concept of risk, and we focus on the arguments for introducing risk as a concept and the methodology development into safety science.

The analysis for this article started with articles introducing the concept of risk in the Dutch journal *De Veiligheid* (The Safety) and their references in *Tijdschrift voor Sociale Gezondheidszorg* (Journal of Social Medicine) and *De Ingenieur* (The Engineer). Furthermore the original reports of specific studies in this period (1970-1990) have been explored: LPG study (TNO,1983), the COVO study the industrialized Rijnmond area (Cremer and Warner, 1982) and the related Canvey Island report (Cremer and Warner, 1980) and the Dutch textbook series on quantitative risk analyses (‘coloured books’) studies. The references were mainly from UK, US or The Netherlands. In addition to the references in these studies we searched journals on the use of terms related to risk. Journal of Hazardous Materials, Reliability Engineering & System Safety and Journal of Risk Analysis were the main sources.

In addition for the period up to 1970 we used sources from the previous four articles of this historical series. Additionally, we studied the report from the CPR (Commission for Prevention of Disasters) and consulted the reports on risk from the Health Council of The Netherlands.

This article focuses on legislation, general policy the public debate and the scientific discussion on the concept of risk.

3. The period up to 1970: the emergence of the risk concept

In the early years of safety science the concept of risk was not common, as discussed in previous articles of this series, more often one spoke of safety technology (Zwaard, 2007). At that time there was no risk-based approach that used the concept of 'probability'. Yet in this early period, the first ideas for a risk-based approach emerged. Heinrich (1931) described the occurrence of an accident as a separate step of the accident process that lead to effects (injury). This was the basis for the domino's metaphor which he described in 1941. Heinrich discussed the causal relations and the severity of effects, but did not explicitly mention the concept of probability. De Blois (1926) introduced the theory of likelihood or probability in safety and devoted a chapter to the difference between chance and probability. He talked about a shift from a universal belief that "accidents just happen" to a new doctrine that "accidents are caused and the relevant causes can be prevented ". He introduced the likelihood doctrine as a theory:

> *"Which deals with the maturity of complex events and brings their occurrence under the exact laws as against leaving their happening to random conjecture."*...

This is illustrated by the example of the probability of sudden crane failure (1 in 10,000), and the probability that an employee who normally works ten minutes of a ten-hour workday under the load, is hit by the load when the cable breaks. The combined probability of such an accident is the product of both independent probabilities: 1/10.000 X 10 / (10X60) = 1/600.000. De Blois did not mention the word risk, but he used some important aspects that would form a central part of the risk-based approach in safety years later: predicting or estimating combined incident probabilities and the lack of information about the "number of successful operations".

The concept of risk was used much earlier in the field of insurance. The first reports relate to ship transports in antiquity (Bernstein, 1996). Later the notion of risk in the calculation of life insurance premiums was used in the actuarial mathematics. Several historical reviews on risk analysis and safety refer to Pierre de Fermat and Blaise Pascal, who in the seventeenth century laid the basis for the calculation of probability and thus prepared a path for modern risk analysis (Ale, 2003; Bernstein, 1996; Saleh et al., 2006). And in the beginning of the twentieth century the axioms of Kolmogorov provided the mathematical foundation for the calculation of the probability of a particular set of independent events as the product of the separate probabilities for these events (Kolmogorov, 1956).

In the period after the First World War we see the idea of probability arising in the areas of operational research, reliability engineering, loss prevention, and related fields. These domains have evolved independently of each other, as is explained in the next paragraphs.

3.1 Operations research

Operational research, later known as operations research, arose between 1930 and 1940 and provided important data for quantifying risks. Operations research is research that focuses on rational decision making based on quantitative models. In the early years, operational research is dedicated to the effectiveness of military operations, maximizing profits, minimizing costs, and minimizing risks. In 1936 the Bawdsey Research Station uses operational research to assess the reliability of the RAF radar installations in preparations for war against Germany. Later, other military operations were analysed (e.g. bombing Germany). The analyses were based on statistical data analysis and probabilistic risk analysis of alternative operations.

After World War II, a massive upscaling of the (chemical) process industry occurred. Increasing production capacities, storage capacities and transportation capacities of hazardous materials led to major incidents and public outcry for betterment. The installations of process industries appeared increasingly unreliable, and this undesired situation led in the seventies to different *loss prevention* research studies (Pasman and Snijder, 1974; Pasman, 1999). A more systemic and scientific approach was needed for the quantification and the management of risks (Boersma, 1974; Ale, 2002, 2003).

3.2 Reliability engineering

Reliability engineering has emerged with the development of mass production and the use of standardized components. The origin of the field goes back to the mass production of weapons and the introduction of interchangeable parts during the American War of Independence (1775 to 1783) and, much later, the mass production in the factories of Henry Ford and the introduction of fragile vacuum tubes (diodes and triodes) at the beginning of the last century. Reliability engineering really developed after World War II when in 1952 in the United States the Advisory Group on Reliability of Electronic Equipment (AGREE) was founded and reliability engineering as a discipline was established in 1957 (Coppola, 1984). Reliability engineering made a significant contribution to the collection and analysis of failure probabilities of components in technical systems and formed an important input for risk assessment in safety studies. This is indicated by two technical standards: TR-1100, Reliability Stress Analysis for Electronic Equipment (1956) and H-217, Military standard for calculation of reliability predictions (1961) (Denson, 1989).

The shift to a risk-based approach according to Griffiths was illustrated by a British standard (British Standard Glossary of Terms used in Quality Assurance - BS 4778:1979). A probabilistic approach was introduced, replacing the traditional practice of safety factors that often amounted to a factor 10 of even 100 (Griffiths, 1981).

3.3 Risks of flooding

In The Netherlands, developments in flood safety had a major impact on the risk-based and probabilistic approach in safety science. Van Veen and Wemelsfelder pioneered this work in the 1930's in their positions as civil servants in the government agency Rijkswaterstaat (Department of Public Works), responsible for the design, construction, management and maintenance of the main infrastructure facilities. Their work led to a fundamentally different approach to flood control. In that time, it was customary to increase the height of levees to slightly above the level of the last flood. In this new approach dike heights were determined by statistical analysis of tidal flood levels. Statistical analysis dictated that an absolutely safe dike did not exist but that there was a probabilistic relationship between the height of levees or sea dikes and flood risk: the higher the dikes, the smaller the risk of flooding. This work paved the way for the warning issued to the government in 1939 of the inadequate protection of the levees in the south-west provinces of The Netherlands in storm-force winds. The warnings were repeated shortly after World War II (Horn of Nispen, 2001) but to no avail.

The probabilistic approach was adopted only after the Great Flood of 1953 which caused more than 1,800 fatalities. Soon after, the Delta Works project was started and policy decisions for flood safety and dike heights were based solely on risk assessments. For a vulnerable part of The Netherlands, a village on the west coast (Hoek van Holland) the exceedance probability was calculated to be 1/250.000 per year. This eventually translated into a maximum permissible exceedance probability of 10^{-4} per year (defined as the probability that the water height is equal to or higher than the dike height (Van Dantzig, 1956; Van Dantzig and Kriens, 1960).

This approach paved the way for the concept of flood risk as probability times impact. Flood risk was defined as the probability of flooding each year multiplied by the amount of damage (defined as number of deaths; Ten Brinke and Bannink, 2004). All other policies for flood defence were abandoned from that point onward.

3.4 Risks and nuclear energy

After World War II, commercial nuclear power became available. The United States pioneered the public debate about the acceptability of risks of nuclear power plants to local residents and the environment. This discussion reached its apex in the 1975 WASH-1400 report (Rasmussen, 1975). This report used probabilistic risk assessment (PRA) to demonstrate that the risks associated with nuclear power plants were relatively small. The WASH report and its various sub-reports were of great importance for the development of quantitative risk analysis in The Netherlands.

3.5 Risks in process safety

Starting from 1975 the Commission for Prevention of Disasters (CPR) published standards for the safe storage of hazardous substances in The Netherlands. In the publications of the predecessors of this commission, the so-called ‘gasoline commission’ (starting from 1927) and subsequently the Commission on Storage of Hazardous Substances (starting from the sixties), sometimes the word risk was used, initially without being quantified or even defined. The CPR standards of 1975 mark the beginning of a 'risk thinking' within the Ministry of Social Affairs and Health.
However, already during the 1950s and 1960s chemical and petrochemical plants, not only in The Netherlands but also in the major industrial countries, had grown much larger than earlier ones and, additionally, were operating at higher temperatures and pressures. One result was an increase in serious accidents with large losses of capital and human life. This led in to the development of a more systematic, comprehensive, and technical approach to safety, known as ‘Loss Prevention’ (Kletz, 1999).

4. The seventies and eighties: the quantification of risks in The Netherlands

Quantitative risk analysis for hazardous substances took off in The Netherlands in the seventies and eighties, building on the previously described national and international developments and insights.

4.1 The need for a quantitative approach

From the end of the sixties, in The Netherlands a broad debate emerged on the calculation of risk as a measure of safety (business, science, government). The focal point of these discussions was on dangerous substances particularly when it came to low probability and high impact events (later called ‘major hazards’). But the discussion went much broader. Social issues were at the heart of the discussion for large-scale technological developments, such as the mooring of LNG tankers in the harbour of Rotterdam, the construction of LNG pipelines to Germany, the use of LPG in cars this leading to the need of LPG refuelling stations, and the development of the chemical industry in Eemshaven, in the north east of Holland. Resolving these social issues called for a new approach to safety (Ale, 2002, 2003).The new approach should deliver a better understanding of the dispersion of hazardous substances in the atmosphere, the type and severity of the potential of such dispersions and all forms of damage it could cause. In addition, there was a need for clear definition and quantification of the concept of risk and of a criterion for an accepted level of safety.

The scientific debate about the long term health risks from prolonged low exposure to hazardous substances took place mainly in the medical, environmental and industrial hygiene disciplines (see 3.11). The discussion about an acceptable risk criterion for exposure to carcinogens showed parallels with the discussion about such a criterion for the risk of a disaster involving hazardous substances. Thus the stage was set for change.

4.2 The concept of risk in the process and nuclear industries

A Dutch congress in 1969 *(inherent hazards of manufacturing and storage in the process industry)* organized by Dutch organizations for chemists and chemical engineers (KNCV and KIVI) and a UK conference in 1971 *(Major Loss Prevention,* in Newcastle) were the predecessors of the first European conference on *Loss Prevention* in 1974 (Pasman and Snijder, 1974). In the opening speech at this first European Congress the Dutch Minister of Social affairs Boersma held a plea for the development of methods for quantitative risk analysis (Boersma, 1974). The scale up in process industries required new insights and methods. New methods were needed to estimate the size and probability of potential disasters and devise the necessary measures against them. Boersma stressed safety regulations for the process industries was similar to regulation of nuclear power plants, where, at that time, the debate centred on the *maximum credible accident* and resulting risks. Buschmann, a chemical consultant working at the Dutch Ministry of Social Affairs, spoke about new challenges for the process industry and referred to the report "The Limits to Growth" of the Club of Rome in 1972 (Buschmann, 1974). Far more efficient and cleaner production processes needed to be developed; new materials and alternative fuels needed to be applied. At this time society was becoming more critical towards the introduction of new technologies which created a need for in-depth analysis methods and clear guidelines whether acceptable risk levels were exceeded. In addition to that it was important to demonstrate that the benefits of new technologies outweighed the risks they created. Buschmann translated this into a challenge for science by asking for quantification of risk. His call had immediate effects. Without delay, a research program was started for determining probabilities of failure and effect modelling. In the end, this effort led to the so-called coloured books in the CPR series (see section 3.6).

The disasters at Flixborough (1974) and Beek (1975) had a huge impact in The Netherlands. DSM, a Dutch company owned the factory in Beek and co-owned the company in Flixborough. Both disasters surprised experts and policy makers because the damage from the explosion was far beyond the expectations (Marshall, 1987). This led to many questions about the explosion severity of released flammable gases and vapours (Cobben et al, 1976). Research on vapour cloud explosions had already started in 1968 after an incident at Shell Pernis. But the explosions at Flixborough and Beek led to a heightened interest in fundamental research (Groothuizen, 1976). Field experiments in the U.S. (Nevada, Texas) and The Netherlands (Mosselbank, TNO) in the seventies gave a first insight into the chemical and physical mechanism of a vapour cloud explosion and the conditions which could worsen a mild deflagration (explosive combustion) into a much more violent and destructive deflagration, and even to a detonation (i.e. an explosion with supersonic velocity and much more powerful than a deflagration). The presence of obstacles, such as piping, was found to be

a major factor increasing the destructiveness of gas and vapour explosions (CPR 14[E], 1979; Van den Berg, 1985).
The quadrennial Loss Prevention conferences focused on the process industry and process safety and therefore were attended largely by safety-oriented engineers and scientists from companies, government and universities. Later, quantitative risk analysis also became a central topic in the congresses of the SRA (Society for Risk Analysis) and ESRA (European Safety and Reliability Association), founded, respectively, in 1980 and 1991. This stimulated further development of the theory of risk analysis in various fields of science.

In international perspective a milestone in the development of Loss Prevention was the publication by F.P. Lees in 1980 of the encyclopaedic textbook ***Loss Prevention in the Process Industries.*** The comprehensiveness, quality and utility of this textbook quickly established the importance of Loss Prevention within the process industry. Central in Loss Prevention is the concept of risk and methodologies for quantifying risk. Lees defined risk as:

Risk is a measure of economic loss or human injury in terms of both the incident likelihood and the magnitude of the loss or injury (Lees, 1980)

This quantitative definition of risk became, and still is, the prevailing definition of risk within the process industry. According to Lees the extension of process safety required a reorientation of the approach to "*safety and loss ".* Lees systematically and comprehensively described the relevant body-of-knowledge, methods, and techniques required in order to prevent damage to property and to prevent adverse health effects. He described the methods for quantification of risks and applications of reliability engineering. He also criticized the traditional standards and codes for the design of installations. The systematic and comprehensive approach in this first edition of this handbook illustrates the revolutionary change in approach that the introduction of risk brought into safety engineering. Another well-known author who advocated a quantitative approach was Trevor Kletz (1971).

4.3 Debating quantitative risk analysis in separate disciplines

The turbulent development in the process industries greatly influenced the focus of research and the development of theories in safety science. This applies in particular to quantitative risk analysis. In the UK, the HSE commissioned a study of the potential hazard to residents in the area of Canvey Island (HSE, 1978). Following the British study a risk analysis was conducted in The Netherlands by Cremer and Warner (1982), the so-called COVO study. COVO was the abbreviation of Safety Committee of residents in the Rijnmond Area (surrounding industrial complexes near Rotterdam). It was the first quantitative risk assessment that identified industrial risks to which the residents were exposed in the vicinity of chemical industry parks. The European 'Seveso Directive' - named after an incident in the Italian town Seveso (1976) - was for a large part based on research on quantitative risk assessment as a follow up of these studies (see section 3.6).

Alongside the rise of quantitative risk analysis, interest grew in the fields of psychology, sociology and public administration concerning the public debate on how to deal with increased risks. Dutch researchers Stallen and Vlek (1979), who presented their findings alongside international researchers (Slovic et al, 1984; Starr, 1969; Fischhof, 1984), gave various definitions of the concept of risk and discussed factors determining for risk perception of local residents (Vlek, 1990). Right from the start the social sciences debate strongly influenced the technical-scientific debate on quantitative risk analysis. The debate between the more technical-scientific approach to risk and the approach of the social sciences is sometimes referred to as the debate between objectivists and constructivists.

4.4 LPG integral study

In 1978 TNO was commissioned to carry out a study on "the safety of current and future activities using LPG in The Netherlands', the so-called LPG integral study" (TNO, 1983). Different methods were used in conjunction, including incident analysis, hazard and operability studies (Lawley, 1974), fault tree analysis and event tree analysis. Later the methods for calculating physical effects (e.g. blast wave of explosion of LPG), assessing failure probabilities, transmission models (e.g. of a toxic cloud through air) and models for calculating possible damage (e.g. resulting from exposure to a toxic cloud) were further elaborated and recorded in the so-called ‘coloured books’, discussed later.

The report of the LPG integral study mentions that due to the complexity of the concept of risk, three different measures were used to assess both the expected consequences of incidents and the likelihood of the occurrence of these consequences:

- The average number of expected deaths
- The probability that an individual person is killed at a particular location or area
- The probability that a certain number of people are killed in the total area affected.

Much later (in 2004) the last two measures became the basis for defining the criteria for the individual risk at a given location (PR) and the Group Risk (GR)[1] in the Dutch Decree on external safety of industrial plants (BEVI). These three types of risk were calculated for different types of incidents and scenarios. The most serious scenario was the BLEVE, a "Boiling Liquid Expanding Vapour Explosion". This is an explosion due to failure of a vessel containing a pressurized liquid at a

[1] Individual Risk (PR) was defined as: The probability that an individual person is killed at a particular location during a period of one year. Group Risk (GR) was defined as: The probability that a certain number of people are killed in the total area affected within one year.

temperature well above its atmospheric boiling point. With flammable liquids (e.g. propane) the initial explosion is usually followed by an intensely burning fireball. Thus, the individual risk of a BLEVE followed by a fireball was calculated as the probability of occurrence of an incident BLEVE (10^{-2} per year) multiplied by the probability of a fatality resulting from exposure to the intense heat radiation of the fireball.

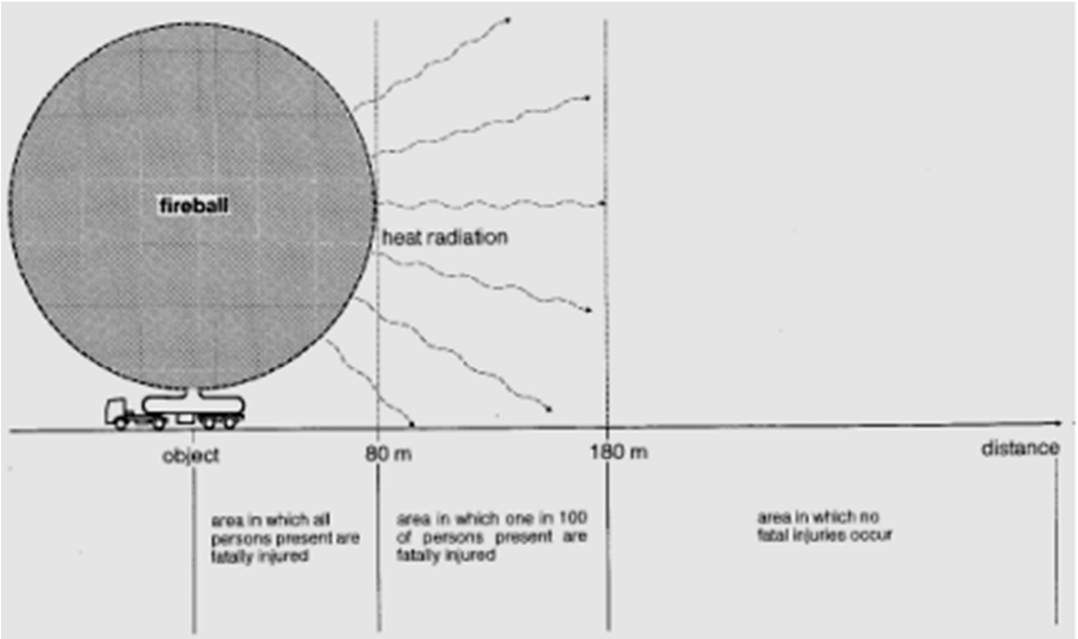

Figure 1: Effects of a BLEVE followed by a fireball (TNO, 1983)

The researchers extensively discussed the uncertainties of the risk analysis, including uncertainties about the design and construction of engineering systems and assumptions about failure probabilities. There was uncertainty about the influence of human factors and the probability of occurrence of consequences. The authors of the TNO report did not include the social acceptability of the activities examined. The reasons the authors stated was that their analysis was limited to a technical risk analysis concerning public safety and thus did not include an analysis of other aspects (such as environmental and economic aspects) that played a role in political decision making on the use of LPG in The Netherlands. Nevertheless, the hard numbers infused into the social debate.

4.5 Quantitative risk analysis published in the Dutch 'coloured books'

After the publication of the LPG integral study need grew in The Netherlands for a pooling of the knowledge about risk analysis of hazardous substances. Commissioned by the Dutch government this knowledge was put together in the so-called "Yellow Book" (CPR 14[E],1979) by experts from ministries, research institutes and industry. The models presented were based in part on reliable scientific knowledge. Blanks or parts of the risk analysis process for which sufficient reliable science was lacking, or essential data were missing, were filled with the available rules of thumb. The reliability of the effects models was tested in laboratory and field tests. For many years the Yellow

Book was internationally used to calculate the consequences of hazardous substance releases in risk analysis studies. The methods were mainly used by designers and engineers of industrial plants and in quantitative risk analysis aimed at assessing 'safe distances' around industrial plants. Later other publications in the same series of 'Coloured books' publications appeared. These treated specific aspects of risk analysis.

The Green Book was the second coloured book following the yellow book (CPR 16, 1989). It described damage models for the determination of possible damage to people and property caused by the release of hazardous substances. The distinction between effect and damage is based on the sequence of the physical *effects* of release of hazardous substances (e.g. an explosion producing a destructive pressure wave (blast)) and the probability of *damage* caused to the persons or properties exposed (e.g. exposed to blast resulting from an explosion). The terms 'effect' and 'damage' thus have different meanings in quantitative risk analysis compared to the same terms in industrial hygiene and occupational safety. Instead of the term 'effect' the term 'exposure' is used in industrial hygiene. And the term 'effect' in occupational safety and industrial hygiene is used for damage (to health and property).

The Green book described effect models for calculation of transmission of released substances in different incident scenarios. Thus, for a toxic gas release in a specific scenario the expected gas concentration as a function of time at a certain distance from the source could be calculated. In the damage models these data were used to determine the risk (i.e. probability of death) for persons exposed to given concentrations for a given time duration. Damage models were also called vulnerability models. These damage models were based on laboratory animal tests and military injury data from explosions and data on the effects of poison gas in World War I and later.

The third book in the series, the Red book (CPR 12^E, 1988), focused on the analysis of failure probabilities, such as the failure rates of individual technical components (e.g. valves, pipes) in order to determine the risk of failure of a technical system. This analysis began with an analysis of the incident probability. This was based on hazard identification and potential accident scenarios and the chain of events leading up to an incident. In addition, both the potential effect as and the potential damage have certain probabilities. These probabilities were included in the calculation of the risk. Figure 2, taken from the Red Book, gives the schematic representation of the quantitative risk analysis process.

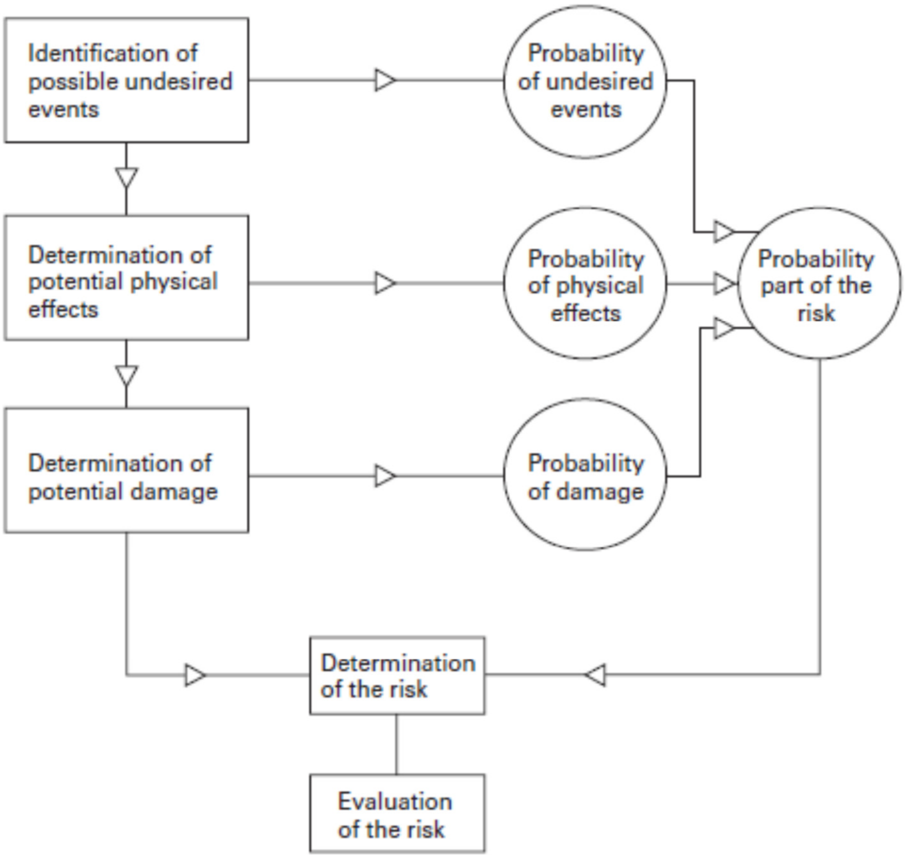

Figure 2: Schematic representation of the quantitative risk analysis (CPR 12^E, 1988)

Perhaps surprisingly, the models in the coloured books were hardly used to assess the safety (safety in terms of risk!) of employees. In fact the risk-based approach entered the occupational safety field only years later (see section 4.8 and 5.3). The fourth book in the series (Purple book) will be discussed in section 5.1.

4.6 Criticism of quantitative risk analysis

The theoretical models of the quantitative risk analysis - fault trees, dispersion models and effects and damage models - were tested as far as possible with real data and adjusted. Field experiments, including those in The Netherlands, gave input for improving dispersion models and better understanding of vapour cloud explosions (Siccama, 1973; CPR, 1982). Detailed research after incidents (such as the LPG disaster in Mexico) was used to improve the damage models (Pietersen, 2009). The models and fault trees formed an important basis for quantitative risk analysis. But the uncertainties were large, as shown by the criticism of Canvey Island report (Cremer and Warner, 1980; Warner, 1981; TNO, 1983).

Expert judgment had a great influence on the estimation of the failure probabilities. The lack of reliable data on failure rates and failure frequencies was in fact already noted by De Blois in 1926 (see section 3). This remains a weak point in the analysis to this day. After all, whilst the result of a risk assessment is dependent on the analyst it is not completely objective. Databases on the reliability of system components were and remain essential for carrying out a QRA. In England oil and chemical companies and Ministry of Defence (UK) and the power industry made their data available through the Systems Reliability Service (SRS) of the UKAEA (United Kingdom Atomic Energy Authority SRS. In the first generation models for quantitative risk analysis, component failure probability data were limited, and, out of necessity, were extended for wider application (e.g. failure probabilities for pressure vessels and process vessels) based on expert judgment. (Pasman, 2011). Doubts can be raised about such a procedure, since it is the numerical values of failure probabilities that largely determine the outcome of quantitative risk analysis.

The criticism of QRA has never ceased. The Hazardous Substances Advisory Council in The Netherlands criticized the software program used for calculation of individual risk and societal risk by the Dutch government as late as 2010 (Hazardous Substances Council, 2010).

4.7 Risk perception

Research in the field of risk perception, risk acceptance, and decision analysis flanked the development of QRA. Stallen and Tomas (1985), for example, described the development of social science research aimed at distinguishing between objective and subjective risks in the public debate on industrial risks and nuclear power.

The scientific debate on risk perception in the vicinity of industrial plants was conducted by a wide range of social scientists, economists and psychologists. The definition of risk was an important aspect of the debate. In 1977, the central question for a social scientist studying risk was not how risky something was, but how acceptable a risky activity was (Rowe, 1977). This in contrast to the more technical-scientific view of QRA, which was – and still is - based on a distinction between risk quantification i.e. how big is the risk? (with risk expressed in terms of adverse effects and probabilities – both quantitatively) and risk assessment, i.e. is the risk acceptable?. However, for several reasons social scientists were questioning this distinction.

Psychological field studies showed that various aspects of risk determine the risk perception of citizens (Slovic et al, 1984; Starr, 1969; Vlek and Stallen, 1979; Rowe 1977). The relevance of a comparison of risks, based on QRA, was therefore questioned. Risk was a multi-dimensional concept with dimensions that were weighted differently by different groups of stakeholders (Vlek, 1990). The most important cognitive dimensions are:

- Potential harm or lethality of a release or spill;
- Controllability by safety and control management;
- Number of persons affected simultaneously;
- Awareness of effects and consequences;
- Voluntariness of exposure and risk

• Type of harm caused and relative fear (e.g. causing cancer is highly feared)

According to Vlek (1990) personal risk acceptance was mainly determined by the interest in the intended or expected benefits, the severity of a (maximum) credible accident, and the supposed process-controllability of the activity (including incidents and effects).

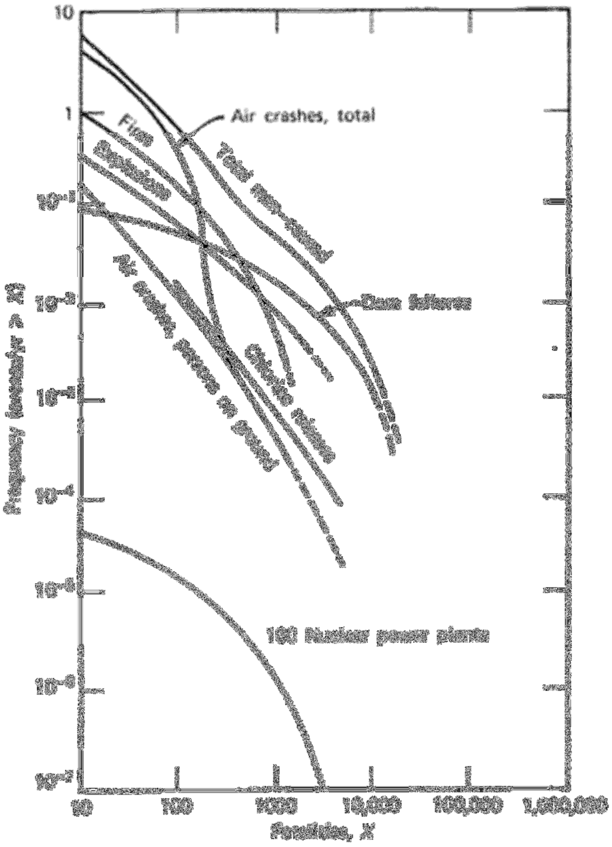

Figure 3: Risk comparison based on the frequency and consequences of human-induced events (Rasmussen, 1975)

Fischhoff and colleagues (1984) argued that there was no definition of risk which fitted for all applications, and the choice of a particular definition was actually a political choice. Risks could not be distinguished from the perceived benefits for citizens of a particular activity (Stallen and Tomas, 1985). The debate on nuclear power was thus a part of a Battle Royal over social choices for future energy supply.

A major point of criticism from psychology concerned the comparison of different types of risks as was made, for example in the WASH 1400 report in 1975. Rasmussen (1975) used a graph comparing common risks –accurately known because of widely available data – with the - on the basis of QRA - calculated individual risk for an incident with a nuclear power plant. The graph clearly shows that the calculated risks of nuclear power are much smaller than many common risks (see Figure 3). This graph was used by many proponents of nuclear energy to 'prove' its safety, and thus the acceptability of nuclear energy. It strengthened their argument that those who opposed nuclear energy on grounds of safety issues were 'not rational'. A fundamental flaw in this use of QRA, which compares calculated results of very different types of risk and was used to 'prove' acceptability, was neglecting the big differences in risk characteristics of the various types of risk considered. This approach did not take account of how the general public actually perceives 'risk', which occurs in a much more multi-faceted framework than the 'reductionist' engineering view of risk. Therefore risk acceptance was not reflected by the presented figures. Thus the criticism from psychology referred to the framing of the risk concept and to omitting several important cognitive dimensions.

There was also criticism from another field about this comparison of risks based on QRA because of the uncertainties involved. The probabilities of the non-nuclear disasters shown in the graph are based on real (i.e. historical) data, and thus had a known reliability. The probabilities of nuclear disasters, however, are calculations based on theoretical models untested by historical data; their reliability is therefore unknown. The report by Cremer and Warner (1980), cited earlier in this article, pointed out the several substantial uncertainties in estimating probabilities and consequences. The authors stressed the need to report these uncertainties, including the influence of the human factor, when discussing the results of a QRA. The quote below summarizes three important sources of uncertainty:

a. *"Application of event and fault tree analysis, can never be shown to represent every possible outcome; there can always be some failure sequence that has not been accounted for. This is like throwing a pair of dice with an unknown number of faces.*
b. *The magnitude of the consequence cannot be exactly calculated; various sources of uncertainty enter the problem. This is like thrown dice where the numbers on the faces are not exact, but are thought to be within certain ranges. The number actually on one particular face is not revealed until the throw is made.*
c. *Only certain elements of the system can be experimented with to test the model. Reliability data for some components, may be available, but other necessary information is inaccessible. This is like throwing dice where only some of the numbers on the faces are known in advance (*Griffiths, 1981)."

4.8 Risk based approach in occupational safety in The Netherlands

In the seventies and eighties the monthly Dutch safety journal 'De Veiligheid' published the first articles discussing the concept of risk and the benefits of a risk-based approach. At that time there was no experience with the concepts of probability and risk in occupational safety in The Netherlands. The legislation and the usual jargon only used the term 'danger'.

Smit (1971) argued for a risk-based approach, because accident statistics were inadequate for policy purposes and were even misleading. Other methods were required to determine whether the safety of a certain workplace was acceptable. Smith introduced the concept of risk very carefully, stating, for example: "We could call risk the product of severity multiplied by probability". A major impact of the risk-based approach is the subsequent necessity of accepting a particular risk, as it is usually not possible to reduce the risk to zero. When discussing acceptable risk criteria he refers to the criteria used in The Netherlands for flood risk. From that point onward, acceptable risk criteria and of the impossibility of zero risk formed important parts of the debate.

A number of articles in the journal 'De Veiligheid' reflected on discussions occurring during several conferences about the risk-based approach (Van der Leij, 1977; Van der Leij and Mutgeert, 1977). Notable was a paper of Van Trier presented at the safety congress in Amsterdam in 1975 (Van Trier, 1975). He changed the original lecture title from "The requirement of maximum safety as a challenge for the engineer" into "Safety and risks in technical systems". Van Trier addressed several key issues in the introduction of the concept of risk in his lecture, such as 100% safety does not exist. He urged the development of a systematic method for risk analysis that incorporates the loss of life, property damage, and social and ecological costs. The degree of voluntariness should be included in the acceptable risk criteria. Van Trier mentioned 10^{-6} [probability of accidental death per year] as a generally accepted criterion for citizens in voluntary risks. The criteria for involuntary risks should be a factor 1,000 lower. Van Trier uses the same factor published in the study of Starr (1969) in which a criterion for involuntary risk should be comparable to the risk of death by natural disasters, namely 10^{-9} [probability of death by natural disaster per year]. This probability figure differs a factor 1000 from figures mentioned by Buschman (1972) or Kletz (1981), see section 4.9.

The introduction of risk analysis would require a lot of explanation in the years following van Trier's 1975 lecture in Amsterdam. Even with a seemingly tiny calculated risk a particular incident could nevertheless occur tomorrow. And something that seemed rationally acceptable was in fact emotionally often not acceptable. The discussion following the reading of Van Trier illustrates this:

> *"Once we start doing risk analysis, and we have assessed the risk of a particular activity or a particular machine or a certain substance, and subsequently we know that something bad can happen with a certain probability, this often raises the question: so it can also happen tomorrow? and that question actually creates a kind of emotional atmosphere in which the risk suddenly becomes unacceptable.*

In The Netherlands around 1990 a risk ranking method was introduced in occupational safety (Henstra, 1992). The method was based on publications of Fine (1971) and Kinney et al (1976). QRA is usually applied to calculate a risk with a low probability and high impact. Occupational safety within companies, however, usually involved risks with relatively large probabilities and relatively small effects. In 1971 Fine presented a method for a simple and semi-quantitative risk assessment suitable for these risk categories. The method was further developed by Kinney and Wiruth in 1976 (Fine, 1971; Kinney et al, 1976). In two brief reports, the authors presented a method for determining the relative seriousness of hazards to support the priorities setting for control measures.

In particular, Fine (1971) discussed the evidence supporting the method. The method was tested in the laboratory, comparing the risk-ranking performed independently by several experts, thus calibrating the ranking method. Based on these risk rankings, the different types and levels of risk were classified with a certain weight and valuation. According to the author this classification could require adjustment in the course of time due to change of insights. The author also stressed that the method is suitable for ranking risks within a given organization.

The severity of the risk was assessed based on the potential consequences of an incident, exposure or frequency of occurrence of a dangerous situation (which can lead to an incident), and the probability that such a dangerous situation could lead to an incident with these consequences. The word scenario was not used, but the method did not allow combining the assessment of several different consequences, because the frequency of exposure and the probability would differ. The method is semi-quantitative. Thus, the probability was not calculated as a product of the probability of successive events, but was estimated as the probability of a sequence of the respective events occurring after each other. The risk score was calculated by the following formula:

Risk score = probability x exposure x consequences

The method presented a rating scale of six of seven categories for each of the three factors. For each factor the two extremes were first determined, such as the most serious and least serious consequence. Then, the intermediate categories were used for the other possible consequences, with the distance between the categories plotted on a logarithmic scale. The assessment of the possible consequences included both personal injury and property damage (see Figure 4).

Likelihood	**Value**
Might well be expected	10
Quite possible	6
Unusual but possible	3
Only remotely possible	1
Conceivable but very unlikely	0.5
Practically impossible	0.2
Virtually impossible	0.1
Exposure	**Value**
Continuous	10
Frequent (daily)	6

Occasional (weekly)	3
Unusual (monthly)	2
Rare (a few per year)	1
Very rare (yearly)	0.5
Possible consequence	**Value**
Catastrophe (many fatalities, or > 10^7 USD damage)	100
Disaster (few fatalities, or > 10^6 USD damage)	40
Very serious (fatality, or > 10^5 USD damage)	15
Serious (serious injury, or >10^4 USD damage)	7
Important (disability, or > 10^3 USD damage)	3
Noticeable (minor first aid accident, or > 100 USD damage)	1
Risk situation	**Risk score**
Very high risk; consider discontinuing operation	>400
High risk; immediate correction required	200 to 400
Substantial risk; correction needed	70 to 200
Possible risk; attention indicated	20 to 70
Risk; perhaps acceptable	<20

Figure 4: Risk ranking in occupational safety (Kinney et al,1976)

Both Fine and Kinney and Wiruth presented the method as a tool for decision support to determine the priority for intervention. With additionally, Fine (1971) argued that routine safety inspections and investigations yielded long lists of hazards, and therefore that the cost of control measures should be justified on the basis of risk instead of the persuasiveness of a safety expert.

This method was more dependent on expert judgement than the QRA methods which were based, partly, on data of fault tree analysis and effect analysis. The risk scores of different types of industry could not be compared and the method was only suitable for ranking risks within a given organization as stressed by Fine (1971).

4.9 The acceptability of risks

QRA was meant to support decisions on risk acceptability. As mentioned earlier (Par. 4.7; in particular, Figure 3), based on a quantitative risk analysis the American National Radiation Council (NRC) argued in 1975 that the probability of death to the public caused by an incident occurring at a nuclear power plant is acceptable, because this risk is much smaller than other generally accepted risks associated with dam breaks or air-travel (Rasmussen, 1975). This argument drew criticism because the risks were not comparable (Griffiths, 1981). Another point of criticism was the incompleteness of the scenario analysis, but this objection was also applicable to the risk analysis of industrial risks, with which the nuclear risks were compared by Rasmussen (Kaplan and Garrick, 1981).

Buschmann (1972) considered a mortality rate of 10^{-7} per year to be negligible. He based this on an accepted probability level for flooding achieved by Dutch coastal protection. At that time the Dutch parliament had decided upon an acceptable accident probability. This had been done when discussing the necessary height of levees along the coast protecting the country against flooding during storms. Balancing the costs of raising the dikes to different levels resulted in an accepted probability of flooding in the coastal areas to once in 10,000 years (10^{-4}). At a mortality rate of about 1:1000(10^{-3}) in a flood, this gives a mortality rate per inhabitant per year of 1×10^{-7}. This is 1/10 of the probability of death due to natural disasters in the United States. "

Zielhuis (1984) addressed a number of tough questions in that period in determining the acceptable risk from occupational exposure to carcinogens. What was needed were quantitative standards for acceptable exposure limits; it was insufficient to state that the exposure "should be as low as possible." There was thus a need for reliable standard setting that could be reviewed and validated by third parties. These standards for exposure limits should be based on transparent criteria for preventing unacceptable health effects in general or, more specifically, for preventing specific health effects for calculated fraction of employees at an exposure of 8 hours per day, 5 days a week for an entire working life**.** Earlier the Health Council of The Netherlands (1978) had published a report on carcinogenicity of chemicals, and one of the first recommendations of the Dutch Expert Commission (WGD) also involved the assessment of the risks of carcinogens. Zielhuis, involved in both publications, discussed in detail the many questions involved in setting standards, at such as variation between individuals, variation in daily exposure, and extrapolation of results of animal experiments to humans. Zielhuis (1984) ended his publication as follows: "from both of the Dutch Expert Commission of the Ministry of Social Affairs (WGD) as well as the occupational physicians in practice, a response is expected in areas that even angels are reluctant to tread". The Health Council of The Netherlands and the WGD (1979, 1980) distinguished between two categories of substances:

1. Substances causing an irreversible self-replicating effect, i.e., causing a permanent change of structure in the DNA: *initiators*
2. Substances that are active through other mechanisms: *promoters or co-carcinogens.*

This distinction was crucial for setting acceptable limits as it explicitly stated that for the first category of substances no safe threshold could be determined. While for the second category a safe threshold could be established based on a *no-effect-level*. For the first category of substances the *one-hit* principle was introduced, meaning: one single molecule of the substance in question in one interaction with a cell can initiate an effect, a change in DNA, causing, with a certain probability, cancer to develop. This *one-hit* principle was adopted from knowledge of health effects of ionizing radiation. For exposure to the first category carcinogenic substances the WGD presented a basis for calculating acceptable risk, as follows: exposure to x micrograms/m^3, for 8 hours per day, 5 days per week, for 35 years, results in a probability of developing a specific form of cancer in 1 in 10,000 employees. By linear extrapolation from this basis and after balancing various interests the Dutch national committee for occupational standard setting could establish an exposure limit that corresponded to a certain accepted risk.

Zielhuis (1984) referred to the Scientific Committee of the Food Safety Council in the U.S. that bases its standards on a 'near-zero' risk of 10^{-6} to a lifetime exposure of the general population. The Food Safety Council proposed this value as a measure of a negligible risk, Later this same value (10^{-6}) appeared in many different policy areas as a criterion for acceptable risk (Kelly, 1991). For the first category of carcinogens the Dutch government applied the same criterion as used for ionizing radiation: a maximum probability of death of 10^{-6} per year. Only in the case of carcinogenic substances was this an accepted risk limit whereas for ionizing radiation it was a target value representing a negligible risk.

On the origin of the value of 10^{-6} per year as a negligible risk level many different views can be found in the literature. Wildavsky (2008) argued that the 10^{-6} criterion had largely a symbolic value. Others mentioned that the limit was based on the belief that the acceptable risk of an industrial activity should not exceed the risks of natural hazards citizens are exposed to, such as floods, earthquakes, and lightning, which are around (or less than) 10^{-6}(Kletz, 1981).

5. The period after 1990: Risk becoming an accepted concept

In the period after 1990, risk and risk-based approaches for safety were accepted and established in The Netherlands. At that time the textbook series ‘Coloured books’ formed a complete methodology for carrying out quantitative risk analysis (QRA) in the area of hazardous substances and received much international recognition. Also in the field of delayed health effects, in particular cancer caused by exposure to carcinogens, the concept of risk was a basic term used in setting standards for exposure to toxic chemicals. In the Dutch occupational safety domain the introduction of the so-called Risk Inventory and Evaluation (RI&E) procedures into the occupational health and safety legislation caused the concept of risk to become a central item in virtually all discussions of safety (Zwaard, 2007).

5.1 Process Safety: quantitative risk analysis methods combined in textbook series

The fourth and final part of the textbook series ‘Coloured books’, the Purple Book (CPR 18, 1999), was published at the end of the nineties. The Purple Book included calculation rules and criteria for performing a QRA. Criteria were given for deciding which installations of a certain industrial plant should be part of a QRA and which could be excluded. This final publication in particular has been strongly criticized. The publication presented the agreements on selecting the installations to be analysed, determination of the relevant occurrences of LOC (Loss Of Containment), relevant subsequent events, corresponding effect and damage calculations, and, finally, presentation of the results. The Purple Book presents the Dutch approach, which is based on criteria of only considering "containments" with more than a certain amount of a specific hazardous substance. Subsequently, for these containments the probability of failure was determined, based on historical data. A more thorough, but also time-consuming method, is a systematic identification of hazards, describing and analysing relevant detailed scenarios using Hazard and Operability Studies (failure analysis). These methods were available at that time (Lawley, 1974). A QRA based on a previously carried out hazard identification and HAZOP would give a better view of the failure probabilities, of conditions and process data specific to the site in question, on relevant human behaviour, and on where and how safety could be improved. The Dutch Ministry of Social Affairs and Employment has always been highly in favor of the latter approach. Later also research was initiated to add management as a modifying factor in the QRA (Sol, 2011).

From the start and first drafts of the 'coloured books' much discussion took place about the uncertainties of the models used. Uncertainty in the parameters of the effect models gave variations in the results of a factor of two to six. The damage models also contained large uncertainties. The green book mentions model uncertainties (inter-individual variation and differences between buildings) and parameter uncertainties (population data, toxicity data, and the influence of escape behavior on exposure time). These uncertainties resulted in a large variation in the final calculated risk. When comparing different research teams, the calculated risk varied by orders of magnitude (Lemkowitz et al, 1995; Pasman, 2011) with large differences for the risk contour around an installation (Hazardous Substances Council, 2010).

5.2 Exposure to carcinogenic substances: basis for determining an acceptable risk level

A standard for a maximum acceptable risk for exposure to genotoxic substances was proposed by the Dutch board for occupational health and safety in 1992 in an advisory report. The Board referred to the ministerial memorandum ‘Dealing with risks of radiation; ionizing radiation limits for workplaces and the environment' from 1990 (Ministry of Housing, 1990). In the Board delegates from employers and employees had different opinions about the maximum difference in risk level between the general population and labour force employers and employees:

> "The delegates of the employees believe that the risk for workers in the field should be equal to that of the general public, i.e. 10^{-6} per year. (...) The employer delegates (...) are of the opinion that the standard risk limit of incidents with fatal result in the so-called safe industry should be used, namely 10^{-4} per year (...)".

The Board proposed to strive for a risk level for each substance of 10^{-6} per year (the so-called target level) and in any case not to accept a higher risk of maximum 10^{-4} per year (the so-called banning level).

5.3 Occupational safety: introduction of the concept of risk inventory and evaluation (RI&E)
In 1989, the concept of risk was formally introduced into the Dutch occupational safety domain through with publication of the EC Framework Directive 'Safety and Health at Work'. In the EU Directive, the main elements of risk were defined. Anticipating on the implementation of the EC Framework Directive (EC, 1989) in The Netherlands methods for risk ranking and semi-quantitative assessment of risks as described above (section 4.8) were being used increasingly by safety engineers in The Netherlands when performing the risk assessment and evaluation (RI&E) that would be anchored in the Dutch health and safety legislation from 1994 (Henstra, 1992). The Dutch regulation spoke moreover not yet of 'risk,' but of an "inventory and assessment of hazards, while the European Framework spoke only of risks. Only in 1999 (when the Working Conditions Act 1998 came into force) did the word "risk" appear for the first time, in Article 5 of the Working Conditions Act (Zwaard, 2009).

6. Discussion and conclusions

We begin this section on providing answers to the three research questions presented earlier, namely:

1. What developments were decisive for introducing the concept of risk in safety science in The Netherlands?
2. Which theories, models, and metaphors were developed in the considered period (1970-1990)?
3. What differences exist between the introduction of the concept of risk into occupational safety and into process safety?

Thereafter we provide some additional discussion and concluding remarks.

6.1 Developments decisive for introducing the concept of risk in safety science in The Netherlands
In the seventies several factors urged for the introduction of the concept of risk into the Dutch safety science field. With the rapid industrial development and up scaling of the process industry the number of incidents increased. These developments required a rationale for decisions concerning the prevention of losses in the process industry. The land use planning with development of new industrial plants, the possibility of major consequences of an incident and the introduction of new technologies (nuclear energy production, introduction of new fuels like LPG) were the subject of a

public debate. The research focused on quantification of risk as a basis for better controllability and acceptability of these developments (Pasman and Snijder, 1974; Ale, 2002 en 2003).
The risk-based approach was seen as a rational tool for decision making about investments for additional control measures (Buschman, 1972). The large scale introduction of LPG as a motor fuel and the development of industrial Rijnmond area were the first cases where QRA methods were applied in The Netherlands. The calculation of the risk served to aid decisions on process adjustment or safety improvement.
Right from the start of the development of QRA in The Netherlands psychological research on risk perception challenged the assumption that the results of this risk analysis formed a sufficient basis to decide on the acceptability of risks (Vlek and Stallen, 1979). This psychological approach challenged the identification of scenarios as well as the comparability of different effects.
But perhaps the most revolutionary aspect of the introduction of the concept of risk was the societal debate on the fact that absolute safety is an ‘idee fixe’ (Smit, 1971; Buschmann 1972). A risk-based approach inevitably introduced the debate on the acceptability of a certain risk level and of the combination of both probability of unwanted effects and the possible benefits (Buschmann, 1972).

6.2 Theories, models, and metaphors developed in the considered period (1970-1990)

In the QRA methods several existing models (HAZOP and fault tree analysis) were combined and developed. Effect and damage models were newly developed specifically for the scenarios considered and related to fire, explosion, and/or toxic effects. In all these scenarios, the properties of hazardous substances played an important role; indeed, the theme “hazardous materials” played a pioneering role in the use of risk models used in QRA (CPR 1982; TNO 1983).

The probabilistic approach developed in flood risk management formed one of the fundaments for the QRA approach in The Netherlands. But the scenario analysis in flood risk management was restricted to the overflowing of the dikes and no other damage models were used. Whereas in QRA the fault tree analyses were used from the operation research approach and failure probability figures were based on input from process industries and from the reports on the nuclear industry.

The development of QRA was based on the theoretical concept of risk as a product of probability and effect and the calculation of the probability of a particular set of independent events, the axioma of Kolmogorov (1956). This concept of risk changed the safety approach in The Netherlands in process safety as well as in flood safety. Quantification of risk formed the new basis for decisions on prioritizing various safety measures.

The introduction of the concept of risk resulted also in a debate about the process of risk assessment. Several variations of this process (see figure 2 as an example) were used but they all clearly distinguished between two fundamentally different questions, namely: 1. How large is the risk? (e.g. with what probability will which number of people be killed?)[1], and 2. Is this risk (quantified and thus known) acceptable or not acceptable?[2] The successive steps of the risk assessment process are summarized as follows:

The first question was the subject of the QRA[3]. This was seen as a scientific procedure which, in theory, can result in an absolutely correct numerical answer. In practice, however, many uncertainties exist due to the complexity of the calculations involved. These usually involve choosing certain scenarios (maybe certain scenarios are missed), making many assumptions (some of which may be incorrect or not be applicable), choosing models (which are always simplifications of reality), and using imperfect data (e.g. data missing, incomplete, or incorrect). Thus the reliability of methods and tools used is open to question and the correctness of the calculated risk cannot be proved. The QRA was at that time the best available knowledge. But the epistemological question, i.e. the question of “reliable knowledge”: “What is true?” was difficult to answer with I.e. is the numerical value of the calculated risk valid/reliable? Is it true?

The second question about the risk acceptability was seen as a societal issue. This question involves the ethical question "What is good?"(i.e. is accepting the risk (ethically)a good or a bad decision?). In practice, however, the difference between these two basic questions was not always recognized. The risk assessment and eventually the risk perception was often an important political issue. Debates about the outcome of a QRA often challenged the validity/reliability of the calculated risk as well as the acceptability of the risk.

6.3 Differences between the introduction of the concept of risk into occupational safety and into process safety

The introduction in the occupational safety field in The Netherlands was delayed by another ten years compared to the major hazard industries. It was introduced in that domain through the assessment of exposure to carcinogenic substances. But in occupational safety, the introduction of risk also initiated a fundamentally different way of thinking. In the years before, the notion of hazard had been the central factor in the safety approach of the professional field of safety technology and in occupational safety regulation. The introduction of the concept of risk added a nuance to the concept of safety: Since absolute safety does not exist, discussions about acceptance of risk levels were forced upon occupational safety experts. This weakened the negotiation position that occupational safety experts had in efforts to convince corporations to invest in greater safety. This weakening of negotiating position was the major reason why the concept of (and word) risk was not formally incorporated into the Dutch health and safety regulation until the end of the last century.

Around 1990, when risk analysis established in most safety-related domains, the need arose for ranking different risk or dangerous situations at the workplace. This was even more challenging

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[2] “Is the risk acceptable or not acceptable?” is related to another type of fundamental philosophical question (the ethical question): “What is good?” I.e. is accepting this risk ‘morally good’ or ‘morally not good’ (thus ‘bad’)?

[3] How large is the risk?” is related to a fundamental philosophical question (the epistemological question, i.e. the question of “reliable knowledge”): “What is true?” I.e. is the numerical value of the calculated risk valid/reliable? Is it true?

than introducing risk into the process industries, as the workplace situation involves not only risks of hazardous substances, but a multitude of types of safety risks involved in the general working situation (e.g. from falling off a ladder in the construction industry to being electrocuted when repairing high voltage power lines).

In occupational safety the introduction of the concept of risk as a function of probability and impact provided a rational basis for ranking of different hazardous situations. In occupational safety there was no debate on whether to broaden the concept of risk and including risk perception, such as had been suggested by a number of psychologists studying around process safety and external safety. The main reason for this seems to be that the calculated risk was not used to assess the absolute acceptability of situations, but was used only comparing different hazardous situations.
The semi-quantitative methods, as described by both Fine (1971) and Kinney and Wiruth (1976) were widely used in The Netherlands after the implementation of the EC Framework Directive. It is striking that this acceptance had occurred with hardly any debate occurring on the reliability and reproducibility of these methods.

6.4 Additional discussion and concluding remarks

Development of quantitative models

The development of QRA represents a major change in the field of safety, in which in post-World War II period the psychological approach had been replaced by epidemiological models (Haddon) and accident theories (Winsemius). Moreover it is a period, in which practical application still considered human failure to be the dominant explanation for the occurrence of accidents (Swuste et al, 2014b). In this light, it is noteworthy that QRA is mainly based on technical failure of equipment. Thus a first criticism of QRA arose, namely the lack of consideration of human factors and management, which was regularly cited in publications. However, in the 1980s, advocates of QRA did not consider it practicable to quantify human failure and failing management (Griffiths, 1981), although among others Kletz (1981) advocated including the probability of human error and the quality of management within the incident scenarios calculation, even if these factors could only be roughly estimated[4].

A second criticism of QRA concerns the restriction of the analysis to conceivable scenarios. The risk assessment is therefore largely determined by the choice of scenarios, thus also those not chosen; in other words, the chosen system boundaries. Methodologies for systematic hazard

[4] In the next article from this series the period (starting from1990) of safety management system and safety culture is discussed, when research focused in particular on the human factor (Swuste et al, 2015)..

identification (e.g. HAZOP) and scenario analysis improved the reliability and reproducibility of QRA [5]. The choice of the scenarios reflect the borderline area between uncertainty and risk, such as Knight in 1921 and Keynes in 1937already discussed (Bernstein, 1996; p 249-265).. If we see risk as a measurable uncertainty, we must clearly distinguish it from the non-measurable uncertainties. Knight cited examples of predictions about future developments that are highly tricky. In the area of safety there are such unimaginable scenarios, which may nevertheless occur, but which are not considered in the QRAs. The distinction made by Knight and Keynes between risk and uncertainty is still relevant in the discussion about safety. An example is the question of who is liable for the damage after a disaster when the company concerned cannot be blamed. The WRR (2008), a Dutch advisory board, has raised this question. Hazards that are not recognized, scenarios that are inconceivable, are, after all, not considered in QRAs. The current Dutch liability legislation is based on the risks that have been estimated, not those which have not been considered. The expansion of liability that the WRR proposes concerns such uncertainties – uncertainties for which no prior estimates can be made, but which nevertheless later turn out to be linked to the cause.

Risk as a new paradigm

QRA paved the way for a new safety paradigm. In the safety science domain QRA became the basis for safety evaluations and acceptance in high-risk industries. Still serious improvements in methods were needed. At the same time a more fundamental debate about the use of this risk concept in societal decisions on risk acceptance was started by social science disciplines as well as within the safety science.

Risk as a concept (or model) based on a combination of probability and impact became widely accepted in many fields, including safety engineering. Models and tools based on this concept of risk are much used, particularly in the area of hazardous substances and hazardous installations (e.g. chemical plants, nuclear facilities). These tools provide a more reliable and substantiated way to quantify risk (risk assessment) than those tools which existed before use of the concept of risk became widespread. However, uncertainties, in particular estimations of failure probabilities, insufficiencies in data, and inadequacies of models (physical and biological) still cause large variations in the calculated risk. The choice whether or not to consider certain scenarios and the definition of system boundaries also can greatly influence the calculated risk. The building blocks for QRA were actually formed in the period under consideration (1970 to 1990), but in the quest for more knowledge and better understanding about what can harm us there is most certainly room for improvement (Hazardous Substances Council, 2010).

[5] Much later methodologies from occupational safety, such as the bowtie model, story builder method, and GISAI, further improved QRA. However, the time period that these methodologies were introduced into QRA falls outside the time period considered in this article (Fisher, 1998; Sol, 2011).

This article discusses the debate both in the safety science domain about the reliability of QRA and in social sciences about the more fundamental issue of using the risk concept for societal decisions on risk acceptability. Buschmann (1972) advocated a risk-based approach to get a clear criterion for the acceptable limit of risk and to evaluate all the social implications of any new technological development, including risk, in advance. Griffiths (1981) added more nuances and also recognized the need that technological activity with the potential to cause damage requires an informed (risk-based) choice of the best technology or justification of investment in security. Dobben (1976) considered quantitative risk evaluation as a step in the process of safety management. Griffiths (1981) advocated using the concept of risk in which different points of view can also be taken into consideration, since involvement of various stakeholders, often with different interests, influences their judgment of a risk assessment and their acceptance of a given risk. The debate on whether or not to fully encompass the concept of risk into a number influenced the debate about the role of the risk-concept in safety in The Netherlands. The publications of Vlek and Stallen (1979) on risk perception contributed to this debate and started the discussion in The Netherlands about a risk concept that incorporated important cognitive dimensions.

The publication of Rowe (1977) had a central place in the reference list of the LPG study (TNO, 1983) and the textbook series ‘Coloured books’. Already at the end of the seventies Rowe suggested that the quantification of risks (risk quantification) is just as important as the judging whether a given quantified risk is acceptable or not acceptable (risk acceptance). Rowe noted further that the subjective perception of risk is the basis of societal acceptance of risk, regardless of the (objectively determined) quantified risk.

> *"One school holds that probabilities are primarily reflections of the actual frequency of occurrence of events; Therefore probabilities are objective. Another school holds that the assignment of probabilities primarily reflects the assigner's belief or confidence that the events in question will occur "(Rowe, 1977).*

It is here in fact argued that the sharp distinction between risk quantification and the judgment of whether risk is acceptable cannot be made. In the eighties pleas were regularly made calling for a clearer distinction between the objective process of risk quantification and subjective interpretation of the significance of the estimated risks.

The discussion concerning the acceptability of risks and the decision making process concerning risks is not yet completed. In The Netherlands, especially after 1990, the search for new models and tools led to a study in which various types of risks were compared (Health Council of The Netherlands in 1996 and 2008). This search also continues to this day.

With the introduction of the concept of risk, both in process safety and occupational safety, the paradigm shift was complete. Quantification of risk became an important part of nearly all safety decision making processes. While methods for quantifying risk are now widely applied and accepted, the proper use of risk perception and risk in the political decision process are still being debated.

7 Literature

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