ELSEVIER Journal of Hazardous Materials 43 (1995) 245–261

JOURNAL OF HAZARDOUS MATERIALS

A framework for risk evaluation

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Received 20 October 1994; accepted in revised form 22 March 1995

Abstract

Human civilizations are threatened by natural hazards and by risks connected to technological progress in civil, chemical and nuclear engineering. The notion of acceptable risk forms the basis for the design of many engineering structures ranging from simple river levees to nuclear reactors, that contribute to human welfare. A frame work is developed to judge the acceptability of risks from an individual and a societal point of view.

Keywords: Design; Acceptable risk; Individual risk; Societal risk; Cost/benefit

1. Introduction

Human civilizations and their environment are threatened by many hazards. Some are centuries old natural hazards like floods, earthquakes, etc. that have increasing consequences in developed societies, others are man-made and result from the technological progress in civil, chemical and nuclear engineering. Human civilizations try to protect themselves against these hazards after their occurrence has shown the consequences or when the risks are felt to be high. Risk is a part of the judgement that people have when they think of activities that are dangerous in some respect, like living beside a chemical plant, flying or driving a motor-cycle. Such judgements of unlikely but imaginable adverse scenario's are subjective and in many cases contradictory to statistical facts, but they form the basis of acceptance.

The idea of acceptable risk or safety may change quite suddenly due to a single spectacular accident. Examples of a sudden loss of a safe feeling are the catastrophe at Bhopal, Chernobyl, the plane crash at Schiphol airport in 1992, and the river floods of 1993 and 1995 in the Netherlands. Public opinion is influenced not only by the accident itself, but maybe even more by the attention which is paid to it by the media.

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0304-3894/95/$09.50
SSDI 0304-3894(95)00041-0

Of course in an advanced technological society politicians should not only base their decisions upon above mentioned subjective interpretations of risk and its acceptability. As the notion of acceptable risk forms the basis for the design of many technological wonders, ranging from simple river levees to advanced nuclear installations, that contribute to the welfare of the western nations, politicians should have a more or less objective framework for risk evaluation. This paper proposes the outlines of a possible framework, that can serve as a rational basis for technological design. Its focus is on the Dutch situation, but taking into account the relation to the size of Holland, the outline should be generally applicable.

2. Acceptable risk

Generally two points of view appear in studies of acceptable risk levels [1–3]. The first point of view is that of the individual, who decides to undertake an activity weighing the risks against the direct and indirect personal benefits. An important aspect is the degree of voluntariness with which the decision is taken and the risk is endured. In the personal sphere these decisions, e.g. to ride a motorcycle, are freely and quickly made knowing that the choice can be immediately amended if the risks turn out to be higher than expected. In the case of societal decisions involving risk however the individual can still make his appraisal in accordance with his own set of standards, but his influence on the final outcome is democratically limited. This might imply a sense of involuntariness and compel him to adopt a sceptical attitude towards (involuntary) risks imposed by societal decisions. The following characteristics result:

(1) The decision to accept risk has a cost/benefit character.
(2) Risk acceptation depends on the degree of voluntariness.

The first point of view leads to the personally acceptable level of risk or the acceptable individual risk, defined in [4] as "the frequency at which an individual may be expected to sustain a given level of harm from the realization of specified hazards". The specified level of harm is narrowed down to the loss of life in many practical cases.

The second point of view is that of the society, considering the question whether an activity is acceptable in terms of the risk involved for the total population. Although in principle the societal decision making process for every project weighs the social benefits against the social costs including risk, in the widest sense, this process of appraisal is not easily made explicit. The socio-political optimization process is accomplished in a tentative way, by trial and error, in which the governing bodies make a choice and the further course of events shows how wise this choice was. By its nature society looks to the total damage done by the occurrence of an accident, which may comprise a number of casualties, material and economic damage and the loss of or harm to immaterial values. Commonly the notion of risk in a societal context is reduced to total number of casualties [1–3] using a definition as in [4]: "the relation between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards". If the specified level of harm is narrowed down to the loss of life, the societal risk may be modelled by the frequency of exceedance curve of the number of deaths, also called the FN-curve due to a specific hazard. In other publications the consequence part of a risk is limited to the total material damage expressed in monetary terms [3, 4]. It should be noted however, that the reduction of the consequences of an accident to the number of casualties or the economic damage may not adequately model the public's perception of the loss. Modelling aims to clarify the reasoning at the cost of comprehensiveness.

To discern the individual point of view from the societal the following example may be helpful. Imagine the introduction of a new, from individual point of view, fairly safe toy causing 10^{-4} deaths per toy per year. In the year of introduction when only 1000 toys are sold (expected deaths 0, 1 per year) there will most probably be no publicly felt consequences. However the following year, when the toy becomes a hit and suddenly 10^7 items are sold, the resulting 1000 deaths per year will not be accepted by society. Ministers will be required to take action. Generalizing from this example it is clear that the societal risk is judged at a national level, i.e. the total risk in a year (casualties as well as material and immaterial damage related to the frequency) connected to a certain activity. This is a wider concept of societal risk than proposed in the approaches of the Dutch Ministry of Housing, Land Use Planning and Environment (VROM) [1] and the British Health and Safety Executive (HSE) [2], where societal risk is defined as the relation between the frequency and the number of casualties per installation per year. The HSE [2] however makes a distinction between local and national risk noting that "small unrestrained developments could add up to a noticeable worsening of the overall situation".

The third characteristic follows:

(3) Acceptance of societal risk takes place on a national level.

3. Risk

Throughout this paper it is assumed that the probability of a fatal accident for one activity i at one place j in one year is small and that the probability of two or more accidents in one year is (very) small and negligible. This assumption and its implication allow us to derive the probability density function (p.d.f.) of the annual number of deaths straightforwardly from the FN-curve, without having to spell out the Poisson process that governs the annual number of accidents. The p.d.f. of the annual number of deaths N_{dij} for activity i at place j can have many forms. Three forms are presented here to facilitate further thinking. The first is a Bernoulli one, that limits the outcomes to zero or N fatalities.

The second, that allows for a greater variation in the outcome, is the exponential distribution. The probability of exceedance curve of the number of fatalities, that can be derived from the exponential form reflects to some extent the FN-curves that result from practical quantitative risk assessment (QRA) studies.

The third is the little known inverse quadratic Pareto distribution. This distribution is of special interest, because it coincides with the type of norm put forward by the Ministry of VROM [1]. The p.d.f.'s and the probability of exceedance curves of all

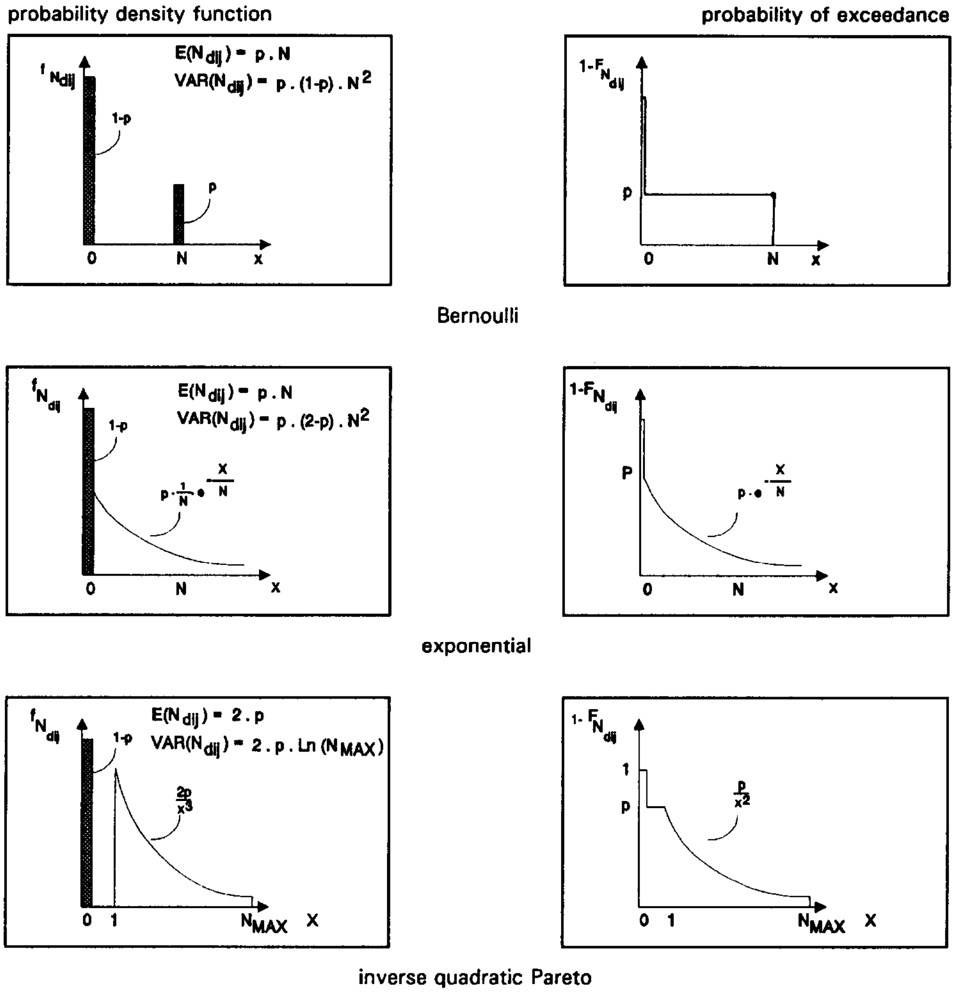

Fig. 1. Theoretical p.d.f.'s and probability of exceedance curves for the number of deaths.

three forms are given in Fig. 1. Exactly the same models could be applied for the material damage that results from a disaster like an explosion or a flood, if the horizontal axis is measured in monetary units.

4. Present safety policy in the Netherlands

Many planning decisions have to be made regarding the location of sometimes hazardous chemical industries. The aspect of hazard to the surrounding inhabited areas in case of a new industrial activity or in case of a new settlement near an existing activity is recognized in the policy of the Ministry of VROM in the Netherlands. The criteria for LPG systems issued by the Ministry [5] and later explained in more detail in the Dutch National Environmental Plan [1] will be described now. Given its task the Ministry concentrates on hazards posed by industrial and other developments to the lives of the inhabitants of surrounding areas. Potential economic losses are not taken into account. The safety of people that are professionally connected to the hazardous activity falls outside the competence of the Ministry of VROM as it is the responsibility of the Ministry of Social Affairs.

4.1. *Personally acceptable level of risk*

The individual acceptable risk is defined as the acceptable probability of death due to an accident attributable to a third party. As a basis for the acceptable risk the life-table for the Dutch population was used. This statistic shows that boys between 6 and 20 yr old, the group most unlikely to die in any single year, have a death rate of 10^{-4}. This probability results from all causes, natural as well as accidents.

An acceptable hazardous activity should add less than 1% to the already existing probability of death. As it is also assumed that a person is present during 24 h a day at the fence surrounding the area where the activity is performed, the acceptable probability of failure from the individual point of view becomes

$$P_{\mathrm{fi}} < \frac{10^{-6}/\mathrm{yr}}{P_{\mathrm{d|fi}}}, \tag{1}$$

where $P_{\mathrm{d|fi}}$ denotes the probability of being killed in the event of an accident. This probability is not used in the binomial sense assuming independence for every individual threatened, but is rather interpreted as a fraction. The criterion should be met everywhere outside the plant's fence. The rule for the acceptable individual risk does not account for the possible beneficial character of the activity as it contains no extra factor to reflect this aspect. It should be stressed however that its intended use is limited to situations of more or less involuntarily imposed risks related to the siting of hazardous activities.

4.2. *Socially acceptable level of risk*

The socially acceptable risk as defined by VROM concentrates on the consequences, in terms of loss of life, of an accident at a single location where an activity is performed. The societal risk of an activity is considered acceptable if the probability of exceedance function of the number of deaths, the FN-curve, fulfils the following requirement:

$$1 - F_{N_{dij}}(x) < \frac{10^{-3}}{x^2} \quad \text{for } x \geqslant 10 \text{ deaths}, \tag{2}$$

where: $F_{N_{dij}}$ is the c.d.f. of the number of deaths resulting from activity i in place j in one year.

Every activity performed at an independent place has to conform to this requirement. For the specific type of inverse proportionality with the square of the number of deaths no explicit reason is given in [1] or [5]. The curve is the outcome of a political process, that finally accepted the death of 10 people in case of the failure of a LPG station with a probability of 10^{-5} per year.

For static installations the application of the rule for the socially acceptable risk poses no special problems. But for transportation the total risk exceeds the norm and the applicability is questionable. One solution requires the definition of a unit to which the norm is applied, e.g. a standard unit of track length or runway. As no theoretical concept guides this definition the choice is rather arbitrary.

5. A framework of acceptable risk

In all concepts the most stringent of the *personally* and the *socially* acceptable level of risk determines the acceptable level of risk. So both criteria have to be satisfied.

It was also stated that every socio-political decision to accept a risk is taken in a cost/benefit framework where risk is only one of the aspects. So in many cases it will be mandatory to include elements of the socio-economic context of the proposed activity, if one intends to decide on a risk level. The framework has to provide some flexibility to allow for cost/benefit considerations or some formal cost/benefit analysis should be included.

The societal risk criterion as presented by the Dutch Ministry of VROM is directed at the plant level and it neglects the total risk on a national scale, both in human lives and in economic damage. This may well be an important cause of the difficulty in applying the criterion to transportation and to the national airport Schiphol.

A philosophy for acceptable risk comparable to [1], that takes into account the last two points, was developed by the Technical Advisory Committee for Water Retaining Structures (TAW) [3]. The philosophy is cast in a cost/benefit mould, albeit not explicitly modelled. The safety standard consists of a flexible evaluation of the individual and the societal acceptable risk but adds to these an economic approach taking the material damage into account. The latter provides the link with the safety philosophy of the Dutch dikes that was developed after the 1953 flood [6, 8].

In the following section a new framework will be developed that combines the strong points of the VROM and the TAW approaches.

5.1. Personally acceptable level of risk

The smallest component of the socially accepted level of risk is the personal assessment of risks by the individual. As an attempt to model this appraisal procedure quantitatively is not feasible, it is proposed to look with the insight gained to the preferences revealed in the accident statistics.

The actual personal risk levels inherent to various activities show statistical stability over the years and are approximately equal for the Western countries, indicating a consistent pattern of preferences. The probability of losing ones life in normal daily

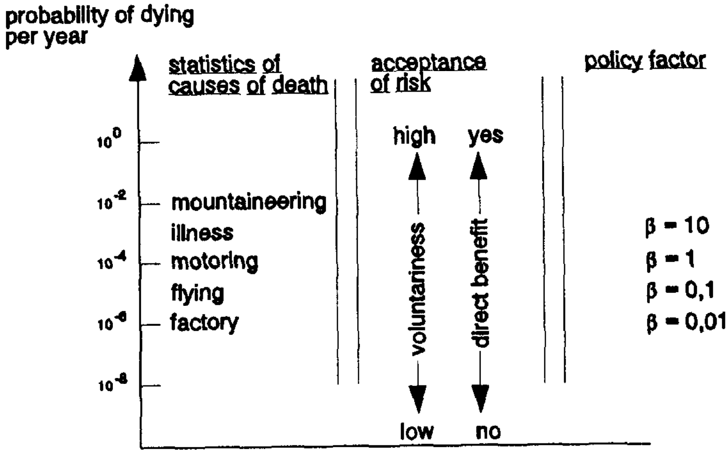

Fig. 2. Personal risks in Western countries, deduced from the statistics of causes of death and the number of participants per activity.

activities such as driving a car or working in a factory appears to be one or two orders of magnitude lower than the overall probability of dying. Only a purely voluntary activity such as mountaineering entails a higher risk. This observation of public tolerance of 1000 times greater risks from voluntary than from involuntary activities with the same benefit was already made by Starr [9]. Fig. 2 gives the acceptable personal risks for a few activities, deduced from the statistics of causes of death and the number of participants per activity.

In view of the consistency and the stability of the death risks presented, apart from a slightly downward trend due to technical progress, it would appear permissible to deduce therefrom a guideline for decisions with regard to the personally acceptable risk. The probability of an accident or failure P, associated with a certain activity should meet the following requirement:

$$P_{\mathrm{fi}} = \frac{\beta_i \cdot 10^{-4}}{P_{\mathrm{d|fi}}}. \tag{3}$$

In this expression the policy factor β_i varies with the degree of voluntariness with which an activity is undertaken and with the benefit perceived. It ranges from 10 in the case of complete freedom of choice like mountaineering, to 0.01 in case of an imposed risk without any perceived direct benefit.

This last case includes the individual risk criterion proposed by VROM for the situation of a hazardous installation sited near a housing area without any direct benefit to the inhabitants, see Eq. (1).

5.2. *Socially acceptable level of risk*

The basis of the framework with respect to societal risk is an evaluation of risks due to a certain activity on a national level. The risk evaluation on a national level has to

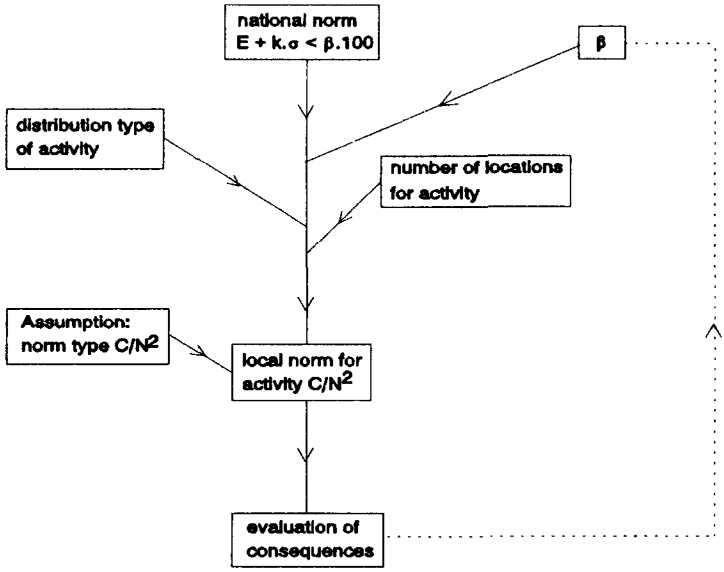

Fig. 3. Framework for risk management.

be translated to local installations or activities in order to support a systematic appraisal by the local authorities. If a risk criterion is defined on a local level as in [1] by VROM, the height of the national risk criterion is determined by the number of locations, where the activity takes place, and by the type of probability density function of the consequences of an accident. The resulting national norm has to be evaluated for its economical, social, environmental, political and safety aspects, as it was not intentionally formulated.

It seems preferable to start with a risk criterion on a national level and to derive the local risk criterion taking due account of the estimated future number of independent places where the activity will take place. The acceptable local risk level has to be evaluated regularly in view of the actual number of installations, the cost/benefit aspects of the activity and the general progress in safety. The local risk criterion should be adapted as a result of this evaluation, making the determination of the norm an iterative process with say a 10 year cycle (Fig. 3).

5.2.1. Nationally acceptable level of risk

The determination of the socially acceptable level of risk starts from the proposition that the result of a social process of risk appraisal is reflected in the accident statistics. It seeks to derive a standard from these revealed preferences. The standard of appraisal for socially acceptable risks should be based on a model for the social perception of risk. As a model hypothesis it is stated that an individual assesses the social risk level on the basis of the events within his circle of acquaintances. Assuming for the moment that the average circle of fairly close acquaintances equates appr. 100 persons, the probability of a death occurring within that circle in consequence of *natural causes* is equal to:

$$Pr(\text{death}) = 10^{-3}/\text{yr} \times 100 = 0.1/\text{yr}. \tag{4}$$

Similarly, the probability of one death among the acquaintances due to a *road accident* in the Netherlands, with a population of roughly 14×10^6 and a number of fatalities of 1500 in 1992 is 1.1×10^{-2} per year.

Using the circle of acquaintances as an instrument of observation, the very low probabilities of a fatal accident, which appear socially acceptable, are perceptible. The recurrence time is within the order of magnitude of a human life span. In seeking to establish a norm for the acceptable level of risk for engineering structures it is more realistic to base oneself on the probability of a death occurring within the circle of acquaintances due to a non-voluntary activity in the factory, on board a ship, at sea, etc. which is approximately equal to 1.4×10^{-3} per year. If this observation-based frequency is adopted as the norm for assessing the safety of activity i, then with due regard to $\beta_i = 0.1$ for the non-voluntary character:

$$\frac{\sum (N_{pi} P_{d|fi} P_{fi}) \times 100}{14 \times 10^6} < \beta_i \cdot 1.4 \times 10^{-2}. \tag{5}$$

After re-arranging this expression, and adopting a rather arbitrary distribution over some 20 categories of activities, each claiming an equal number of lives per year, the following norm is obtained for an activity i in the Netherlands:

$$P_{fi} N_{pi} P_{d|fi} < \beta_i \cdot 100. \tag{6}$$

This norm should be interpreted in the sense that an activity is permissible as long as it is expected to claim fewer than $\beta_i \times 100$ deaths per year (in general: $\beta \cdot 7 \times 10^{-6} \times$ national population size). However the formula looks only to the expected number of deaths and does not account for the standard deviation, which will certainly influence acceptance by a risk averse community.

Risk aversion can be represented mathematically by adding a confidence requirement to the expectation before testing against the norm. For this purpose, the mathematical expectation of the total number of deaths, $E(N_{di})$, is increased by the desired multiple k of the standard deviation before the situation is tested against the norm:

$$E(N_{di}) + k\sigma(N_{di}) < \beta_i \cdot 100, \tag{7}$$

where k is the risk aversion index.

To determine the mathematical expectation and the standard deviation of the total number of deaths occurring annually in the context of activity i, it is necessary to take into account the number of independent places N_A where the activity under consideration is carried out. The number of such independent places does not influence the expectation of the number of deaths, if the total number of participants N_{pi} counted over all places is kept constant, but it does affect the standard deviation.

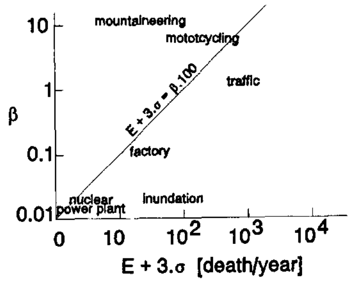

Fig. 4. The risks of some activities; the annual number of expected death is marked on the horizontal axis, the vertical axis indicates the policy factor β including the degree of voluntariness of the activity.

The model is tested for several activities, using $k = 3$ (Fig. 4). The agreement between the norm derived in this study for reasonable values of N_A and $0.01 < \beta_i < 10$ and the risk accepted in practice in the Netherlands seems to support the model.

If the exponential distribution of the number of deaths is introduced instead of the Bernoulli p.d.f., the acceptable probability of failure is halved in all cases.

5.2.2. Locally acceptable level of risk

The translation of the nationally acceptable level of risk to a risk criterion for one single installation or location where an activity takes place depends on the distribution type of the number of casualties for accidents of the activity under consideration as shown above.

In order to relate the new framework to the present one, it is assumed that on a local level the societal risk criterion is of the type proposed by VROM:

$$1 - F_{N_{di}}(x) < \frac{C_i}{x^2} \quad \text{for all } x \geqslant 10. \tag{8}$$

Assuming a Bernoulli distribution of the number of casualties, the probability of an accident, p, should fulfil the requirement (see also Fig. 1):

$$p \leqslant \frac{C_i}{N^2}. \tag{9}$$

From this condition it follows that for a single location,

$$E(N_{dij}) \leqslant \frac{C_i}{N}, \qquad \sigma(N_{dij}) \leqslant \sqrt{C_i}. \tag{10}$$

Substituted in the national criterion, Eq. (7), taking account of N_{A_i} independent locations, gives for the value of C_i:

$$C_i = \left[\frac{-k\sqrt{N_{A_i}} + \sqrt{k^2 N_{A_i} + 4 N_{A_i}/N \beta_i \cdot 100}}{2 N_{A_i}/N} \right]^2. \tag{11}$$

If the expected value of the number of deaths is much smaller than its standard deviation, which is often true for calamities, the previous result reduces to

$$C_i = \left[\frac{\beta_i \cdot 100}{k\sqrt{N_{A_i}}}\right]^2. \tag{12}$$

Similar results are obtained for the exponential distribution. The national societal acceptable risk criterion leads to a local acceptable risk criterion of the VROM-type, which is inversely proportional to the number of independent places N_A and the square of the policy factor β_i:

$$1 - F_{N_{dij}}(x) \leqslant \frac{C_i}{x^2} \quad \text{for all } x \geqslant 10, \tag{13}$$

where

$$C_i = \left[\frac{\beta_i \cdot 100}{k\sqrt{N_{A_i}}}\right]^2.$$

The factor β_i reflects the relative voluntariness and the economical benefits of the activity under consideration. The VROM-rule, as published in [1], is proven to be a special case of the general framework for acceptable risk: with $C_i = 10^{-3}$, $N_A = 1000$ (the approximate number of chemical installations) and $k = 3$, it follows that $\beta = 0.03$ which is according to Fig. 2 not unreasonable for an involuntarily imposed risk. It should be noted, that rule making bodies like HSE and VROM have to estimate N_A for some future period to set the rule (13) for an industry. After this period the development of the industry and N_A have to be assessed in view of an adaptation of the rule.

5.3. *Economically optimal level of risk*

The problem of the acceptable level of risk can also be formulated as an economic decision problem. The expenditure I for a safer system is equated with the gain made by the decreasing present value of the risk (Fig. 5).

The optimal level of safety indicated by $P_{f_{opt}}$ corresponds to the point of minimal cost.

$$\min(Q) = \min(I(P_f) + PV(P_f S)), \tag{14}$$

where Q is the total cost, PV the present value operator, and S the total damage in case of failure.

In many cases where structures are degrading over time the cost of maintenance should be included as this cost can mostly be reduced by choosing a stronger structure at the start. Mathematically the expression for the total cost is expanded as follows:

$$\min(Q) = \min(I(P_f) + PV(P_f S + M(P_f))), \tag{15}$$

where $M(P_f)$ is the cost of maintenance.

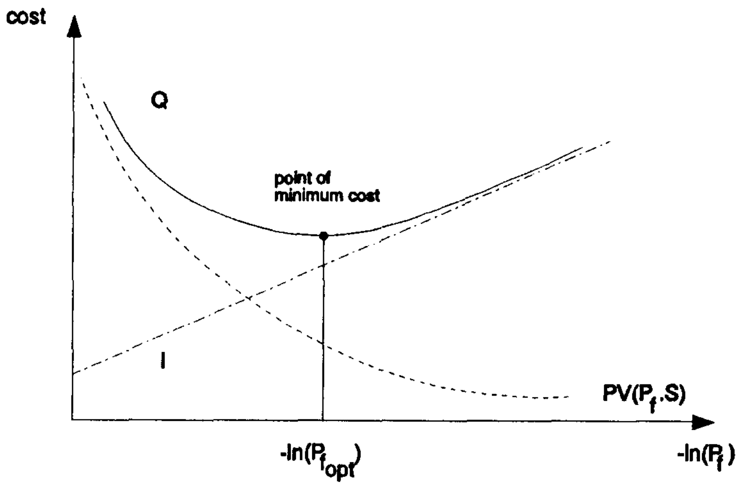

Fig. 5. The economically optimal probability of failure of a structure.

This problem has been solved for many practical situations. The optimization of the Europoort breakwater [7] gives an example. One of the best known examples in the Netherlands is the approximation of the optimal probability of inundation of Holland by Van Dantzig [4, 6]. The result formed the basis for the political choice of the return period of 10,000 yr for the design flood in the Delta-project.

If, despite ethical objections, the value of a human life is rated at s, the amount of damage is increased to:

$$P_{\mathrm{d|fi}} N_{\mathrm{p}i} s + S, \tag{16}$$

where N_{pi} is the number of participants in activity i.

This extension makes the optimal failure probability a decreasing function of the expected number of deaths. The problem of the valuation of human life is in this paper solved by choosing the present value of the nett national product per inhabitant. The advantage of taking the possible loss of lives into account in economic terms is that the safety measures are affordable in the context of the national income.

A limitation of the mathematical-economic approach is that it presupposes the total loss in the event of a failure to be small in comparison with the national economy as a whole. In fact it is the confidence in the economy that makes repair a viable proposition.

6. The framework into practice

In order to give an idea of the effect of the framework on various activities, we give some general examples.

Example 1. *LPG-stations:* The norm for societal risk, as put forward by the Ministry of VROM ($1 - F_N \leqslant 10^{-3}/N^2$) was originally developed for LPG-stations and chemical plants. Assuming a total number of locations where these activities take place $N_{A1} = 1000$, a value of $k = 3$ and $\beta = 0.03$, the new frame work yields $C_1 = 10^{-3}$, which is in accordance with the VROM-rule.

Suppose the probability of an accident at an LPG-station, that claims 10 fatalities is 10^{-5} per year. This Bernoulli p.d.f. fulfils the requirement of the VROM-rule, so the station is allowed. The total number of LPG-stations does not influence the requirements per station.

It will be shown that the total number of stations is of interest. Suppose the number of stations increases to $N_{A1} = 30\,000$. Now on average every third year an accident claiming 10 third party lives will occur. This seems not acceptable at first view, but now is it judged within the proposed framework. The expected value and the standard deviation of the total number of deaths in a year at a national level is found by summation over all stations:

$$E(N_{d1}) = N_{A_i} p N = 30{,}000 \times 10^{-5} \times 10 = 3.0,$$

$$\sigma(N_{d1}) = \sqrt{(N_{A_i} p)}\, N = \sqrt{30{,}000 \times 10^{-5}} \times 10 = 5.48. \tag{17}$$

If the national rule is applied to judge the acceptability:

$$E(N_{d1}) + k\sigma(N_{d1}) = 19.44 < \beta_1 \cdot 100, \quad \text{for } \beta_1 < 0.05, \tag{18}$$

the situation with 30,000 stations appears to be out of bounds, although each station complies with the VROM-rule. If the exponential distribution with $N = 10$ was a better description of the consequence of failure, the standard deviation of N_{d1} would increase to 7.75 and the situation would be even stronger disapproved.

Using the new frame work the value of C_1 should have been decreased from 10^{-3} to 8.3×10^{-5} reflecting the growth of the number of installations.

Example 2. *Airports:* At Schiphol airport, surrounded by inhabited areas, 90,000 planes leave and arrive every year. So the total number of movements is 180,000 per year. The probability of an accident is on the basis of historical data estimated on average at 5.0×10^{-7} per movement [8]. The probability of a crash is $180\,000 \times 5.0 \times 10^{-7} = 0.09$ per year. The number of fatalities at the ground (excluding passengers and crew) in case of a crash is estimated at 50, when in a first approximation every crash is assumed to hit inhabited areas.

According to the VROM-rule for societal risk one single flight movement (per year) is already unacceptable because

$$5.0 \times 10^{-7} > \frac{10^{-3}}{N_{di}^2} = \frac{10^{-3}}{50^2} = 4.0 \times 10^{-7}. \tag{19}$$

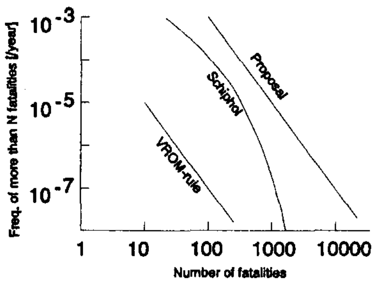

Fig. 6. FN-curve for Schiphol, in relation to the VROM-criterion, and the new proposed criterion.

Moreover due to the large number of aircraft movements the expected value and the standard deviation of the total number of fatalities in a year are not very small.

$$E(N_{di}) = N_{A_i} pN = 180{,}000 \times 5.0 \times 10^{-7} \times 50 = 4.5,$$

$$\sigma(N_{di}) = \sqrt{(N_{A_i} p)}\, N = \sqrt{180{,}000 \times 5.0 \times 10^{-7}} \times 50 = 15. \tag{20}$$

A dramatical improvement of aircraft safety would be required, if the total airport operations were to meet the VROM requirement. If the risk of Schiphol is judged on a national level as seems appropriate for a national airport, the result is:

$$E(N_{di}) + k\sigma(N_{di}) = 49.5 \leqslant \beta_i \cdot 100. \tag{21}$$

The societal risk is only acceptable if $\beta \geqslant 0.5$. This means that the situation depicted here will not be acceptable without discussion.

Refined computer calculations [8] show a more acceptable picture than the crude computations presented above. However the 10^{-5} and the 10^{-6} individual risk contours are, respectively, just and far outside the perimeter of Schiphol. This may be unacceptable according the VROM-rule for personal risk, but using the framework developed here the situation might be accepted if $\beta = 0.1$.

The FN-curve calculated in [8] is more favourable than the simple approximation presented above, but unacceptable by several orders of magnitude compared with the VROM-rule for societal risk (Fig. 6). If the framework of this paper is applied and C_i is adapted using Eq. (13) with $N_{Ai} = 1$, one national airport, and $\beta_i = 0.1$ (in other words if judgement is placed at a national level and the benefits are taken into account, then the FN-curve might be acceptable (see Fig. 6). The benefits of the airport have to be weighed against the external risk and the possibilities of improvement have to be studied, before a political decision to increase β_i to 0.1 can be taken. Additionally one has to decide that Schiphol will be the only major airport in Holland. Implicitly the Dutch government has taken both decisions, when it proposed to accept the personal as well as the societal risk connected to Schiphol.

Important, but outside the scope of the VROM-rule, is the question of the risk for passengers. The personal risk amounts to 10×10^{-7} per flight, if it is assumed that every crash claims the lives of the passengers on board. The personal risk depends on the number of flights a person makes per year. With 10 flights the risk becomes 10^{-5} per year. If a person flies 100 times in a year the resulting personal risk is 10^{-4} per year. The framework views 10 flights per year as an acceptable personal risk. In the case of 100 flights per year the risk level reaches the order of magnitude of the risk of car traffic, that is normally voluntarily accepted ($\beta = 1.0$). If a plane crash occurs, the number of fatalities including passengers might well be 200 persons. The expected value and the standard deviation of the total number of deaths per year can be calculated by:

$$E(N_{di}) = N_A pN = 180{,}000 \times 5.0 \times 10^{-7} \times 200 = 18,$$

$$\sigma(N_{di}) = \sqrt{(N_A p)}\, N = \sqrt{(180{,}000 \times 5.0 \times 10^{-7})} \times 200 = 60. \quad (22)$$

If judged on a national level,

$$E(N_{di}) + k\sigma(N_{di}) \quad (23)$$

the societal risk, would only be acceptable if a value $\beta \geqslant 2$ reflected the attitude of the society towards the airport. It seems likely that the situation will not be acceptable without a lengthy discussion.

Finally it is important to note that the framework contains a standard of appraisal based on a mathematical-economic optimization. It seems advisable to include an economically based approach in a philosophy of acceptable risk concerning Schiphol.

7. Conclusions

(1) From the personal point of view, the probability of failure (a fatal accident) should meet the following requirement:

$$P_{fi} \leqslant \frac{\beta_i \cdot 10^{-4}}{P_{d|fi}} \quad (24)$$

The VROM approach of personally acceptable risk correspond to a policy factor of $\beta_i = 0.01$. From the point of view of this paper, such a stringent norm would be justified in case of an involuntarily imposed risk, that brings no clear direct benefits to those affected by the risk. In many practical cases, a less stringent norm, specifically chosen from the range $10 > \beta_i > 0.01$, might be justifiable. HSE allows for a similar variation of $1.0 > \beta_i > 0.01$ under the ALARP principle.

(2) The societal acceptable risk is judged at a national level by placing an upper-bound upon the expected number of fatalities per activity per year. However limiting only the expected number of deaths does not account for risk aversion. Risk aversion can be represented mathematically by adding a confidence requirement to the norm. For this purpose, the mathematical expectation of the total number of deaths due to an activity i is increased by the desired multiple of the standard deviation before the

situation is tested against the norm:

$$E(N_{di}) + k\sigma(N_{di}) < \beta_i \cdot 100, \tag{25}$$

where $k = 3$; risk aversion index.

The synthesis of this national risk criterion and the VROM-type of local societal risk criterion approach leads to an upper-bound to the FN-curve of the local activity, which is inversely proportional to the number of independent places N_A and the square of the policy factor β_i:

$$1 - F_{N_{di}}(x) \leqslant \frac{C_i}{x^2} \quad \text{for all } x \geqslant 10 \tag{26}$$

where $C_i = \left[\frac{\beta_i \cdot 100}{k\sqrt{N_A}}\right]^2$.

The numerical value of the tolerable frequency can, within certain limits mentioned above, be tuned by the factor β_i. This factor β_i reflects the relative voluntariness and economical benefits of the activity under consideration. For $\beta_i = 0.03$, $N_A = 1000$ and $k = 3$ the rule is equal to the existing Dutch criterion for chemical plants.

(3) A mathematical-economic approach of the acceptable risk should be included in the philosophy of acceptable risk. It is important to weigh the reduction of risk in monetary terms against the investments needed for additional safety. In this way an economic judgement of the safety level proposed by the two other approaches is added to the information available in the decision making process.

(4) In assessing the required safety of a system the three approaches described above should all be investigated and presented. In a specific case the most stringent of the three criteria should be adopted.

(5) Finally it should be realized that the philosophy and the techniques set out above are just means to reach a goal. One should not loose sight of the goal managed safety, when dealing with the tools, that are provided as instruments to measure an aspect of the entire situation.

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