Acceptable risk as a basis for design

J. K. Vrijlinga, W. van Hengelb & R. J. Houbenc

aDelft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands
bRijkswaterstaat, Building Division, Utrecht, The Netherlands
cSimtech, Rotterdam, The Netherlands

Historically, human civilisations have striven to protect themselves against natural and man-made hazards. The degree of protection is a matter of political choice. Today this choice should be expressed in terms of risk and acceptable probability of failure to form the basis of the probabilistic design of the protection. It is additionally argued that the choice for a certain technology and the connected risk is made in a cost-benefit framework. The benefits and the costs including risk are weighed in the decision process. A set of rules for the evaluation of risk is proposed and tested in cases. The set of rules leads to technical advice in a question that has to be decided politically. © 1998 Elsevier Science Limited.

1 INTRODUCTION

Over the centuries all human civilisations have been threatened by natural hazards like bad weather, floods, earthquakes, etc., that claimed the lives of individuals or entire groups bound by their residence or profession. Many activities have been deployed to protect man against these hazards. Even today, money is spent to avoid or prevent natural hazards, because the consequences in developed societies have increased considerably. Other more recent hazards are man-made and result from the technological progress in transport, civil, chemical and energy engineering. One of the tasks of human civilisations is to protect individual members and groups against natural and man-made hazards to a certain extent. The extent of the protection was in historic cases mostly decided after the occurrence of the hazard had shown the consequences. The modern approach aims to give protection when the risks are felt to be high. This gives rise to the rather novel idea of acceptable risk.

As long as the modern approach is not firmly embedded in society, the idea of acceptable risk or safety may, just as in the old days, be quite suddenly influenced by a single spectacular accident, like the catastrophe at Chernobyl, the plane crash at Schiphol airport in 1992, or even by non-calamitous threats like the Dutch river floods of 1993 and 1995. Here the political process is at work and public opinion is influenced not only by the accident itself, but also by the attention paid to it by the media and the politicians.

However, according to the modern approach the politicians in an advanced technological society should not base their decisions to provide protection fully upon the above-mentioned subjective and historical ideas of acceptable risk, but also use the outcome of risk analyses and probabilistic computations as a more objective basis. As the notion of probability of failure and the consequent risk forms the basis for the design of many technological systems, from simple river levees via multi-purpose dams to advanced jumbo-passenger-jets, that contribute to the welfare of modern nations, politicians should have an objective set of rules for the evaluation of risk. This paper proposes a possible set of rules that may serve as a rational and more objective basis for technological design.

2 ASPECTS OF ACCEPTABLE RISK

In almost all studies of acceptable risk levels1-3 two points of view are chosen. One is the point of view of the individual, who decides to undertake an activity weighing the risks against the direct and indirect personal benefits. The second is the point of view of the society, considering if an activity is acceptable in terms of the risk–benefit trade-off for the total population.

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 are quickly made, knowing
that they can be immediately amended if the risks exceed
the expectation. In the case of societal decisions involving
risk, however, the individual can still make their appraisal
in accordance with their own set of standards, but their
influence on the final outcome is democratically limited.
This implies a sense of involuntariness and compels them
to adopt a critical attitude towards risks imposed by societal
decisions.

These observations result in the conclusion that the
decision to accept risk is not based on the absolute notion
of one acceptable risk level but has some flexibility as the
judgement depends on the cost/benefit ratio and the degree
of voluntariness.

The first point of view leads to the personally
acceptable level of risk or the acceptable individual risk,
defined in the Institute of Chemical Engineering (ICE)3 as
'the frequency at which an individual may be expected to
sustain a given level of harm from the realisation of speci-
fied hazards'. It should be noted that in many prac-
tical cases the specified level of harm is limited exclu-
sively to the loss of life, which is not necessarily
representative. Most probably, society will also look to the
total damage caused by the occurrence of a hazard.
This comprises the number of casualties, material and
economic damage, as well as the loss of or harm to non-
material values.

Similarly, the notion of risk in a societal context is
reduced to total number of casualties1-3 using a definition
as in ICE2: 'the relation between frequency and the number
of people suffering from a specified level of harm in a
given population from the realisation of specified
hazards'. If the specified level of harm is limited in this
way 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.

The consequence part of a risk may also be limited to the
total material damage expressed in monetary terms3,5-7.
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 potential loss. The aim of the
schematisation is to clarify the reasoning at the cost of
accuracy.

It is clear that the societal risk is judged at a national
level. The total risk in a year (casualties as well as material
and non-material damage related to the frequency) con-
ected to a certain activity is estimated by averaging the
total actual damage caused at accident locations over a
span of years. The distinction between local and national
risk seems a necessary addition, noting that 'small unrestr-
rained developments could add up to a noticeable worsen-
ing of the overall situation'2.

An important fact is that in many countries certain risks
are managed and regulated by different ministries and
regulatory agencies, although in some cases their cause
is common. The risk approach is most favoured by
planning agencies, while other institutions seem to prefer
deterministic measures. The following subdivision, here
ranked according to increasing benefit to the persons at
risk, is frequently found:

<table>
<thead>
<tr>
<th>Category</th>
<th>Object</th>
<th>Ministry of</th>
</tr>
</thead>
<tbody>
<tr>
<td>External</td>
<td>Third party</td>
<td>Planning and Environment</td>
</tr>
<tr>
<td>Internal</td>
<td>Users/passengers</td>
<td>Traffic</td>
</tr>
<tr>
<td>Internal</td>
<td>Personnel</td>
<td>Labour</td>
</tr>
</tbody>
</table>

It could be argued that one unified approach to these
categories will improve the clarity, the coherence and the
focus of governmental risk policies.

3 THE MODELLING OF RISK

In most practical studies the societal risk of an installation
is given in the form of a numerical FN-curve. In order to
bring the use of the tools provided by the theory of prob-
ability within reach, the FN-curve should be seen as an
exceedance curve 1 - F_X(x) with a related probability
density function (p.d.f.) of the number of deaths f_X(x).

The p.d.f. of the number of deaths N given an accident
for activity i at place j can have many forms. A few types
are presented here to stimulate further thinking. The first
conditional p.d.f. is the Dirac, that limits the outcomes to
exactly N fatalities. Other possibilities that allow a larger
variation in the outcome are the exponential and the log-
normal p.d.f. The probability of exceedance curves of
the number of fatalities that can be derived from these
two forms reflects to some extent the FN-curves found in
practical quantitative risk assessment (QRA) studies.

A fourth is the inverse quadratic Pareto distribution that
accidentally coincides with the norm put forward by
the Dutch Ministry of Housing, Land Use, Planning and
Environment (VROM)4. The Pareto p.d.f. has no finite stan-
dard deviation unless the right tail is truncated (see Fig.
1(a,b)).

Exactly the same models could be applied for the material
damage that results from a disaster, if the horizontal axis is
measured in monetary units. It should be noted that the
proposed conditional p.d.f.s have to be multiplied by
the probability p of an accident and that the outcome of
zero fatalities with probability 1 - p should be added
to find the complete p.d.f. of the number of deaths
(Fig. 1(a,b)). The classical measures of expected value
and standard deviation will appear to be very useful
numbers to classify the risk.

4 A SET OF RULES FOR THE ACCEPTABILITY
OF RISKS

In most countries where risk criteria for the siting of hazar-
dous installations and the development in their vicinity are
adopted, both the personally and the socially acceptable
levels of risk have to be satisfied. So the most stringent of the criteria determines the acceptable level of risk.

One of the first sets of rules meant to regulate planning in conjunction to risk was conceived by VROM. A philosophy for acceptable risk comparable to VROM, that takes into account the cost–benefit and the voluntariness aspect, was developed by the Technical Advisory Committee on Water Retaining Structures (TAW). This set of rules consists of a flexible evaluation of the individual and the societal acceptable risk but adds to these an economic evaluation of the material damage.

The latter provides the link with the safety philosophy of the Dutch dikes that was developed by van Dantzig after the 1953 flood. A philosophy integrating the VROM and TAW approach will be presented. The basic assumption of this philosophy of acceptable risk is that risk cannot be judged separated from other aspects of the activity as proposed in VROM. The acceptance can only be understood in a cost–benefit framework in the widest sense. Personal gain, national gain, capital outlays, running costs, damage to the environment, and the risk play a part in the weighing process. As this complicated process cannot be adequately modelled, two crude approximations are proposed in this paper. The first is to accept the pattern of the accident statistics as the outcome of the weighing process. The second is a risk-oriented technical cost–benefit model that expresses all consequences of failure in monetary terms.

4.1 Personally acceptable level of risk

The smallest component of the social acceptance of risk is the personal cost–benefit assessment by the individual. Attempts to model this appraisal procedure quantitatively are not feasible, therefore it is proposed to look at the pattern of preferences revealed in the accident statistics.

The fact that the actual personal risk levels connected to various activities show statistical stability over the years and are approximately equal for the Western countries indicates a consistent pattern of preferences. The probability of losing one’s life in normal daily 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 (Fig. 2). 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.

In view of the consistency and the stability, apart from a slightly downward trend due to technical progress, of the death risks presented, it seems permissible to use them as a basis for decisions with regard to the personally acceptable probability of failure in the following way:

$$P_{i} = \frac{\beta_i \cdot 10^{-4}}{P_{d|\beta}}$$

where \(P_{d|\beta}\) denotes the probability of being killed in the event of an accident. In this expression the policy factor \(\beta\) varies with the degree of voluntariness with which an activity \(i\) is undertaken and with the benefit perceived. It ranges from 100, in the case of complete freedom of choice like mountaineering, to 0.01 in the case of an imposed risk without any perceived direct benefit. This last case includes the individual risk criterion proposed by VROM for the siting of a hazardous installation near a housing area without any direct benefit to the inhabitants.

A proposal for the choice of the value of the policy factor \(\beta\), as a function of voluntariness and benefit is given in Table 1. It should be noted that a \(\beta\)-value has to be

- It is noted that people tend to reject risks when asked directly. However, in their more anonymous role as a citizen of the society they effectively accept it.

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Fig. 1. (a) Probability density function for the number of deaths by an inverse quadratic Pareto. (b) Probability of exceedance curve for the number of deaths by an inverse quadratic Pareto.

Fig. 2. Personal risks in Western countries, deduced from the statistics of causes of death and the number of participants per activity.
Table 1. The value of the policy factor $\beta_i$ as a function of voluntariness and benefit

<table>
<thead>
<tr>
<th>$\beta_i$</th>
<th>Voluntariness</th>
<th>Direct benefit</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Completely voluntary</td>
<td>Direct benefit</td>
<td>Mountaineering</td>
</tr>
<tr>
<td>10</td>
<td>Voluntary</td>
<td>Direct benefit</td>
<td>Motorbiking</td>
</tr>
<tr>
<td>1.0</td>
<td>Neutral</td>
<td>Direct benefit</td>
<td>Car driving</td>
</tr>
<tr>
<td>0.1</td>
<td>Involuntary</td>
<td>Some benefit</td>
<td>Factory</td>
</tr>
<tr>
<td>0.01</td>
<td>Involuntary</td>
<td>No benefit</td>
<td>LPG-station</td>
</tr>
</tbody>
</table>

chosen for each threatened group, that differs in its relation to the activity. For instance, the pilots, the passengers and people living under the flight paths each have a specific relation to air travel and consequently different visions on the acceptability of a certain level of risk.

4.2 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 on a national level is the aggregate of the risks of local installations or activities. Without mentioning it specifically, the risk criteria as developed by VROM$^1$ and HSE$^2$ are meant to support a systematic appraisal by the local authorities.

If a risk criterion is thus defined on a local level the height of the national risk criterion is determined by the number of locations, where the activity takes place and by the p.d.f. of the consequences of an accident. The acceptability of the resulting national norm has to be assessed separately as it was not intentionally formulated.

It seems preferable to start with a risk criterion on a national level and to evaluate the acceptable local risk level, in view of the actual number of installations, the cost–benefit aspects of the activity and the general progress in safety, in an iterative process with say a 10-year cycle (Fig. 3).

4.3 Nationally acceptable level of risk

The determination of the socially acceptable level of risk starts from the assumption that the accident statistics reflect the result of a social process of cost–benefit appraisal. If these statistics reveal the preferences, a standard can be derived from them. It can be shown that the very low probabilities of a fatal accident, which appear socially acceptable, are perceptible using the circle of acquaintances as an instrument of observation.

The recurrence time of an accident, claiming the life of an acquaintance from the circle, is of the order of magnitude of a human life span.

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 due to a non-voluntary activity in the factory, on board a ship, at sea, etc., which is approximately equal to $1.4 \times 10^{-5}$/year, than on the number of casualties in the car traffic, which seems on the verge of acceptance.

If this observation-based frequency is adopted as the norm for assessing the safety of activity $i$, then after rearranging the 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 $i$ with $N_{pi}$ participants in the Netherlands:

$$P_{\beta} \cdot N_{pi} \cdot P_{d|\beta} < \beta r^{-100}$$

This norm states that an activity is permissible as long as it is expected to claim fewer than $\beta r^{-100}$ deaths per year (more general: $\beta r^{-7} \times 10^{-6}$–national population size).

The formula does not account for risk aversion, which will certainly influence acceptance by a community or a society. Relatively frequent small accidents are more easily accepted than one single rare accident with large consequences, although the expected number of casualties is equal for both cases. The standard deviation of the number of casualties will reflect this difference.

Risk aversion can be represented mathematically by increasing the mathematical expectation of the total number of deaths per year, $E(N_{d})$, by the desired multiple

\[^{1}\text{It is noted that Slovic et al.\textsuperscript{10} shed doubt on this assumption, but here risk aversion is adopted.}\]

Fig. 3. Flowchart for risk management.
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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. In order to relate the new local risk criterion to the present one proposed by VROM ($C_i = 10^{-3}$), a societal risk criterion of the following type is preferred.

$$C_i = \frac{\beta_i\cdot100}{k\cdot\sqrt{N_A}}$$

where $k = \text{risk aversion index}$. The VROM-rule is a special case of this general rule for acceptable risk, with $C_i = 10^{-3}$, $N_A = 1000$ (the approximate number of chemical installations) and $k = 3$, it follows that $\beta_i = 0.03$ which is according to Fig. 2 not unreasonable for an involuntarily imposed risk.

4.5 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 decreasing the present value of the risk (Fig. 4). The optimal level of safety indicated by $P_{fa}$ corresponds to the point of minimal cost.

$$\min(Q) = \min(I(P_f) + PV(P_f\cdot S))$$

where $Q = \text{total cost}$, $PV = \text{present value operator}$, $S = \text{total damage in case of failure}$. If, despite ethical objections, the value of a human life is rated at $s$, the amount of damage is increased to:

$$P_{fa}\cdot N_p\cdot s + S$$

where $N_p = \text{number of participants in activity i}$. This extension makes the optimal failure probability a decreasing function of the expected number of deaths. The valuation of human life is chosen as the present value of

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$k$ of the standard deviation before the situation is tested against the norm:

$$E(N_{di}) + k\cdot\sigma(N_{di}) < \beta_i\cdot100$$

where $k = \text{risk aversion index}$. The norm with $k = 3$ is tested for several activities in the Netherlands by Vrijling et al. The agreement between the norm for reasonable values of $N_{ai}$ and $0.01 < \beta_i < 100$ and the actual risks accepted in practice seems to support the model.

4.4 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. In order to relate the new local risk criterion to the present one proposed by VROM ($C_i = 10^{-3}$), a societal risk criterion of the following type is preferred.

$$1 - F_{N_{ai}}(x) \leq \frac{C_i}{x^2} \text{ for all } x \geq 10$$

Assuming a Bernoulli distribution for the number of casualties at each of $N_{ai}$ independent locations, the expected value and the standard deviation of the casualties at national level are:

$$E(N_{ai}) = N_{ai}\cdot P_f\cdot N_{dj|f}$$

$$\sigma(N_{ai})^2 = N_{ai}\cdot P_f\cdot (1 - P_f)\cdot N_{dj|f}^2 = N_{ai}\cdot P_f\cdot N_{dj|f}^2$$

where $N_{ai}$ is the number of independent locations, $P_f$ and $N_{dj|f}$ are the probability of failure at a location and the number of fatalities given failure respectively.

If the Bernoulli distribution of the number of casualties at each location complies with criterion (4), it follows that for a location $E(N_{di}) \leq C_i/N$ and $\sigma(N_{di}) \leq C_i/N$. Substituting these values in eqn (5) and subsequently in the national criterion (3), and solving the resulting quadratic equation in $p_f$, gives the value of $C_i$:

$$C_i = \left[ \frac{-k\cdot\sqrt{N_A} + \sqrt{k^2\cdot N_A + 4\cdot N_{ai} \cdot \beta_i\cdot100}}{2\cdot\frac{N_{ai}}{N}} \right]^2$$

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

$$C_i = \left[ \frac{\beta_i\cdot100}{k\cdot\sqrt{N_A}} \right]^2$$

Similar results are obtained if the conditional p.d.f. of the number of deaths is exponential instead of Dirac.

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 $\beta_i$:

$$1 - F_{N_{ai}}(x) \leq \frac{C_i}{x^2} \text{ for all } x \geq 10, \text{ where } C_i = \left[ \frac{\beta_i\cdot100}{k\cdot\sqrt{N_A}} \right]^2$$

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Theoretically, the use of a quadratic utility function is preferred. This, however, leads to less transparent units of utils such as $\$2$ or death$^2$. Therefore, eqn (3) is preferred. A discussion is presented by Vrijling and van Gelder.
The nett national product (NNP) 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. Risk aversion may also be included in the economic approach as shown by Slijkhuis et al. 13.

5 THE APPLICATION IN PRACTICAL SITUATIONS

To gain experience and to test the proposed framework on practical situations, especially the group risk criterion, the framework was applied to a number of activities. The activities comprise LPG-stations, the extension of the national airport Schiphol, the transport of dangerous chemicals over water, the flooding of polders, chemical plants and the car traffic. Not all activities comply with the risk criteria. The testing leads in the case of the group risk for line sources like canals and pipelines to a small redefinition.

5.1 Example 1: LPG-stations

The norm for societal risk, as put forward by VROM ($C_1 = 10^{-3}$) was originally developed for LPG-stations. Assuming a total number of locations where these activities take place $N_A = 1000$, a value of $k = 3$ and $\beta_1 = 0.03$, the new rule yields $C_1 = 10^{-3}$, which is in accordance with the former rule.

To show the effect of a national norm, let us suppose the probability of an accident at an LPG-station, that claims 10 fatalities, is $10^{-5}$/year. This Bernoulli p.d.f. fulfills the requirement of the VROM-rule, so the station is approved, without any reference to the total number of LPG-stations.

Suppose that the future number of stations increases to $N_A = 30000$. On average every third year an accident claiming 10 third party lives will happen, which does not seem immediately acceptable. To judge it within the proposed framework of a national rule, the expected value and the standard deviation of the total number of deaths in a year at a national level are assessed by summation over all stations:

$$E(N_{d|f}) = N_A \cdot p_{|f} \cdot N_{d|f} = 30000 \times 10^{-5} \cdot 10 = 3.0$$

$$\sigma(N_{d|f}) = \sqrt{E(N_{d|f}) \cdot \sigma(N_{d|f})} = \sqrt{30000 \times 10^{-5} \cdot 10} = 5.48$$

If the national rule is applied:

$$E(N_{d|f}) + k \cdot \sigma(N_{d|f}) = 19.44 < \beta_1 \cdot 100 \text{ for } \beta_1 < 0.03,$$

the situation with 30000 stations appears to be out of bounds, although each station complies with the VROM-rule. If the exponential distribution with $N_{d|f} = 10$ was a better description of the consequence of failure, the standard deviation of $N_d$ would increase to 7.75 and the situation would be disapproved of even more.

Using the new set of rules the value of $C_1$ should have been decreased from $10^{-3}$ to $8.3 \times 10^{-5}$ reflecting the growth of the number of installations. The required probability of failure of one installation will become $8.3 \times 10^{-7}$ per year if the conditional death count is not reduced below 10.

5.2 Example 2: Airports

At Schiphol airport, surrounded by inhabited areas, 90 000 planes leave and arrive every year bringing the total number of movements to 180 000 per year. As the probability of an accident, averaging historical data, is estimated at $5.0 \times 10^{-7}$ per movement14, then the probability of a crash at Schiphol is $180000 \times 5.0 \times 10^{-7} = 0.09$ 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) would already be unacceptable because:

$$5.0 \times 10^{-7} > \frac{10^{-3}}{N^2_{ai}} = \frac{10^{-3}}{50^2} = 4.0 \times 10^{-7}$$

As might be expected due to the large number of aircraft movements the expected value and the standard deviation of the total number of fatalities in a year is considerable:

$$E(N_{d|f}) = N_A \cdot p_{|f} \cdot N_{d|f} = 180000 \times 5.0 \times 10^{-7} \times 50 = 4.5$$

$$\sigma(N_{d|f}) = \sqrt{E(N_{d|f}) \cdot \sigma(N_{d|f})} = \sqrt{180000 \times 5.0 \times 10^{-7} \times 50} = 15$$

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

\[ E(N_{di}) + k \cdot \sigma(N_{di}) = 49.5 \leq \beta_i \cdot 100 \]  

A value of the policy factor \( \beta_i \approx 0.5 \) should be chosen, which means that the situation depicted here will not be acceptable without discussion. In Table 1 the range of the policy factor \( 0.1 > \beta_i \geq 0.01 \) seems advisable.

The refined computer calculations\(^{14}\) 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 is unacceptable according to the VROM-rule for personal risk, but using the framework developed here the situation might be acceptable if \( \beta_i = 0.1 \) for a national airport used by a considerable number of the citizens.

The FN-curve calculated in NLR\(^{14}\) is also more favourable than the crude approximation presented above, but unacceptable by several orders of magnitude when compared with the VROM-rule for societal risk (Fig. 5). If the new set of rules is applied and \( C_i \) is adapted to 11, because \( N_{ai} = 1 \) for one national airport and \( \beta_i = 0.1 \) (in other words if the judgement is placed at a national level and the benefits are taken into account), the FN-curve is acceptable as Fig. 5 shows.

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 \( \beta_i \) 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 the extended Schiphol.

5.3 Example 3: Air travel

It is interesting to study the safety of air travel besides the safety of the airport because this regards passengers instead of third parties. The personal risk equals approximately \( 5 \times 10^{-7} \) per flight (take-off and landing), if one assumes that half of the passengers die in a crash. The personal risk depends on the number of flights that the individual makes in a year. With 10 flights the personal risk becomes \( 10^{-5} \) and with 100 flights \( 10^{-4} \) per year. The former is according to the rule for acceptable individual risk acceptable, the second will only be endured on a voluntary basis (\( \beta_i = 1 \)) or in case of a direct benefit (pilot).

The societal risk level of the air traffic approaching and leaving the airport can be calculated if the simplifying assumption is made that, say, half of the passengers (i.e. about 200) will die in a crash. The expected value and the standard deviation can be found by:

\[ E(N_{di}) = N_{ai} \cdot p_{\beta_i} \cdot N_{ai/j} = 180000 \times 5.0 \times 10^{-7} \times 200 = 18 \]

\[ \sigma(N_{di}) \approx \sqrt{N_{ai} \cdot p_{\beta_i} \cdot N_{ai/j}} = \sqrt{180000 \times 5.0 \times 10^{-7}} \times 200 = 60 \]  

(17)

The national criterion indicates:

\[ E(N_{di}) + k \cdot \sigma(N_{di}) = 198 \leq \beta_i \cdot 100 \]  

(18)

that the societal risk would be acceptable, if \( \beta_i = 2 \) describes the attitude of the society towards air travel. It seems likely that the situation sketched will require a national debate to decide if improvements have to be made, as \( \beta_i = 0.1 - 1 \) reflects the public attitude better.

5.4 Example 4: Polders

The half of Holland that lies below the sea level is divided in \( N_{ai} = 40 \) more or less independent polders surrounded by dike-rings. If it is assumed that at some future date each polder will house \( N_{pi} = 1000000 \) inhabitants, an estimate of the number of casualties in case of flooding can be made. In 1953 approximately 1% of the inhabitants drowned, giving a value of \( p_{\beta_i} = 0.01 \). Little is known of the influence of modern technological development on this number, but the failure of energy and communication networks during the minor floods in Limburg point to a limited beneficial influence.

The expected value and the standard deviation of the number of deaths in 40 independent polders per year are equal to:

\[ E(N_{di}) = N_{ai} \cdot p_{\beta_i} \cdot P_{dl} \cdot N_{ai/j} = 40 \cdot p_{\beta_i} \cdot 0.01 \times 10^6 \]

\[ \sigma^2(N_{di}) = N_{ai} \cdot p_{\beta_i} \cdot (1 - p_{\beta_i}) \cdot (P_{dl} \cdot N_{ai/j})^2 \]  

\[ = 40 \cdot p_{\beta_i} \cdot (1 - p_{\beta_i}) \cdot (0.01 \times 10^6)^2 \]  

(19)

If these expressions are substituted in the national norm eqn(3) the solution for \( \beta_i = 1 \) becomes \( p_{\beta_i} = 3 \times 10^{-7} \) per year. In case the averision of the inhabitants against flooding is more extreme and \( \beta_i = 0.1 \), the acceptable probability of failure of the dike ring is \( p_{\beta_i} = 3 \times 10^{-9} \) per year.
For the Brielse dike ring near Rotterdam, an FN-curve (Fig. 6) has been drawn estimating the probability of failure of the existing dikes at $10^{-4}$ per year. The FN-curve shows that there are five equally likely scenarios with death counts varying from 15 to about 5000 people. As these scenarios are assumed to be independent, the combinations that claim even more casualties, are less likely by an order of magnitude.

Developing the local criterion for a dike ring using the values mentioned above, the constant becomes $C_i = 27.8 - 0.278$ for $\beta = 1 - 0.1$. Thus the present situation based on the philosophy developed by the Delta committee in 1960 seems insufficiently safe in the light of modern developments. Following the normative framework developed here the acceptable probability of failure of the dike equals $6.3 \times 10^{-7}$ to $6.3 \times 10^{-9}$ depending on the value of $\beta$.

5.5 Example 5: Road safety

The car traffic forms an interesting example to test the theory, because the number of independent installations $N_a = 4 \times 10^6$ is very large and the victims are passengers/users. If the number of people in the car is assumed to be 2 and the probability to die in a crash is $p_{df} = 0.1$, then the conditional expectation and the standard deviation of the number of deaths per car are equal to 0.2 and 0.42 respectively. Using the general formulae mentioned, the expected value and the standard deviation at national level are calculated:

$$E(N_{di}) = N_a p_{df} \cdot E(N_{df|f})$$

$$\sigma(N_{di}) = \sqrt{N_a p_{df} ((1 - p_{df}) \cdot E(N_{df|f})^2 + \sigma(N_{df|f})^2)}$$

Substitution of these expressions in the national norm eqn (3) gives an expression with $p_{df}$ as unknown.

If $\beta = 1.0$ is adopted the acceptable probability of a car accident is $9.0 \times 10^{-4}$ per year per individual. The expected total number of casualties amounts to 72 per year with a standard deviation of 8.8. A choice of $\beta = 10$ leads to an increase of the acceptable probability of an accident to $1.1 \times 10^{-3}$ per car per year. The expected total number of casualties amounts to 972 per year with a standard deviation of 30.8. This is more in line with the actual situation, where the traffic claims approximately 1200 lives per year.

Here a contradiction arises between the acceptable individual and the societal risk. The $\beta = 1$ value that follows from the individual viewpoint with respect to car traffic would ask for a considerable reduction of the actual societal risk of 1200 to an acceptable level of approximately 72 deaths per year. However, observing the efforts of Dutch NGO Safe Traffic one could argue that the public finds the societal risk too high and strives for a reduction.

5.6 Example 6: Transport of dangerous substances

The transport of dangerous goods over water, road and rail should comply with the safety norms. To prevent hasty and incorrect decisions the Dutch Ministry of Transport decided to start with an inventory of existing risks along waterways before proposing a norm. The calculated FN-curves for the passages of cities and villages appeared to exceed the VROM-norm by far. Arguing that the norm was developed for point sources like plants and not for line sources like a waterway, the norm was rather arbitrarily applied to every single kilometre of waterway.

A better approach defines the city or village as the entity that needs protection and calculates the FN-curve per settlement. Applying the framework with choices of $\beta = 0.1$ and $N_a = 100$ settlements along Dutch waterways the value of $C_i = 0.11$ results. In Fig. 7 the lines for $C_i = 10^{-5}, 10^{-3}$ and $10^{-1}$ are drawn. Apart from Flushing, all villages comply approximately with the norm. It is a political decision, if $\beta_i = 0.1$ expresses the societal preferences adequately.

5.7 Example 7: High-speed train

The High-speed train (HST) section between Amsterdam and Antwerp is meant to improve the environment by substituting car and air travel with a more energy-efficient rail link. In addition to this the management has set the goal to provide a mode of transport that improves the safety in comparison with the substituted modes. A safety plan is
Acceptable risk as a basis for design

Table 2. Present situation

<table>
<thead>
<tr>
<th>Mode</th>
<th>(E(N_{di}))</th>
<th>(\sigma(N_{di}))</th>
<th>(E(N_{di}) + k\sigma(N_{di}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>7.1</td>
<td>2.7</td>
<td>15</td>
</tr>
<tr>
<td>Airplane</td>
<td>0.3</td>
<td>4.1</td>
<td>13</td>
</tr>
<tr>
<td>Train</td>
<td>0.05</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td>7.5</td>
<td>4.9</td>
<td>22</td>
</tr>
</tbody>
</table>

being made that includes a safety philosophy with risk criteria formulated along the lines explained above.

Several groups can be distinguished, each of them having their own specific involvement with the HST, characterized by the degree of voluntariness and personal cost/benefit assessment (passenger, staff, resident, passer-by). For each of these groups a personal and a societal acceptable level of risk is tentatively determined.

The acceptable risk levels are based on a comparison with historical accident rates and the national criterion. In Table 2 Table 3 the comparison of the societal risk is made between the multi-mode situation and the situation where the HST is functioning.

Society will perceive the safety of the HST in terms of the total yearly number of accidents vs casualties. The basic measure for personal risk perception is the risk per trip or the risk per passenger kilometre, which can be translated to the probability of dying per year for the 'average' passenger (see Table 4).

After the acceptable risk levels for each group have been finally set, the design of the HST transportation system has to fulfill these safety requirements. Using decomposition of the system, an optimization of the distribution of the occurring risk over the several subsystems including the management, with respect to costs, is pursued.

6 CONCLUSIONS

A set of rules has been proposed that can indicate the acceptable probability of failure of technical systems over a wide range of economic activities and for categories of people with different relations to the system (personnel, users, third parties). A personal and a societal point of view are discerned.

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

\[
P_{\beta_i} \leq \beta_i \times 10^{-4}
\]

(21)

The policy factor \(\beta_i\) has to be chosen specifically for each category of systems and for different groups as personnel, users and third parties, depending on the risk, the benefit and the voluntariness of exposure. In Table 1 values for \(\beta_i\) are proposed. In land-use planning, where third party risk is one of the factors, the most stringent value \(\beta_i = 0.01\) is frequently proposed by regulatory agencies.

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:

\[
E(N_{di}) + k\sigma(N_{di}) < \beta_i \times 100
\]

(22)

where \(k = 3\), the 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 \(\beta_i\):

\[
1 - F_{N_{di}}(x) \leq \frac{C_i}{x^2} \text{ for all } x \geq 10, \text{ where } C_i = \left[ \frac{\beta_i \times 100}{k \sqrt{N_A}} \right]^2
\]

(23)

The numerical value of the tolerable frequency can, within certain limits mentioned above, be tuned by the factor \(\beta_i\).

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.

It is advised to include in this approach an estimate for the value of a human life (present value of the nett national income per capita) to help avoid decisions that implicitly attach unrealistic high values to loss of live.

In assessing the required safety of a system the three approaches described above should all be investigated and presented. The most stringent of the three criteria should be adopted as a basis for the 'technical' advice to the political decision process. However, all information of the risk assessment should be available in the political process.

Finally, it should be realised that the philosophy and the

Table 3. Future situation with old traffic substituted and new traffic generated by HST

<table>
<thead>
<tr>
<th>Mode</th>
<th>(E(N_{di}))</th>
<th>(\sigma(N_{di}))</th>
<th>(E(N_{di}) + k\sigma(N_{di}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST substituted</td>
<td>0.03</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>HST generated</td>
<td>0.02</td>
<td>0.25</td>
<td>0.8</td>
</tr>
<tr>
<td>Total</td>
<td>0.05</td>
<td>0.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 4. Proposed risk criteria for the Dutch HST-South

<table>
<thead>
<tr>
<th>Object</th>
<th>Individual risk</th>
<th>Societal risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(P_{\beta_i})</td>
<td>(E(N_{di}))</td>
</tr>
<tr>
<td>Passenger</td>
<td>2 \times 10^{-6}</td>
<td>0.15</td>
</tr>
<tr>
<td>Train personnel</td>
<td>2 \times 10^{-5}</td>
<td>-</td>
</tr>
<tr>
<td>Rescue personnel</td>
<td>ALARA</td>
<td>-</td>
</tr>
<tr>
<td>Third party</td>
<td>1 \times 10^{-6}</td>
<td>-</td>
</tr>
<tr>
<td>Suicides</td>
<td>-</td>
<td>10</td>
</tr>
</tbody>
</table>
techniques set out above are just means to reach a goal. One should not lose sight of the goal managed safety, when dealing with the tools that are provided as instruments to measure an aspect of the entire situation.

Thus, after the construction of the technical system and the start of the activity, a control-system should be put in place to observe the failure frequencies and the consequences as far as possible.

REFERENCES