Safety and Reliability for Managing Risk – Guedes Soares & Zio (eds)

A generalized approach for risk quantification and the relationship between individual and societal risk

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ABSTRACT: In this paper a generalized approach for the quantification of individual and societal risk is proposed which can be used over different domains. These general formulations could contribute to the improvement of consistency of outcomes of risk analyses and a relatively easy application of QRA to new terrains. It is shown how the formulations can be used to give a mathematical verification of the relationship between individual and societal risk. To demonstrate the application of the general formulations to various terrains, some schematized but characteristic examples are given.

1 INTRODUCTION

Within a quantitative risk analysis (QRA) the risks for a given system are quantified as a basis for evaluation and decision-making. In different sectors, e.g. chemical and aerospace sector, there is substantial experience with QRA, see e.g. (Bedford & Cooke, 2001). As outcome of the QRA generally fatality risks are expressed with so-called risk measures. A risk measure is defined as an expression or graph which quantifies or depicts risk as a mathematical function of the probabilities and/or consequences of a set of undesired events. Different risk measures have been proposed in literature that deal with various consequence types, see Jonkman *et al.* (2003) for an overview. In this paper, risk measures related to loss of (human) life are further elaborated. These are individual and societal risk. Individual risk is concerned with the probability that an individual (at a certain location) gets killed, whereas societal risk is concerned with the probability of a multi-fatality accident. Existing definitions are described in more detail in section 2.

In this paper a generalized approach for risk quantification is proposed which can be used over different domains. These general formulations, which are proposed in section 3, will allow improvement of consistency of outcomes of risk analyses and a relatively easy application of QRA to new terrains.

A related issue concerns the relationship between individual and societal risk. Although several authors have pointed at this relationship (see e.g. Ale *et al.*, 1996b; Alp & Zelensky, 1994; Ball & Floyd, 1998; CIB, 2001; Francis *et al.*, 1999; Trbojevic, 2004), a final confirmation is not given in literature other than with numerical calculations (Ball & Floyd, 1998). The proposed general approach for risk quantification offers the possibility to further verify the relationship between individual and societal risk, as will be shown in section 4.

To enable a wider application of the general formulations for risk quantification, several extensions for specific situations are proposed in section 5. In the final sections it is shown how the generalized formulations can be applied to different sectors in some schematized, but characteristic examples (section 6); and some concluding remarks are given (section 7).

2 DEFINITIONS OF INDIVIDUAL AND SOCIETAL RISK

2.1 *Individual risk*

Individual risk is used to indicate the distribution of the risk over the various individuals in the (potentially) exposed population. Ichem (1985) defines the individual risk as "the frequency at which an individual may be expected to sustain a given level of harm". In the external safety domain[1] in the Netherlands it is defined as "the probability that an average unprotected

[1] External safety domains is concerned with (the risks) of transport and storage of dangerous goods, and airport safety

person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity" (Bottelberghs, 2000). Due to the assumption of permanent presence, the individual risk becomes a property of a location and as such it may be useful in land use planning. Following this above definition the individual risk can be displayed on a map with so-called (iso-) risk contours. In order to determine the actual individual risk other definitions exist that consider whether or not the individual is actually present (see e.g. Bohnenblust, 1998).

2.2 *Societal risk*

Ichem (1985) defines societal risk as "the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards". Often a more narrow definition is used, and societal risk is expressed as the probability of exceedance (in one year) of a certain number of fatalities due to one event in a given population. Then, societal risk can be depicted in an FN curve, which displays the probability of exceedance of a certain number of fatalities on a double logarithmic scale. Various other risk measures are used to express societal risk, for example the expected number of fatalities, see Jonkman *et al.* (2003) for a more comprehensive overview.

3 GENERALIZED FORMULATIONS FOR THE QUANTIFICATION OF INDIVIDUAL AND SOCIETAL RISK

3.1 *Elements in quantitative risk analysis*

In a quantitative risk analysis the probabilities and consequences of a set of defined critical events are determined as a basis for decision making. More in detail, the following general steps can be distinguished within risk quantification.

1 *Determination of the probability of occurrence a critical event and the intensity of released physical effects*: The occurrence of critical event at the risk source will lead to failure and consequent release of physical effects. The probability of failure is indicated by p_f, which is expressed as a probability per year. Following failure certain initial physical effects with intensity (c_0) will be released at the risk source. The intensity of such effects can for example be expressed as the heat release rate of a fire, explosion pressure, or the inflow discharge of water through a breach. The conditional probability density function (pdf) of the intensity of initial effects given failure is noted as $f_{C0|f}(c_0)$. One (deterministic) initial release is generally indicated as a scenario. The (unconditional) pdf of the intensity of initial effects $f_{C0}(c_0)$ is then obtained as follows (see Figure 1 for a sketch):

$$\begin{aligned} f_{C0}(c_0) &= 1 - p_f \qquad & c_0 = 0 \\ f_{C0}(c_0) &= p_f f_{C0|f}(c_0) \qquad & c_0 > 0 \end{aligned} \tag{1}$$

2 *Analysis of the dispersion of physical effects*: Spatial and temporal dispersion of effects can be assessed with a dispersion model. Dispersion will depend on the substance properties, local topography, and climatic conditions, etc. The intensity of physical effects c at location (x,y) will depend on the intensity of the initial release and the dispersion model and it is indicated as: $c(c_0, x, y)$ (also see Figure 2).

3 *Determination of the number of exposed people (N_{EXP})*: This is determined based on the extent of the area exposed to physical effects (A) and the population density $m(x, y)$ in that area.

4 *Estimation of mortality and loss of life amongst the exposed population*: Mortality will depend on the local intensity of physical effects. It can be estimated by means of a dose response function $F_D(c)$,which gives a relationship between the intensity of physical effects and the mortality in the exposed population (see Figure 2). By combination with the number of exposed people the actual number of fatalities can be estimated.

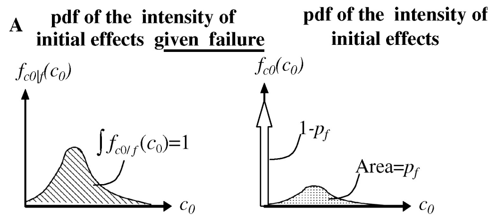

Figure 1. Pdf of the intensity of initial effects.

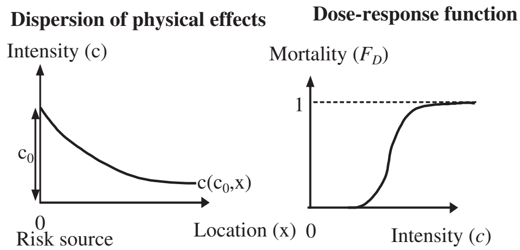

Figure 2. Dispersion of physical effects (left) and dose-response function (right).

In the consequent elaboration the generalized formulations for the above elements are adopted. It is assumed in this section that the dose response and dispersion functions give a deterministic outcome.

For example for the dose response function, this implies that the dose response function results in one certain value of mortality for each concentration. It is also assumed that $f_{C0|f}(c_0)$ en $F_D(c)$ are continuous and differentiable functions.

3.2 *General approach for risk quantification*

General formulations for risk quantification can be obtained based on reliability theory, as expressions for individual and societal risk can be derived from the classical load – resistance paradigm. The probability of death can be derived using the limit state function Z in its standardized form:

$$Z = R - S \tag{2}$$

In this case the load (solicitation) S consists of physical effects to which people are exposed. R denotes the human resistance to a certain concentration load, and its distribution is represented by the dose response function. The critical concentration at which human failure occurs equals c_R, leading to the general formulation of the dose response function:

$$F_D(c) = P(c_R < c) \tag{3}$$

As the the concentration of physical effects c represents the load on human beings, the limit state function can be conceptually re-written as:

$$Z = c_R - c \tag{4}$$

By multiplication of the pdf of effects and the dose response function, the pdf of mortality is obtained that is shown in the left part of Figure 3. The area under this last pdf signifies P(R < S) = P(Z < 0), and gives the probability death of an individual. This notion forms the basis for further determination of the general expressions for individual and societal risk.

To further elaborate and solve the limit state function (equation 2) it is necessary to obtain a load and resistance term. The dispersion model and dose response function are combined by substitution. The resulting expression gives the probability of death at location (x,y) for a certain initial release (c_0):

$$F_D(c) = F_D^*(c_0, x, y) \qquad for \quad c(c_0, x, y) \tag{5}$$

This expression is labeled the combined dose response function and it can be used as the distribution for the resistance term in equations 2 or 4. The pdf of the intensity of initial effects $f_{C0}(c_0)$ can be used as the load term.

3.3 *Determination of individual and societal risk*

Below it shown how individual and societal risk can be determined analytically. Individual risk gives the probability of death at location (x,y) in one year and it

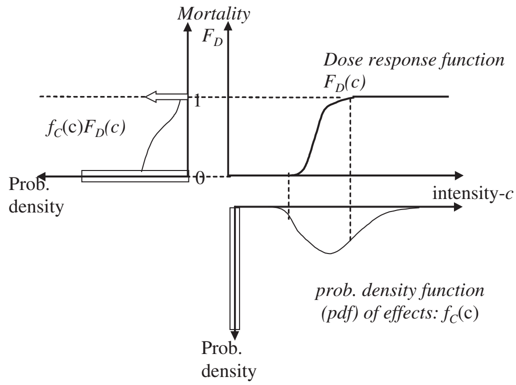

Figure 3. Combination of load (S – in this case effects c) and resistance (R – in this case the dose response function $F_D(c)$) to obtain the pdf of mortality.

can be found based on the limit state function derived above. Following assumptions stated earlier, the IR is calculated for an individual permanently present. The probability of "failure of the individual" (i.e. death) at location (x,y) is found by integrating over all initial releases that can expose the location:

$$IR(x,y) = P(Z(x,y) < 0) = \int_0^\infty f_{C0}(c_0) F_D^*(c_0, x, y) dc_0$$
$$= \int_0^\infty p_f f_{C0|f}(c_0) F_D^*(c_0, x, y) dc_0 \tag{6}$$

In order to determine societal risk the number of exposed people (N_{EXP}) is determined. It is found by integrating the population density over the exposed area A:

$$N_{EXP} = \iint_A m(x,y) dxdy \tag{7}$$

The number of fatalities will be a certain function of the initial release (c_0). It can be found by combining the dose response function, the dispersion model and the number of exposed people. Thus, the number of fatalities for one initial release (scenario) yields:

$$n = g(c_0) = \iint_A F_D^*(c_0, x, y) m(x,y) dxdy \tag{8}$$

Most of the existing risk measures for societal risk are based on (moments of) the probability density function of the number of fatalities (Jonkman *et al.*, 2003; Vrijling & van Gelder, 1998). The pdf of the number of fatalities $f_N(n)$ can be obtained from the pdf of initial effects by using the Jacobian. If a relationship exists between variables u and v, the Jacobian can be used to derive the pdf of variable v from the pdf of variable u. Suppose that variable v is a function

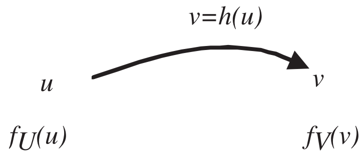

Figure 4. Schematic display of derivation of the pdf of v from the pdf of u.

of variable u with a function h, so that $v = h(u)$ and $u = h^{-1}(v)$, also see Figure 4.

$$f_V(v) = f_U(u)\frac{du}{dv} = f_U\left(h^{-1}(v)\right)\frac{d\left(h^{-1}(v)\right)}{dv} \tag{9}$$

Equation 9 can be used to derive the pdf of the number of fatalities. The relationship between initial effects and the number of fatalities is given by equation 8. As a result, the following expression is obtained:

$$f_N(n) = f_{C0}(c_0)\frac{dc_0}{dn} = f_{C0}\left(g^{-1}(n)\right)\frac{d\left(g^{-1}(n)\right)}{dn} \tag{10}$$

The distribution of the number of fatalities is obtained by integration:

$$F_N(n) = \int_0^n f_N(n)dn = \int_0^{g^{-1}(n)} f_{C0}(c_0)dc_0 \tag{11}$$

Societal risk is often expressed in an FN curve, showing the probability of exceedance of a certain number of fatalities, so $1 - F_N(n)$. This is the complement of the distribution curve of the number of fatalities. The above elaboration shows that the FN curve can be derived analytically from the pdf of initial physical effects and that it can be modeled as a continuous function. Societal risk can also be expressed with the first moment of the pdf of fatalities, the expected number of fatalities ($E(N)$):

$$E(N) = \int_0^\infty f_N(n)ndn \tag{12}$$

In literature Potential Loss of Life (PLL) is often used as a synonym for expected value of the number of fatalities. Vrijling & van Gelder (1998) prove that the expected value from societal risk can also be found by taking the area under the FN curve. For some purposes, for example emergency management, it is interesting to have information on the likelihood of a certain number of fatalities in the case of an accident. The above approach also allows the derivation of the conditional pdf of the number of fatalities given failure $f_{N|f}(n)$:

$$f_{N|f}(n) = f_{C0|f}(c_0)\frac{dc_0}{dn} = f_{C0|f}\left(g^{-1}(n)\right)\frac{d\left(g^{-1}(n)\right)}{dn} \tag{13}$$

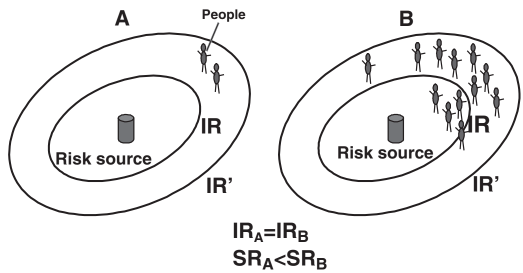

Figure 5. The difference between individual and societal risk (based on Stallen *et al.* (1996)).

4 THE RELATIONSHIP BETWEEN INDIVIDUAL AND SOCIETAL RISK

Individual risk, according to the definition of Bottelberghs (2000), gives the probability of dying at a certain location regardless of the presence of people. Individual risk contours can be displayed on a map and IR is therefore directly applicable for land use planning and corresponding zoning purposes. Societal risk takes into account the actual presence of people and gives a risk number for a whole area, no matter precisely where the harm occurs within that area. The difference between individual and societal risk is schematically shown in Figure 5. Both situations A and B have the same individual risk levels (shown by IR' and IR). Due to the larger population density of situation B, it has a larger societal risk than situation A, also see Stallen *et al.* (1996).

Several authors mention that individual and societal risk are linked via expected value of number of fatalities (see e.g. Ale *et al.*, 1996b; Alp & Zelensky, 1994; Ball & Floyd, 1998; CIB, 2001; Francis *et al.*, 1999; Trbojevic, 2004). However, a final confirmation of their precise relation is not given other than with numerical calculations (Ball and Floyd, 1998). In order to check the mutual consistency of individual and societal risk calculations, the formulations for the expected number of fatalities that are obtained with both approaches are compared.

The expected value of the number of fatalities from individual risk follows from integration of individual risk contours with population density (see e.g. Laheij *et al.*, 2000; CIB, 2001):

$$E(N) = \iint_A IR(x,y)m(x,y)dxdy$$
$$= \int_0^\infty \iint_A f_{C0}(c_0)F_D^*(c_0,x,y)m(x,y)dxdydc_0 \tag{14}$$

Many authors, e.g. (Francis *et al.*, 1998), now state that this equation must be identical to 12 (i.e.

$E(N)=\int_0^\infty f_N(n)ndn$), but they do not give a further substantiation of this statement. This check can be achieved by using this expression for the expected number of fatalities from societal risk. Substitution of the expression for the number of fatalities for one initial release (eq. 8) yields:

$$\begin{aligned} E(N) &= \int_0^\infty f_N(n)ndn \\ &= \int_0^\infty f_N(n)\iint_A F_D^*(c_0,x,y)m(x,y)dxdydn \end{aligned} \tag{15}$$

Consequent substitution of the Jacobian of equation 10 gives:

$$E(N)=\int_0^\infty\iint_A f_{C0}(c_0)F_D^*(c_0,x,y)m(x,y)dxdydc_0 \tag{16}$$

As equation 16 is identical to equation 14 we conclude that the expected values obtained from individual and societal risk are equivalent. This confirms the relationship between individual and societal risk.

Although it is theoretically obvious that individual and societal risk calculations should lead to equal expected values, several assumptions and modelling choices in risk calculations might influence this relationship in practice. Ale *et al.* (1996a) give a comparison between expected values obtained from individual and societal risk (labelled as PLLI and PLLF respectively) using outcomes of risk analyses for different hazardous installations in the Netherlands. They show that calculated PLLI and PLLF values deviate, sometimes several orders of magnitude. Further analysis of the data of Ale *et al.* suggests that not all these differences could be explained by differences in assumptions and modelling choices. This indicates the relevance of a verification of the relationship between PLLI and PLLF in the risk calculation. The two different "routes" of calculating the expected number of fatalities can be followed to verify the consistency of individual and societal risk calculations for a given installation. After consistency is assured, assumptions in individual and societal risk calculations could be differentiated, e.g. with respect to presence and protection of people.

5 EXTENSION OF THE GENERAL FORMULATIONS FOR RISK QUANTIFICATION

To enable a wider application of the general formulations for risk quantification, several extensions for specific situations are proposed. These include the correction for reduction of actual presence of people e.g. due to evacuation (5.1); and inclusion of the spatially distributed accidents (5.2) and direction dependent hazards (5.3).

5.1 *Correction for the actual presence of people*

Following the definition for individual risk discussed in section 2 permanent presence of persons has been assumed in previous elaborations. However, some alternative definitions concern the actual presence of people in an area in order to determine the actual individual risk. Within the individual risk calculation an occupation factor (Carter & Hirst, 2000) or residence time fraction (Matthijsen, 2003) can be introduced that indicates the fraction of the time that people are present[2] at a certain location. Similarly, the effects of evacuation can be discounted in risk quantification. Especially for events that are predictable and for which the effects are developing relatively slow, evacuation might be possible, e.g. for floods. The exposed population at a location can be reduced by evacuation, so that:

$$\alpha(x,y)=1-F_E(x,y) \tag{17}$$

Where: α(x,y) – occupation factor [-]; $F_E(x,y)$ – fraction of the population evacuated at location (x,y) [-]

This occupation factor can be included to correct for the actual exposure of the population and evacuation in the expressions for individual and societal risk:

$$N_{EXP}=\iint_A \alpha(x,y)m(x,y)dxdy \tag{18}$$

$$IR(x,y)=\int_0^\infty f_{C0}(c_0)F_D^*(c_0,x,y)\alpha(x,y)dc_0 \tag{19}$$

5.2 *Risk quantification for spatially distributed accidents*

The presented general formulations in the previous sections assumed one risk source at a fixed location, i.e. "a point source". This situation will be representative for a stationary installation, where the physical effects will develop as coming from one source. However, for many applications, for example transport of dangerous materials, flood protection or airport safety, accidents can occur at different locations (e.g. sections of the road or dike, or all locations near an airport). Then it is necessary to take into account the spatial distribution of accident locations and the exposed area by each accident in risk quantification. To show the conceptual approach for spatially distributed accidents the

[2] The complement of the factor: 1 – α(x,y) indicates the time of the day that people are elsewhere, e.g. for school or work.

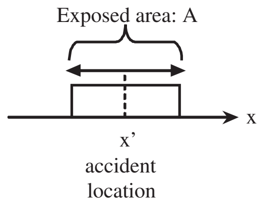

Figure 6. Schematic view of exposed area A in case of an accident at location x’.

situation is elaborated for a one-dimensional example. Assume that an accident occurs at location x' (3). The effects will occur within the exposed area with a certain “footprint” area A. All locations within the accident footprint will be exposed to the effects of the accident at x’, see figure 6.

The probability of exposure at a certain location to the effects of spatially distributed accidents can be determined as follows. Assume that the probability of an accident equals p_f. The (conditional) distribution of the accident location given an accident can be described with: $f_{x'|f}(x')$ for a one dimensional situation. The probability of exposure at location x equals the probability that location x will be within the accident footprint:

$$P(\exp osure\ at\ x) = P(x - A/2 < x' < x + A/2) \\ = \int_{x-A/2}^{x+A/2} p_f f_{x'|f}(x')dx' \tag{20}$$

If the accident footprint A becomes larger this will lead to an increases the probability of exposure and consequently the individual risk. It is noted that for some applications, e.g. for transport routes, an alternative notation might be preferable, because the accident probability is a function of the location. Then, a failure intensity $\lambda_f(x')$ with unit [1/length] can be used, also see (JCSS, 2001). The dependency on length x expresses the variability in circumstances along the length, leading to variations in accident intensity (JCSS, 2001).

5.3 *Meteorological conditions and direction dependent hazards*

For some hazards meteorological conditions can influence the dispersion of physical effects and the extent of the exposed area, also see (Alp & Zelensky, 1994) for extensive discussion. For example for the release of toxic gasses, the wind direction will determine the contour of the released gas plume and the exposed area (Vilchez *et al.*, 2004). For such situations the

[3] Index (‘) is used to denote the difference between crash location (x’) and location of exposure (x)

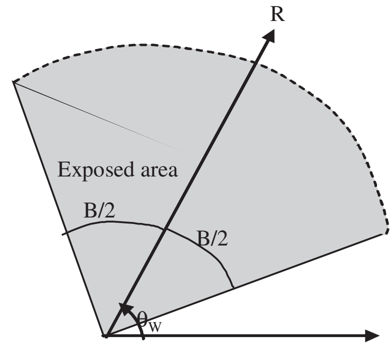

Figure 7. Exposed area to effects in case of wind direction θ_W in a polar coordinate system.

exposed area, the consequences (and risk levels) will be direction dependent. The influence of meteorological conditions can be included in risk quantification. The occurrence of certain meteorological conditions, e.g. wind direction θ_W, is described with a probability density function: $f_W(\theta_W)$. A polar coordinate system is generally used where angle and distance relative to the risk source are described with angle [rad] and radius R [m] respectively. The exposed area or “footprint” stretches out at radius B/2 on both sides of the occurring wind direction and it is assumed here that effects disperse over very large distance, so that R approaches infinity, see figure 7.

Suppose that we assess some location at radius θ. The probability of exposure in this direction θ is found by summing over all wind directions that result in exposure (Logically, it is assumed that wind direction is independent of failure):

$$P(\exp osure\ at\ \vartheta) = \int_{\vartheta-B/2}^{\vartheta+B/2} p_f f_W(\vartheta_W)d\vartheta_W \tag{21}$$

Individual risk at location (R,θ) is assessed by combining the probability of exposure, with the dose response function and the dispersion model (formulated as $c(c_0, R, \theta)$ and substituted in the dose response function):

$$IR(R,\vartheta) = \int_{\theta-B/2}^{\theta+B/2}\int_0^{\infty} p_f f_W(\vartheta_W) f_{C0|f}(c_0) F_D^{\ *}(c_0, R, \vartheta)dc_0 d\vartheta_W \tag{22}$$

For direction dependent hazards (e.g. toxic releases) the consequences of the event will depend on the meteorological situation at the moment of occurrence of the event, and the dispersion of effects relative to population concentrations.

6 EXAMPLES

To demonstrate the application of the general formulations and the proposed extensions to various terrains, different examples are elaborated in this section. The examples are conceptual and highly schematized, but characteristic for different applications. Some main results are presented, further detailed elaborations can be provided by the first author.

6.1 *Simple fictitious example*

First, a simple and fictitious example is elaborated to indicate the applicability of the general formulations and the equivalence of expected values from IR and SR. In this simple example it is assumed that effects and population density are uniformly distributed over a certain area. This situation can be schematized as a point source in a "point city".

The probability of failure of risk source equals $p_f = 0{,}5.10^{-3}$ [yr^{-1}]. The conditional pdf of the intensity of initial effects given failure is described with an inverse quadratic Pareto pdf:

$$f_{c0|f}(c_0) = 0 \qquad\qquad 0 \le c_0 < 1$$

$$f_{c0|f}(c_0) = \frac{a}{c_0^{\,3}} = \frac{2}{c_0^{\,3}} \qquad\qquad c_0 \ge 1 \tag{23}$$

Where: a – constant with value 2 [$1/c_0^2$]; c_0 – intensity of initial effects (in more practical examples this could for example be a concentration [mg/m^3]).

The (unconditional) pdf of the intensity of initial effects is shown in figure 8.

Given the chosen schematization of a point city the dispersion of physical effects is not relevant, so $c_0 = c$. The mortality for an event can now be directly estimated as a function of initial effects with a dose response function:

$$F_D(c_0) = b\sqrt{c_0} \qquad 0 \le F_D \le 1 \tag{24}$$

Where: b – constant [$1/[c_0^{0,5}]$]

b is assumed to be very small, so that $F_D(c_0)$ approaches 1 for very large values of c_0. The number of people in the exposed area equals N_{EXP}. The individual risk is found by combining the pdf of initial effects with the dose response function:

$$IR = \int_0^\infty p_f f_{C0|f}(c_0) F_D(c_0)\,dc_0 =$$

$$\int_1^\infty p_f \frac{a}{c_0^{\,3}} b c_0^{\,0,5}\,dc_0 = 2/3abp_f \tag{25}$$

The expected value of the number of fatalities from individual risk is found by multiplication with the number of exposed people, so that $E(N) = 2/3abp_f N_{EXP}$.

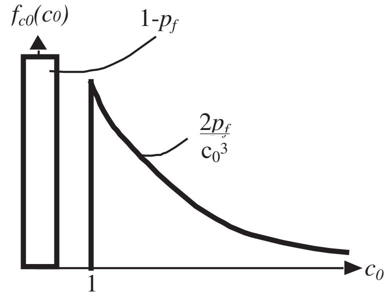

Figure 8. Probability density function of the intensity of initial effects.

For the derivation of societal risk, the number of fatalities n is found as a function of initial effects and exposed population

$$n(c_0) = F_D(c_0)N_{EXP} = bN_{EXP}c_0^{\,0.5} \tag{26}$$

The probability density function of the number of fatalities can be derived as follows (note the transition of integration boundaries):

$$f_N(n) = f_{C0}(c_0)\frac{dc_0}{dn} =$$

$$f_{C0}(c_0)\frac{2c_0^{\,1/2}}{bN_{EXP}} = \frac{2ap_f(bN_{EXP})^4}{n^5} \qquad d \le n < \infty \tag{27}$$

$$d = n(c_0 = 1) = bN_{EXP}$$

Integration of this pdf yields the expected value of the number of fatalities:

$$E(N) = \int_d^\infty n f_N(n)\,dn$$

$$= \int_d^\infty \frac{2ap_f(bN_{EXP})^4}{n^4}\,dn = 2/3abp_f N_{EXP} \tag{28}$$

Following earlier discussion it is shown that expected values obtained from individual and societal risk are equivalent. The distribution function of the number of fatalities and the FN curve are found by integration over n:

$$F_N(n) = \int_0^n f_N(n)\,dn$$

$$1 - F_N(n) = \frac{2ap_f(bN_{EXP})^4}{4n^4} \qquad d \le n < \infty \tag{29}$$

Below, the corresponding FN curves are shown for $a = 2$; $b = 10^{-5}$; $p_f = 0{,}5.10^{-3}$ and $N_{EXP} = 10^5$.

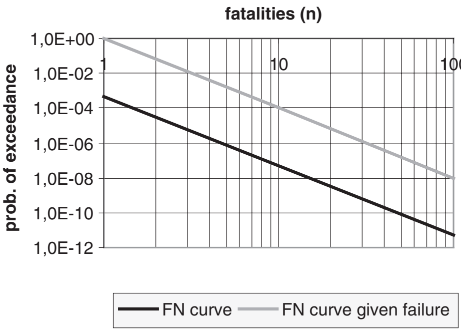

Figure 9. FN curve for the simplified example.

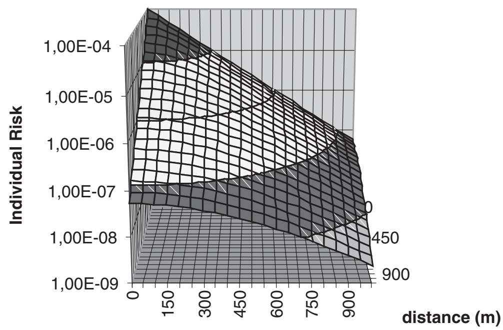

Figure 10. Individual risk levels for the point source example.

Similarly, the pdf, distribution and FN curve for the number of fatalities given failure can be derived. Note that the FN curves have a slope of −4. This can be derived from the combination of the pdf of effects, the Jacobian and the square rooted dose response function. Thus, this shows that the steepness of the FN curve will depend on the pdf of initial effects and the dose response function. Note that the (unconditional) FN curve for the number of fatalities intersects the vertical axis at the value of the probability of failure $p_f = 0{,}5 \,.\, 10^{-3}$ per year of killing at least one person. The conditional FN curve given failure is shifted vertically with the factor p_f.

6.2 *Point source with radial dispersion of effects*

In the second example a point source is treated as representative for a chemical installation. The same pdf for intensity of initial effects and dose response function are used as in the previous section (5.1). It is assumed that effects will disperse radially, which could for example correspond to dispersion of gas in a situation without wind. The concentration of effects will decrease exponentially as a function of (radial) distance to the source:

$$\begin{aligned} &c(c_0, R) = c_0 e^{-\alpha R} \\ &F_D(c) = b\sqrt{c} \quad \Rightarrow \quad F_D^*(c_0, R) = b c_0^{0.5} e^{-0.5\alpha R} \end{aligned} \tag{30}$$

Where: R – radial distance to source [m]; α – constant determining decrease of effects as a function of distance [m^{-1}].

The individual risk is now determined as a function of radial distance to the source:

$$\begin{aligned} &IR(R) = P(Z(R) < 0) = \int_1^\infty p_f f_{C0|f}(c_0) F_D^*(c_0, R) dc_0 \\ &= \int_1^\infty p_f \frac{a}{c_0^3} b c_0^{0,5} e^{-0,5\alpha R} dc_0 = 2/3abp_f e^{-0,5\alpha R} \end{aligned} \tag{31}$$

Based on the previous equation the distance to an individual risk contour is determined with:

$$R(IR) = -\frac{2}{\alpha} \ln\left(\frac{3IR}{2abp_f}\right) \tag{32}$$

Individual risk levels are shown in figure 10 as a function of distance to the risk source for $a = 2$; $b = 0.15$; $p_f = 0{,}5.10^{-3}$; $\alpha = 0.015$. Because radial dispersion and no influence of wind is assumed, the risk contours have a radial shape. The above formulation shows that for this case (exponential decay of physical effects) the distances between successive individual risk contours will be identical This shows that individual risk contours are two-dimensional projection of the three dimensional distribution of individual risk on a map.

In a similar way as in the previous paragraph the societal risk can be determined analytically, if the population distribution is known.

6.3 *Point source with direction dependent dispersion of effects*

The above example concerns the (hypothetical) situation of radial dispersion without the influence of wind. As released (toxic) substances will be dispersed by the wind the consequence and risk levels will depend on the wind direction. The inclusion of direction dependent hazards is illustrated in the following example. In this example the already introduced schematisations are used for the occurrence of initial effects ($f_{C0}(c_0)$), dispersion of effects ($c(c_0, R)$) and the dose response function ($F_D(c)$). We assume that the pdf of the occurring wind direction (θ_W – [rad]) can be described with:

$$f_W(\theta_W) = \frac{1}{\pi}\cos^2\frac{1}{2}\vartheta_W \qquad 0 \le \vartheta_W \le 2\pi \tag{33}$$

Note that the dominating wind direction is the western wind ($\theta_W = 0$) and that integration of the pdf over all wind directions yields 1. The actually exposed area

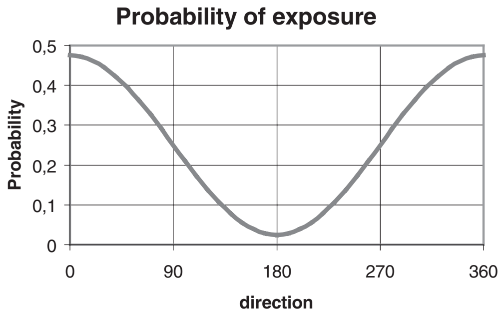

Figure 11. Probability of exposure in a certain wind direction.

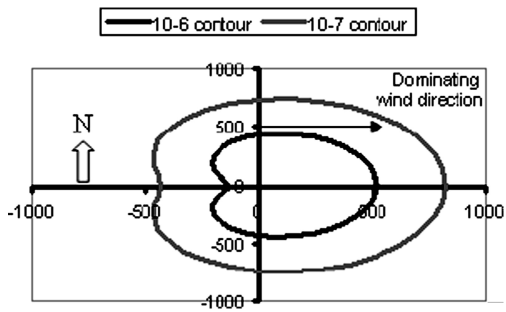

Figure 12. Individual risk contours for a hazardous facility taking into account the dominating wind direction.

or "footprint" stretches along 45° (or $\pi/4$ in radials) on both sides of the occurring wind direction (see figure 7). The probability of exposure in direction (θ) is shown in Figure 11. Note that the probability of exposure will be higher than the probability of a certain wind direction due to the add-on effects associated with the width of the exposed area.

Based on formula 22 the individual risk contours can be determined. Figure 12 shows the 10^{-6} and 10^{-7} risk contours for the parameter values that have been given earlier. It clearly shows the effects of the dominating western wind direction. This causes the IR contours to reach much further at the eastern side of the facility, as the wind direction is often west.

7 CONCLUSION

In this section a generalized framework for risk quantification has been proposed that is based on the principles of reliability theory. Individual and societal risk can be quantified by combining four general elements: information on the probability of occurrence of initial effects at a risk source, the dispersion of effects, consequent exposure of the population, and mortality amongst the exposed population. This subdivision makes it also possible to analyze the effects of risk reduction measures in a systematic way. The framework proofs applicable to different terrains and provides insight in the factors that will influence individual and societal risk levels.

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