Propositions for loss-of-life modelling in risk assessment

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Abstract

In assessing the safety of engineering systems in the context of risk analysis the potential consequences of accidents are often expressed in terms of loss of life. In this paper "small probability – large consequences" events within the engineering domain are dealt with. A general approach for loss of life modelling is proposed which includes the following steps: 1) the assessment of physical effects associated with the event; 2) determination of the number of exposed persons (including effects of warning and evacuation); 3) determination of mortality amongst the exposed population. The typical characteristics of these elements are discussed. It is demonstrated how the approach can be integrated into risk analysis. The application is shown in two case studies considering tunnel fires and floods.

Keywords: loss of life, mortality, consequence modelling, quantitative risk analysis

1 Introduction

From a technical point of view, the extent of the risks and the effects of risk reduction measures can be quantified in a quantitative risk analysis (QRA). QRA can thus provide a basis for rational decision-making regarding risks. The process of risk analysis is schematically shown in figure 1, defining some of the main terms used in this paper. In the figure, the process of risk analysis is related to the sequence of events leading to and following after a critical event. Certain causes can result in the occurrence of a *critical event* in an originally normally operating system. This event might lead to the occurrence of *physical effects* (e.g. smoke for fire). When persons and/or objects are exposed to them, this can result in certain *consequences*. A fault tree is generally used to determine the probability occurrence of a critical event, taking into account the possible causes and their sequence. In an event tree all possible events following a certain initiating event are shown, and it is generally used to assess the effects and consequences of a certain critical event.

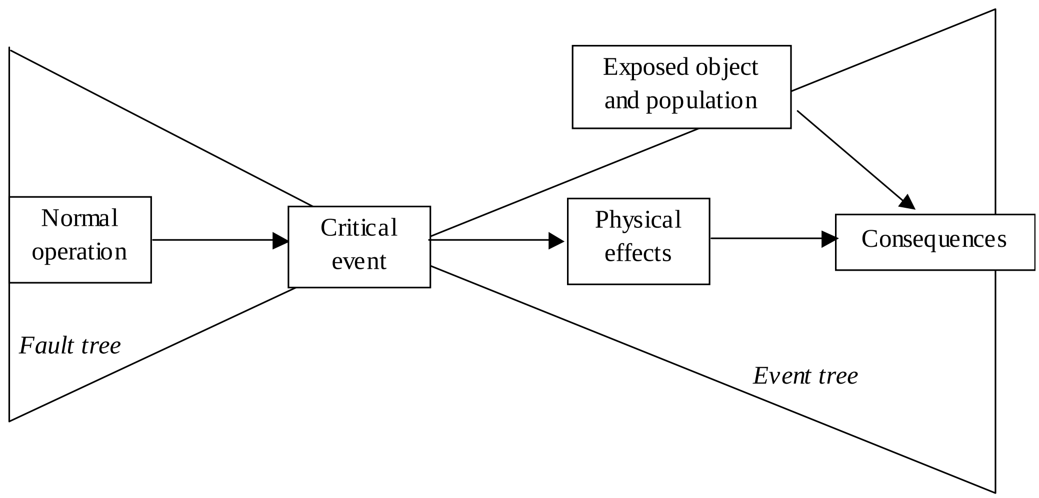

Figure 1: Evolvement of a critical event and steps in risk analysis

In the context of quantitative risk analysis, consequences are generally expressed in terms of expected economic damage or loss of life (Jonkman et al., 2003). This paper considers the modelling of loss of life within risk analysis. There is a considerable amount of literature dealing with the quantification of loss-of-life consequences from technical failure for individual event types. However, parallels existing between different cases have been mostly neglected, and relatively little attention has been paid to the general principles of loss-of-life estimation. When trying to predict the number of lives lost due to accidents in the engineering domain, it is most helpful to rely on some kind of general methodology. Especially, as it is observed that the existing approaches of life estimation in different fields include similar steps, as further discussed in section 2.

Both authors have completed previous work on this issue. Lentz and Rackwitz (2004) focused on formulating an event-type independent methodology, whereas Jonkman dealt with different event types separately, such as floods (2002) and tunnel fires (2004). Therefore, the aim of the paper is twofold: To validate a general methodology by confronting it with the case-specific approaches and to put the case-specific approaches in a larger context at the same time. Within the general framework, new event types can be dealt with more efficiently, because a generalized approach points out the traits common to all kinds of event types. In addition, this general approach will allow the use of specific event data for other events types, given that relevant event characteristics and the level of detail of analysis are comparable.

As such, the proposed model serves two purposes. Firstly, it can be used to estimate the loss-of-life as input for the determination of quantitative risk levels for a system. Secondly, it allows the assessment of the effects of risk reducing measures on consequence and risk levels. However, it should be noted that models for loss-of-life estimation can also be used for the presentation of the outcomes of deterministic accident scenarios.

Scope of this study

In order to position the applicability of the framework, the development of effects and consequences over time is discussed for different types of events, as is schematically shown in figure 2:

- Curve a is representative for those events, for which effects and consequences manifest within relatively short time period (seconds, hours, sometimes days). Most fatalities are directly caused by the physical forces of the disaster and they occur during or shortly after the event. Due to the delay in the occurrence of medical effects, fatalities occurring within the first week after the event are generally included (also see Coburn and Spence, 2002). Examples of such events are floods, earthquakes and tunnel fires. (Consider e.g. a flood: Most fatalities will occur within first few days, while there might be a small increase in mortality due to post event stress (see Bennet, 1971)).

- Curve b schematises so-called long-term or chronic exposure (Lentz & Rackwitz, 2004b). This long-term exposure can influence (increase) mortality. In general no single "event" can be identified. Examples of this type include exposure to air pollution, or other noxious substances in the environment (e.g. dioxins).
- Curve c schematically shows events which form a combination of the first two types. Chemical and nuclear accidents might have both direct and more longer-term effects and consequences. For example for a nuclear accident many fatalities will occur due to the initial radiation release, and these will occur both directly and with a certain delay. In addition a certain level of radiation will persist after the accident and this will contribute to longer term mortality

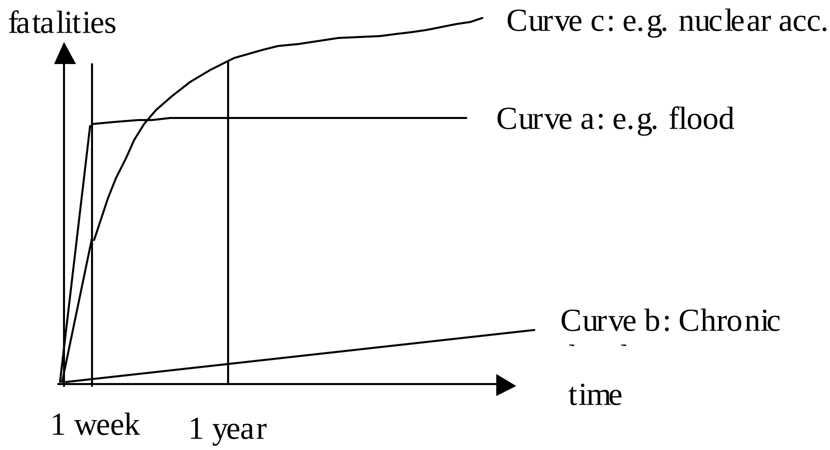

Figure 2: Development of the number of fatalities over time for different accidents (use log scale on x-axis)

This paper focuses on the assessment of loss of life for "immediate" events for engineering systems (type a). So-called "small probability – large consequences" events are considered within the engineering domain. In this domain the issues with respect to safety are often related to engineering design issues and technical measures. Examples of considered events are: floods, airplane crashes, tunnel fires and chemical accidents.

2 General approach for loss of life estimation

In order to estimate loss of life due to a certain event, usually a mortality fraction is determined. Mortality is defined as the fraction of fatalities amongst the exposed population. For some event types, mortality will be well predictable without further extensive modelling: for example for airplane crashes the mortality amongst persons on the ground within the area affected by airplane crash proves to be relatively constant (Piers et al., 1992). For other event types, mortality shows larger variation over different single events, due to their dependence on various event-specific variables. As an illustration, the number of fatalities is plotted against the number of exposed persons for tunnel fires in figure 3, lines with constant mortality are shown in the figure.

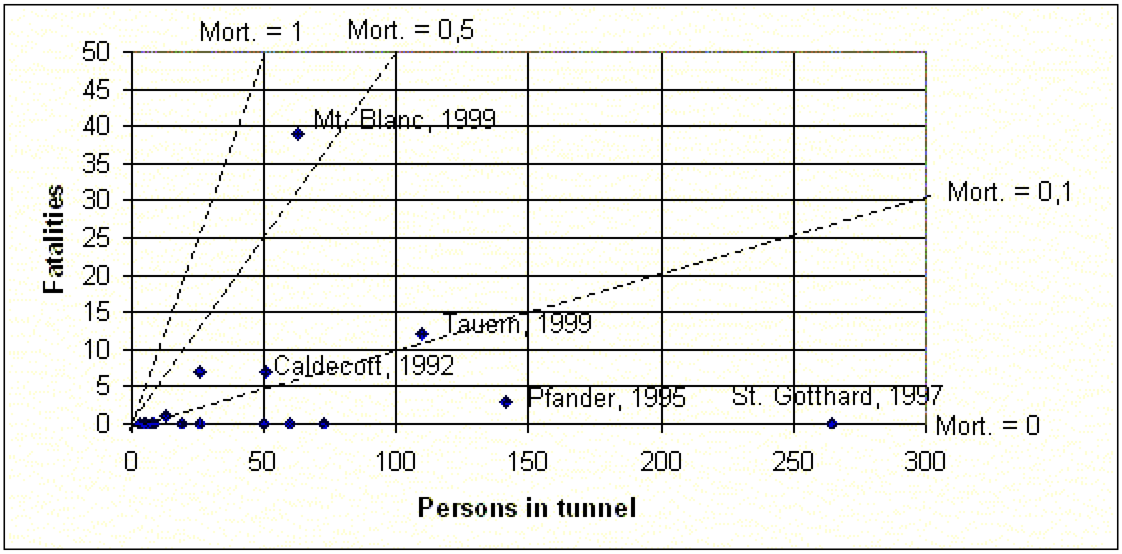

Figure 3: Fatalities and number of affected persons in tunnel fires (Amundsen, 2001, analysis by O. Kübler, note that in this approach the number of persons in the tunnel is proportional to the tunnel length). For some characteristic events tunnel name and year are indicated.

Similar figures are available in literature for floods (Jonkman, 2005) and earthquakes (Coburn & Spence, 2002) and also indicate large deviations in mortality between events. For these cases, case-specific mortality can obviously only be predicted on a sufficient level of accuracy, if the event modelling itself moves onto a sufficient level of detail and tries to include the relevant event-specific variables.

A selection of loss of life models has been studied over various sectors in order to derive general principles for loss-of-life estimation; an overview is given in table 1. All these models have been developed in the context of quantitative risk analyses.

Table 1: Overview of models for estimation of loss of life due to a critical event, for different fields of application

Field / disaster type	**Model description**	**Reference**
Floods	Overview of methods for loss of life estimation for river, coastal and dam break floods	Jonkman et al., 2002
Earthquakes	Earthquake Protection	Coburn & Spence, 2002
Tunnel accidents	Assessment of consequences for fires and explosion in road tunnels	Persson, 2003
Airport Safety	Method for determination of fatalities on the ground due to airplane crashes near Schiphol airport (NL)	Piers et al., 1992
Chemical accidents	Dutch guidelines for estimation of consequences for chemical accidents	CPR, 1989

It has been observed that the existing approaches of life estimation in different fields include the following similar steps, which correspond to the elements in the right hand side of figure 1:

1. The assessments of physical effects associated with the critical event and the extent of the area affected by these effects;
2. Determination of the number of exposed persons in the affected area, taking into account possibilities for warning and evacuation;
3. Estimation of the mortality amongst the exposed population as a function of the mentioned effects.

Note that such an approach is very similar to the load-resistance approach in structural engineering. The physical effects form the loads, and the resistance of the exposed population determines the mortality. This concept is further discussed in section 5.

By combining these three main elements loss of life can be estimated as is shown in the general framework proposed in figure 4. As a starting point an undesired event with physical effects (*x*) is assumed to occur. *x* is a general vector signifying the event's intensity, which is represented by the physical effects, such as arrival time of effects, concentration, etc.. The number of persons exposed will depend on the number of persons present N_{PAR}(x) ("people at risk") in the affected area and the fraction of persons that will be able to evacuate ($F_E(x)$). Both depend on *x*, as outlined in section 3. Event-specific mortality is generally determined by means of so-called dose-response relations, which determine mortality (F_D) as a function of the physical effects. Then the number of fatalities (*N*) is now found as follows (Lentz & Rackwitz, 2004):

$$N(x) = F_D(x)(1 - F_E(x))N_{PAR}(x)$$

Following from this analysis also the number of evacuated persons and survivors are found. Note that both F_D and F_E can be formulated as typical distribution functions, with: $0 \leq F \leq 1$
Their forms and characteristics are discussed in the following sections.

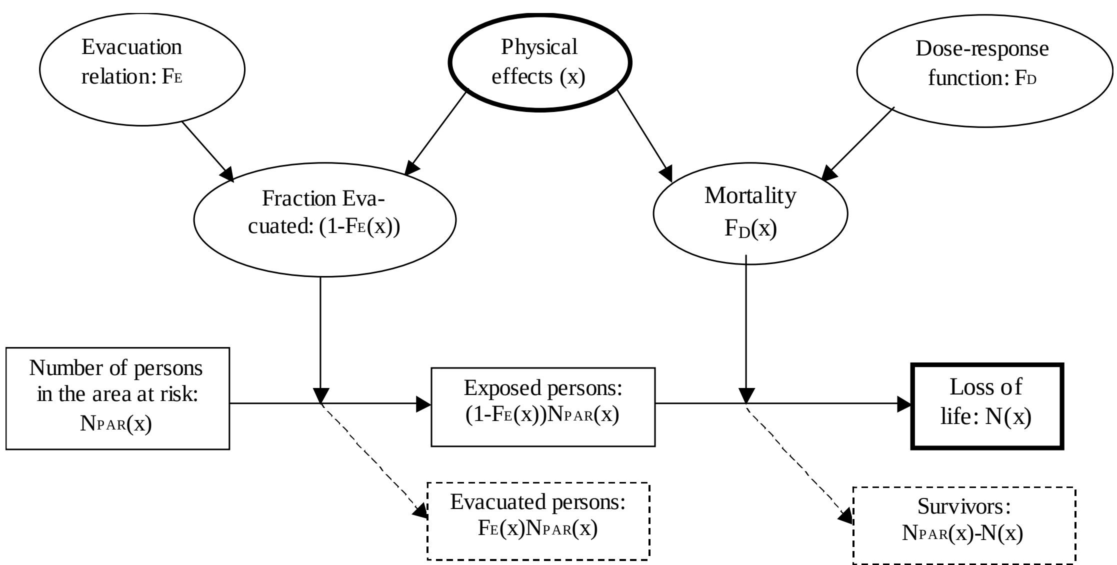

Figure 4: Framework for loss of life estimation

We assume that the (probability of) occurrence of an event with certain physical effects can be well predicted by reliability theory. For different fields, extensive research has been undertaken on the simulation of physical effects and available methods are not discussed in detail here. Then the framework is divided in the following two parts. Section 3 describes the left hand side of the figure: the assessment of the number of exposed persons and evacuation. Section 4 discusses he methods for estimation of morality. The further application of the methodology of figure 4 in risk analysis is described in section 5.

3 Evacuation modelling and estimation of the number of exposed persons

3.1 Determination of the population at risk

All individuals present within the reach of the physical effects of an event before any signs or warnings can be perceived are referred to as "people at risk" or $N_{PAR}(x)$. N_{PAR} depends on the extent on the affected area, which, again depends on the extent of the physical effect, which leads to $N_{PAR} = N_{PAR}(x)$. For larger areas this number is often smaller than the population in the area (N_{POP}), because a part of the reference population will be busy elsewhere most of the time. However, in some cases the number of people at risk might be larger than the original population, for example when many people visit the affected area. Depending on the field of application N_{POP} can be seen as the registered population in an area, for other fields it can equal the maximum number of people to be expected in a certain type of facility (people in cars during traffic jam in a tunnel; all employees affiliated to an office etc.). More specific approaches for determining N_{PAR} are discussed in Lentz & Rackwitz (2004).

3.2 Determination of the exposed population

The number of persons exposed to the effects of the event (N_{EXP}) is found by first correcting the population at risk for the number of evacuated persons:

$$N_{EXP} = (1 - F_E(x))N_{PAR}$$

Here, the probability for successful evacuation $F_E(x)$ describes the fraction of people at risk N_{PAR} that are able to leave the affected area, *before* conditions become potentially harmful.

A general classification of the phases of the evacuation process applied over different disasters is supported by the literature, as the relevant evacuation phases are very similar over different disasters. For example, Mileti and Peek (2000) state that the principles of how humans respond to warnings remain constant across hazard agents as diverse as floods, earthquakes, tornadoes, explosions, and toxic chemicals. In general the probability of successful evacuation can be determined by comparing the available time until occurrence of the physical effects (T_A) and the required time for evacuation (T_R). In case of a successful evacuation the required time is smaller than the available time. The probability of successful evacuation (F_E) is found as follows:

$$F_E(x) = P\left(T_R(x) \leq T_A(x)\right)$$

Required time T_R(x) depends on the time needed to complete the different phases of an evacuation. There is a delay until a warning is issued $T_{pd,}$ which is usually needed for prediction, detection and decision-making. Then there is another delay until the warning is received by those endangered (T_{warn}) and finally another delay (T_{resp}) until those who received the warning will respond. In addition, the partial "failure" of these phases has to be accounted for by taking into account the possibility of failure of warning (% not-warned) and the fact that people do not respond to warnings (non-compliance). Finally, there is the time needed to cover the distance into safety $T_{evac}(x) = v/s(x)$, i.e. movement speed divided by distance. The distance depends on the area affected, depending, again, on x.

Available time depends on the extent x of the physical effects, i.e. $T_A = T_A(x)$. Obviously, an event with physical events of a greater extent x will lead to potentially lethal conditions faster than a smaller event, thus reducing $T_A(x)$.

For larger affected populations the different phases can be described by distribution functions, which can be combined in one overall distribution of $T_R(x)$. Figure 5 schematically shows the distribution curve over the population for the time required for the evacuation process. If the available time is known, the fraction of the persons that is able to evacuate equals: $F_E(T_A)$ (also see figure 5).

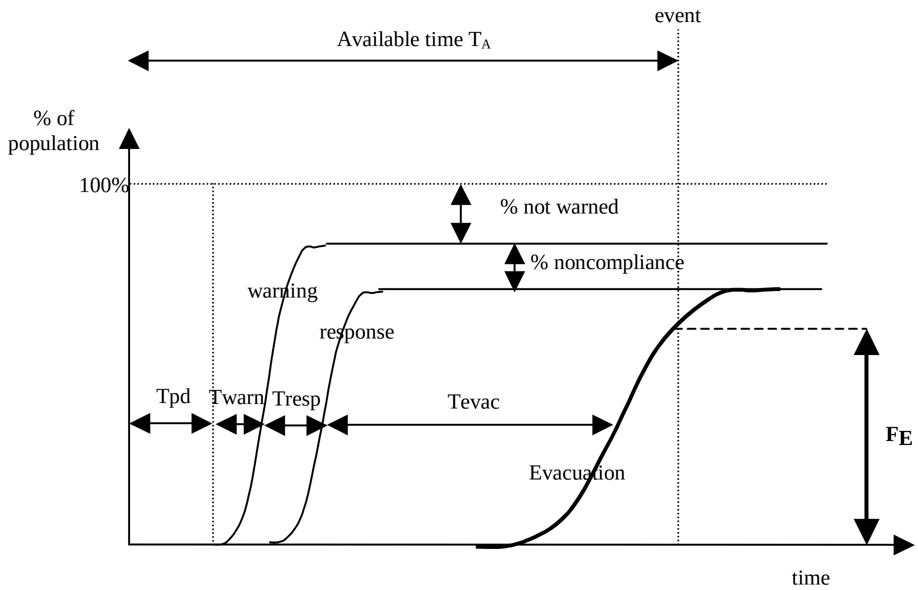

Figure 5: Distribution function of time required for evacuation, and comparison with available time

The above approach is most suitable for large-scale events with a large number of people at risk. For certain events, for instance for fires in tunnels or buildings, an actual analysis on a more individual level is preferable. In this case, the progress of an escaping individual can be schematically shown in a space, time (or *x,t*) diagram and it can be combined with development of physical effects, see figure 6. Assume that the event will occur at a certain location or origin x=0. The available time until occurrence of physical effects will depend on a persons' location relative to this origin: $T_A(x)$.

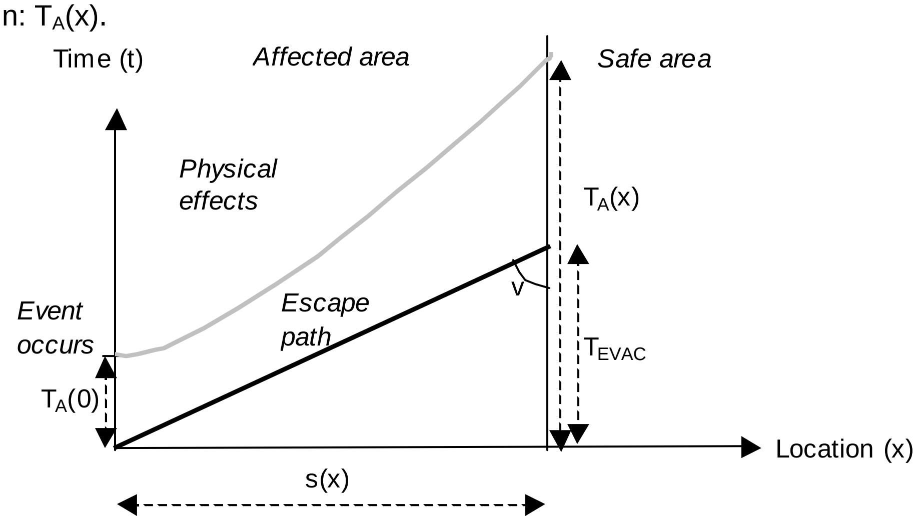

Figure 6: Time, space (x,t) diagram, indicating escape progress and development of physical effects (note that in the example it is assumed that T_{PD}=T_{warn}=T_{resp}=0; and the persons initiates escape before occurrence of the event)

In this case, it is often difficult to treat the two questions of evacuation and consequences in case of unsuccessful evacuation completely independently. For example, when a person escape through fire, walking speed might be reduced due to limited visibility and irritation of airways.

This issue is briefly addressed in the following section (see the part on the sudden vs. non-sudden approach).

Figure 6 clearly indicates that the possibilities for evacuation will be clearly related to 1) the available time before the critical event occurs ($T_A(0)$), and 2) the development speed of the physical effects relative to persons' escape velocity.
The relevance of evacuation for loss of life estimation will differ between event types. Instantaneous events, such as (sudden) explosions, airplane crashes and earthquakes, will allow neither escape time before the event, nor sufficient time for escape after the event[1]. For such events it can thus be assumed that F_E=0 , thus the population at risk will be exposed. Other events will be better predictable in advance and physical effects will develop relatively slower. For example, (some) floods will allow the evacuation of large fractions of the population.
For longer-term events (type c of figure 2) the concept of evacuation will be of lesser relevance, but slightly different concepts should be used to determine the exposed fraction of the population at risk. For example, it has to be determined which persons in a population are exposed to certain emissions.

4 Estimation of mortality: dose response functions

4.1 Approaches for mortality estimation

Dose-response functions give a relation between the extent of physical effects and the mortality in the exposed population. They are thus very similar used to so-called fragility curves used to model the probability of failure of structures under given loads, for example for earthquakes and buildings. Dose response curves model the human resistance to a certain level of effects.

Two main types of such dose-response relations can be distinguished. In the first approach mortality will be a function of a certain level of physical effects, usually an occurred maximum value (x_{max}). Mortality can then be conceptually written as:

$$F_D = f(x_{\max})$$

Examples of this approach are the proposed mortality functions for floods (Jonkman, 2004), where mortality is determined as a function of (maximum) water depth. For explosions mortality can eb determined as a function peak pressure (CPR, 1989). Similar types of criteria are proposed for earthquakes, where mortality is a function of earthquake intensity, representing the degree of damage to buildings (e.g. Coburn & Spence, 2002).

The second approach relates mortality to the sustained dose of physical effects (i.e. effects integrated over time, e.g. a sustained dose of toxic substances over time) and it can be used if the variation of physical effects over time is relevant ($x(t)$). It is generally used in the estimation of mortality due to toxic substances for chemical accidents, with so-called probit functions (also see below).

$$F_D = f\left(\int x(t)dt\right)$$

Irrespective of which of the two concepts suits the individual case better, another modelling choice has to be taken. The choice is between two modes named sudden and non-sudden in Lentz and Rackwitz (2004). The sudden approach is static, i.e. either (a fraction of the) persons are exposed or evacuated. The exposed persons have a certain probability of being killed.
In the non-sudden approach, the spatial and temporal development of both physical effects and evacuation progress have to be considered. For cases, such as slowly rising floods or tunnel

[1] In these cases the development of physical effects can is approximated with an (almost) horizontal line as ds/dt is very large

fires, persons can escape/survive the danger in a certain zone at a given moment, and have to undertake another escape/survival in the next moment due to the spatial propagation of the danger zone. The individual can only survive the whole event, if he/she survives each single time step. Such dynamic simulations will generally be included in computer models.

In the above concepts, the dependency of F_D on intensity of physical effects is discussed. However, for many applications, mortality functions can be adjusted to account for differences in area and population vulnerability. For example, for both earthquakes and floods building collapse will influence mortality. Mortality from explosions will depend on indoor or outdoor exposure of persons. For some fields of applications (floods and earthquakes) the effects of rescue on mortality can be discounted. In this way the model will be better equipped to account for event / system specific circumstances that influence the accident consequences. The number of factors involved will determine the possibilities to account for risk reductions due to measures.

Apart from the numbers of factors involved (see above), mortality estimation amongst the exposed population can be performed at different levels of detail:

1) the individual level, thus accounting for individual circumstances and behaviour;
2) group level, distinguishing groups of persons with comparable circumstances;
3) overall exposed population level, estimation of one mortality number for whole exposed population.

Approaches 1 and 2 will require summation over individuals or groups to obtain overall population mortality. The most suitable level of detail to estimate the consequences of a certain event and the number of factors to be involved, will depend on several issues, including:

- The event process considered, the extent of affected area and the local variability of effects and population vulnerability (what level of detail is needed for a realistic consequence estimation)
- The amount and level of detail of available accident data for calibration and the insight in accident processes (what is available and what is possible);
- The level and type of information required or requested by the responsible decision makers (what is needed).

4.2 Dose response functions

With respect to the derivation of dose response functions a distinction can be made between the physical and empirical approach.

Physical dose response relations are directly based on physical laws. For example a criterion used for determination of human instability in water can be derived from the momentum equilibrium of a person standing in flowing water (see e.g. Lind, 2000). However, given complexity of events during disaster, and the number of phenomena and causes determining mortality a fully physical approach is generally not adopted.

Therefore empirical functions are derived, which relate mortality statistically to variables representing the intensity of the event, without accounting for the exact causes of loss of life. Empirical dose response functions can be based on either observed mortality data from past disasters, or on animal tests. Observations from disasters have the advantage that they are “representative”, but data is often difficult to obtain during crisis situations and data will be collected under uncontrolled circumstances. Animal tests have the advantage that they can be performed in controlled settings, but large uncertainties exist with respect to transferring / scaling the results to humans.

Characteristic forms of dose response functions

In the simplest form of a dose response relation a constant mortality fraction F_D is assumed amongst the exposed persons, irrespective of the magnitude of physical effects. Examples of such functions are the values applied to ground fatalities for airplane crashes (F_D=0,28 within the crash affected area (Piers et al., 1992)) and for explosions in tunnels (F_D=1; Kootstra and Molag, 2003).

The dependency of F_D can also be displayed in discrete form (i.e. As a constant mortality fraction). For example, if a certain critical threshold value of physical effects (x_{cr}) is exceeded mortality will equal a certain (constant) value (a):

$$F_D = 0 \qquad x < x_{cr}$$

$$F_D = a \qquad x \geq x_{cr}$$

For example, for human stability in flowing water a critical product number of water depth and flow velocity has been derived by Abt et al (1989) to indicate the limit for instability.

In general mortality will depend on the intensity of the event. If discrete mortality values are given for different situations and levels of physical effects, these can be displayed in a table. Examples of this approach are given by Graham (1999) for dam break floods. Earthquake-caused building collapse includes so many side constraints that it is impossible to express F_D other than in tables listing typical values for different building types, failure mechanisms, heights etc.(e.g. Coburn & Spence, 2002, Murakami, 1992)

In more advanced approaches functional relations have been developed which express mortality as a (continuous) function of the level of physical effects. These dose response relations are in fact distribution functions. Some typical shapes found in literature are discussed below.

In some cases, data are not sufficient in order to establish an absolute dose-response function. Then, one can alternatively determine **a linear relationship**, where a change in dose is related to a change in response. This is typical the case, when an epidemiological study on the effect of some toxic substance, has to limit itself to a small population cohort for some reason (See e.g. Wahrendorf & Becher, 1990).

Lind (2000) also uses a **normal distribution** function to account for uncertainties in occurrence of instability of persons in flowing water.

Probit function (=lognormal function)

In the assessment of consequences of (tunnel) fires, and (chemical) accidents involving toxic substances the probit function is used. Probit functions are standardised functions that give a relation between the dose and response for different substances and effects. In (de Weger and Reuzel, 1992) probit functions are given for the response of humans to explosions, toxic substances and heat radiation. Probit equations are established using (toxicity) data on response and exposure. As few toxicity data for man are available, especially in the higher response percentages, human probit functions are generally derived by extrapolating from animal data.

The mortality fraction (F_D) is found as follows: $F_D = \Phi\left(\frac{\Pr - \mu_D}{\sigma_D}\right)$ with μ = 5 and σ = 1

The general expression[3] for the probit value is:

$$\mathrm{Pr} = a + b \cdot \ln(C^n t)$$

Where

Pr probit value [-]

a,b,n probit constants [-]

t exposure duration [min]

In the above approach mortality is estimated with two equations, which in total contain five variables (*a,b,n,* μ_D and σ_D). It can be shown that the current probit approach is equivalent to a lognormal distribution, where mortality is directly expressed a lognormal function of the sustained dose.

In the most[4] of the proposed probits in the Netherlands (de Weger, 1993) either the value of *n* or b is assumed to equal 1. If *n*=1, mortality can be expressed as a function of the sustained dose (*D*):

$$F_D = \Phi\left(\frac{\mathrm{Pr} - \mu_D}{\sigma_D}\right) \qquad and \qquad \mathrm{Pr} = a + b\ln(D)$$

$$F_D = \Phi\left(\frac{a + b\ln(D) - \mu_D}{\sigma_D}\right) = \Phi\left(\frac{\ln(D) - 1/b(\mu_D - a)}{\sigma_D / b}\right)$$

Thus, mortality has a lognormal distribution as a function of dose, with the following variables

$$F_D = LOGN(D, \mu_{LN}, \sigma_{LN}) \qquad \mu_{LN} = \frac{\mu_D - a}{b} \qquad \sigma_{LN} = \sigma_D / b$$

Probits are generally derived based on a limited number of observations on dose and response for animals. Given this limited basis, the value of the laborious probit concept (2 equations, 5 variables) can be questioned. It is suggested here that a direct derivation of a lognormal distribution of the lethal dose based on measurements is more insightful, as this limits the number of equations and parameters.

Empirical analysis of historical data shows that the correlation between flood mortality and water depth can be described with an **exponential distribution** (Jonkman, 2004):

$$F_D = e^{-\frac{h-A}{B}} \qquad 0 \le h \le A$$

Where: *h* – water depth;

A,B – parameters of the distribution curve (Note that A equals the water depth at which mortality equates 1).

[3] The original general expression for the probit can also be formulated as: *Pr*=*a*+*b*1ln(*C*)+ *b*2 ln(*t*); with *b*=*b*2 and *n*=*b*1/*b*2

[4] Of the 22 probits proposed in (de Weger, 1993) only for Chlorine, either n or b does not equal 1.

5 Integration of the framework into risk analysis

The problem of mortality and loss-of-life estimation is very similar to the classical load-resistance problem used in structural engineering. In this case the load consists of physical effects, and the resistance curve of an individual equals the dose response function. Assume that $f_S(x)$ is the probability density function (pdf) of the occurrence of physical effects x, expressed as a probability of occurrence: yr^{-1} and $F_D(x)$ gives the dose response function. The probability of death can thus be found by combining $f_S(x)$ and $F_D(x)$ as is shown in figure 7.

$$P(S = x) = f_S(x)dx$$

$$P(D \leq x) = F_D(x)$$

$$\Rightarrow \quad P(S = x \cap D \leq x) = f_S(x)F_D(x)dx$$

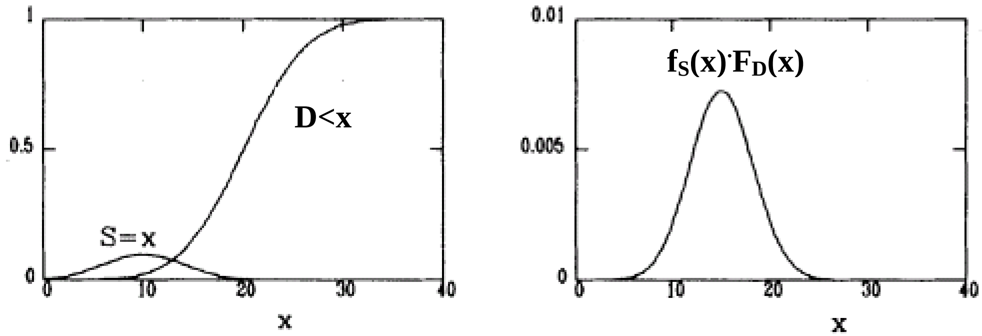

Figure 7: Combination of load and resistance in order to obtain probability of failure (in this case probability of death) (Kuiper & Vrijling, 1998)

For a person at risk the probability of successful evacuation has to be included and the pdf of death is obtained as follows:

$$f_{D|PAR}(x) = f_s(x)F_D(x)(1 - F_E(x))$$

Inclusion of the number of people at risk and integration over all possible extent values x yields the expected number of lives lost:

$$E(N) = \int_0^\infty f_S(x)F_D(x)(1 - F_E(x))N_{PAR}(x)dx$$

Note that in most practical risk analyses not the continuous distribution of the effects of potential accidents are considered, but a limited number of (deterministic) scenarios. To each of these scenarios probabilities are assigned. And for each scenario effects and consequences can be determined in order to obtain the distribution of the consequences can be found by summation over different scenarios.

If the pdf of the number of fatalities is known further quantities, often labelled as risk measures, can be derived (Jonkman et al., 2003). Examples of such risk measures are the FN curve or the expected number of fatalities. Based on such an analysis the reduction of life expectancy can be derived, which forms input for risk acceptance criteria, such as the one derived from the LQI (see Rackwitz, 2004): The criterion relates the change in mortality due to a safety investment to the loss of average income due to the direct or indirect contribution to this investment by each citizen in a society. The change in mortality dm can be calculated as $dm = dE(N)/N_{POP}$, where $dE(N)$ is the change in the expected number of lives lost $E(N)$ and N_{POP} is the reference population (also see section 3). Further applications of the methods in risk analysis will be given in the next section.

6 Case studies

In order to show the application of the proposed approach three case studies are elaborated for different types of hazards. Firstly a case study for a tunnel fire is discussed, which considers one (deterministic) accident scenario. In the second case study flood risks are assessed for a flood prone area in the Netherlands, by combining different flood scenarios. The third case discusses the probabilistic analysis of earthquake risks for a case study area in Japan.

6.1 Estimation of loss of life for the Mt. Blanc tunnel fire (1999)

In order to test the proposed approach a simulation has been made to hindcast the fire in Mt. Blanc tunnel of 24 March 1999. A fire occurred in a heavy goods vehicle, which stopped near the middle of the tunnel near lay by 21. Due to natural ventilation the smoke mainly developed towards the French side. Here, the fire spread over 34 vehicles and eventually caused 39 fatalities, which all occurred within 500 metres from the accident on the French side.

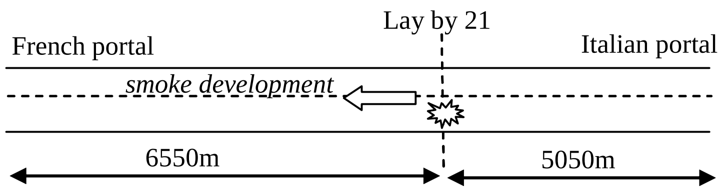

Figure 8:Schematic view of the Mt. Blanc tunnel and the fire location

Physical effects have been simulated with available analytical expressions for development of smoke, heat and toxicants (Persson, 2003). Mortality has been estimated with available criteria for toxicants and heat (ISO, 2002). To provide input values for the simulation of physical effects descriptions and reports of the accident have been used (Lacroix, 1998; TFTI, 1999; PIARC, 2002). In this case the spatial and temporal progress of effects and escape are simulated using a space, time (x,t) diagram.

It is estimated that the fire reaches a maximum HRR in first phase of 135 MW within 5 minutes. The development of radiant heat, temperature and CO has been modelled. Only the effects in the French direction are considered, as the smoke mainly developed in that direction. By combining the physical effect calculations with dose response functions the development of mortality boundaries can be shown in the x,t graph (figure 9) .

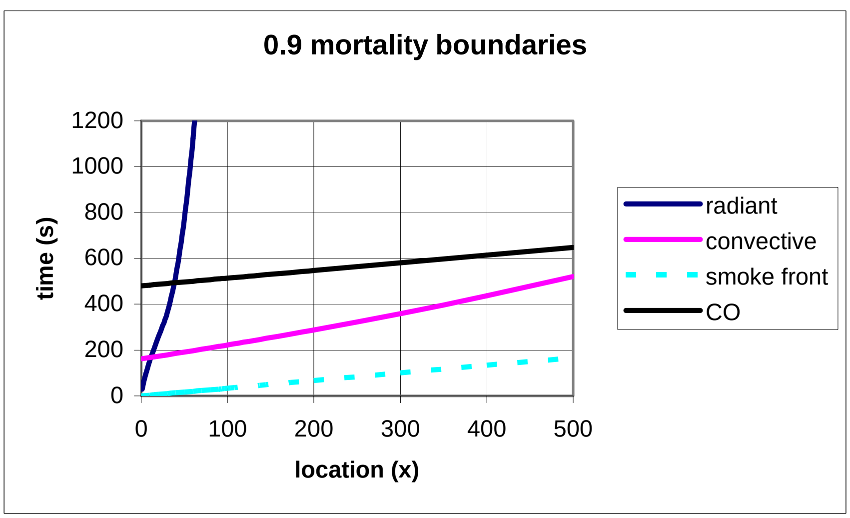

Figure 9: x,t diagram with 0,9 mortality boundaries for the Mt. Blanc tunnel fire.

It shows that radiant heat will be the dominating criterion very near the accident and convective heat for the other parts of the tunnel. Critical levels of CO will be reached after critical levels for convective heat. Given the rapid evolvement of lethal circumstances it is considered likely that all 27 persons who stayed in their vehicles were killed in the fire within several minutes.
11 people left their motor vehicles and attempted to escape. 2 of these persons went into a shelter and 2 persons entered another vehicle. To account for the possibility of escape a dynamic calculation has been undertaken on the individual level. The escape path of the person and the sustained dose are taken into account. Calculations are made for one person, representative for others in the tunnel with respect to escape path variables and mortality. The person starts at 50 metres from the accident (x_0=50) and is assumed to have a wake up time of 60 seconds (t_w=60). As the person is covered by smoke before the actual initiation of escape, a walking speed (v_E) of 0,5 m/s is assumed. For this case it is found that after 230s and 135m travelled lethal circumstances due to convective heat are reached. Further sensitivity analyses show that also for other values of escape variables and fire growth lethal circumstances will be reached within a few minutes without the possibility to escape.

Then, the total number of fatalities is determined by "extrapolating" the individual mortality over the persons believed to be in similar circumstances. All 7 persons escaping away from the fire could not survive. In total (adding the number of persons staying in their cars) the number of fatalities is estimated at 36, no analysis is given for the persons in the shelter. The actual number of fatalities amounted 39. Overall, the above findings correspond to the reported consequences of Mt. Blanc tunnel fire (Lacroix, 1998): both persons who stayed in their cars and those who tried to escape could not survive this fire.

6.2 Flood risks for a flood-prone area in the Netherlands

The proposed approach is applied to a case study to estimate the potential number of fatalities and risks for a flood prone area in the Netherlands. The area is located in the South Eastern part of the Netherlands and it has 420.000 inhabitants. It is bounded on the north side by the river Meuse. To distinct different potential flood patterns with different consequences, 12 flood scenarios are distinguished, as is shown in figure 10. For each of these scenarios breach growth, and flood development are simulated with a 2 dimensional flood model. For the sake of the example the probability of each scenario is assumed to be $8.33.10^{-5}$ per year, leading to an overall flooding probability of the area of 10^{-3} per year (yet, more realistic probabilities will be calculated in ongoing research).

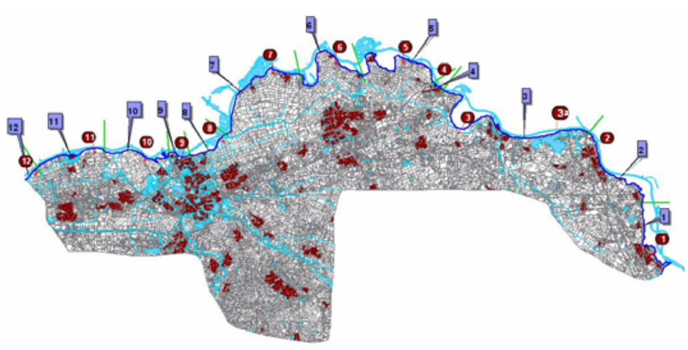

Figure 10: Overview of studied area and considered flood scenarios, indicated with arrowed boxes.

With the results from the flood simulations the number of fatalities has been estimated for all of these scenarios. Based on the available prediction models and consultation of experts, the available time for evacuation is estimated at 24 hours. With the developed evacuation model (Barendregt, 2002) the fraction of evacuated persons F_E is estimated for each scenario. For the considered scenarios F_E values lie around 0.6. For each scenario the mortality fraction F_D is estimated with the functions proposed in (Jonkman, 2004). As flood circumstances are relatively mild (slow rising, low water depths) mortality fractions lie in the order of magnitude of 10^{-4} to 10^{-3}. In the worst case scenario the number of fatalities is estimated at 220. By combining F_D, F_E and the number of affected (see section 2) the number of fatalities is estimated for each scenario. By combining these results with the probability of flooding the risk level can be presented in two forms. Firstly, the expected number of fatalities per year is estimated $E(N)$= 0.088 fatalities per year. Secondly an FN curve is compiled. The FN curve basically is an adjusted display of the distribution function of the number of fatalities. It shows the probability of exceedance as a function of the number of fatalities, on a double logarithmic scale. Note that the area under the FN curve equals the expected value of the number of fatalities, as has been shown by Vrijling and van Gelder (1998).

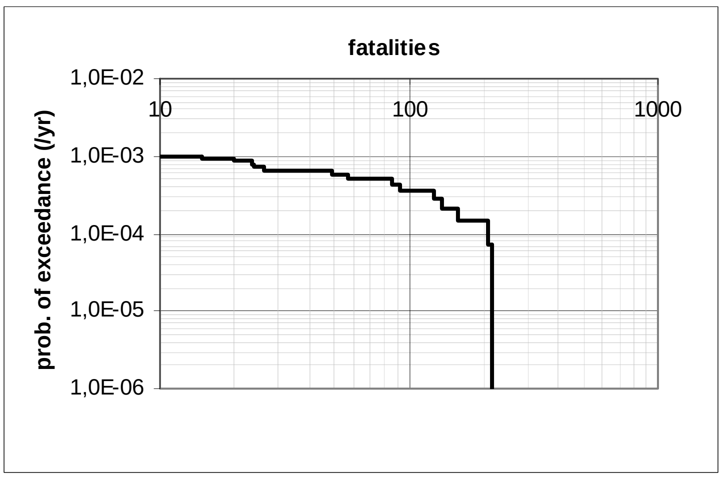

Figure 11: FN Curve for the considered area

The FN curve is a useful instrument to show the risk reducing effects of measures. Actions reducing the number of fatalities (such as better warning systems, increase of building quality, spatial planning) will shift the line in the horizontal direction. A reduction of the probability of flooding, e.g. by strengthening the dikes, will lead to a vertical shift of the line.
The results obtained will provide a basis for the discussion on the level of flood protection of large parts of the Netherlands. To support such discussion the FN curve obtained for a flood prone area can be compared with existing FN curves for other sectors in society, such as chemical facilities and airports. The method has been applied by the Dutch government in a recent evaluation of the current level of flood risks in the country (RIVM, 2004).

6.3 Estimation of fatality risks for an earthquake in the Tokyo area

In a simplified example a probabilistic estimation of the loss of life for earthquakes in the Tokyo area is shown. For the Tokyo area in Japan the yearly probability of exceedance of a certain peak ground velocity (PGV) has been estimated by Kanda & Nishijima (2004) by Monte Carlo simulations. The generalized pareto distribution of the PGV forms the best approximation of this data, also see figure 12(Nishijima, 2004):

$$F(x) = \exp\left[-\lambda\left(1 + k\frac{(x-u)}{\sigma}\right)^{-1/k}\right] \qquad \text{for } x>u$$

Where:
x peak ground velocity [cm/s]
u,k, λ,σ variables of the generalised pareto distribution

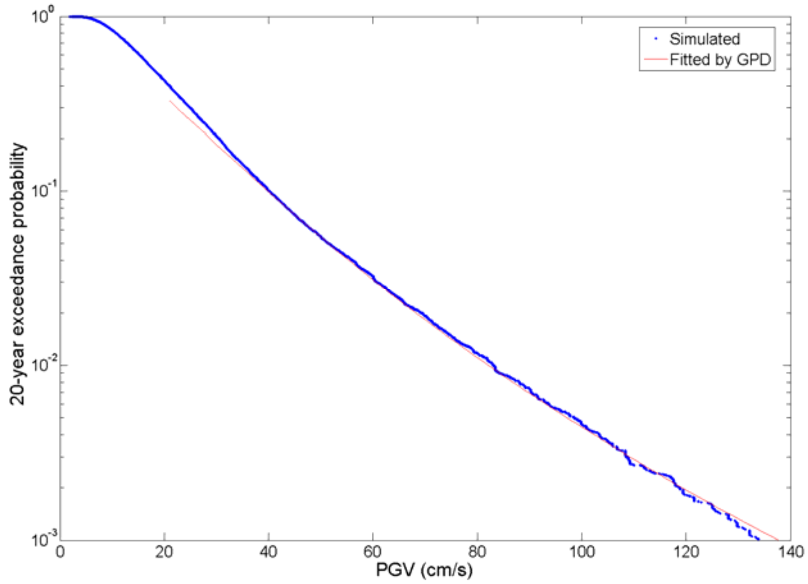

Figure 12: Probability of exceedance of PGV's simulated for Tokyo area (Kanda Nishijima, 2004) and fit obtained with the generalised Pareto distribution (Nishijima, 2004), variables: u=20; k=0,126; σ=12,95; λ=0,428

The probability of the collapse of buildings as a function of PGV can be estimated with a so-called fragility curve. The total total collapse of buildings can be estimated with a lognormal distribution function (Kanda and Nishijima, 2004):

$$F_B(x) = \Phi\left(\frac{\ln(x) - \ln 250}{0.4}\right)$$

Where: $F_B(x)$ - fraction of buildings totally collapsed

Due to the collapse of buildings a certain number of inhabitants is assumed to be killed. Based on empirical data for Japanese historical earthquakes Kanda and Shah (1997) show that the ratio between fatalities and collapsed houses equals 0,1. Assuming 2,5 inhabitants per house a mortality fraction of 0,04 is obtained. Coburn and Spence (2002) estimate a much higher mortality of 20% in masonry buildings. However, this number is related to those people not being able to escape, which is given as $1 - F_E = 0.5$ for the ground floor and as 1 for all higher stores. Also, it has to be considered that most people will not spend 24 hours a day at home, neither at work, so that $N_{PAR,i}/N_{POP,i}$ will be not 1, but approximately 0.65 for a and only about 0.25 for an office building, where $N_{POP,i}$ denotes the inhabitants or employees, respectively, for a building *i*. Multiplication of $F_D(x)$ with $(1 - F_E)$ and $N_{PAR,i}/N_{POP,i}$ will therefore yield values in the order of magnitude of the 0.04 mentioned above, as long as high-rise buildlings are not considered.
Now the dose response-curve for mortality can be written as follows:

$$F_D(x) = 0.04 \cdot \Phi\left(\frac{\ln(x) - \ln 250}{0.4}\right)$$

Where: $F_D(x)$ – Mortality amongst exposed persons as a function of PGV

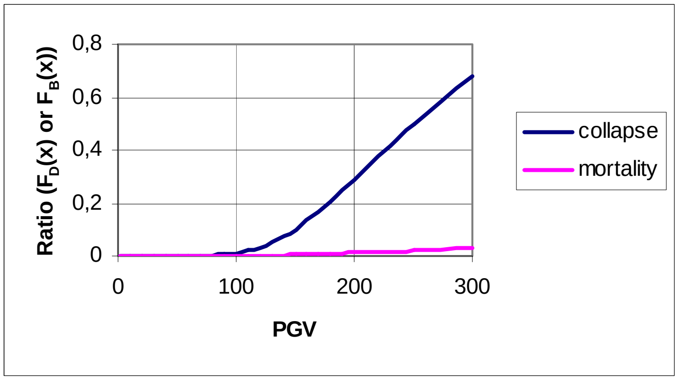

Figure 13: Fragility curve for collapse of buildings and mortality curve as a function of PGV

As an earthquake generally occurs unexpectedly no evacuation is possible and F_E is assumed to equal 0. the number of exposed persons in the Tokyo area is assumed to equal N_{EXP}=12 million.

By combining this information the probability of exceedance of a certain number of fatalities is obtained, in a so called FN Curve.

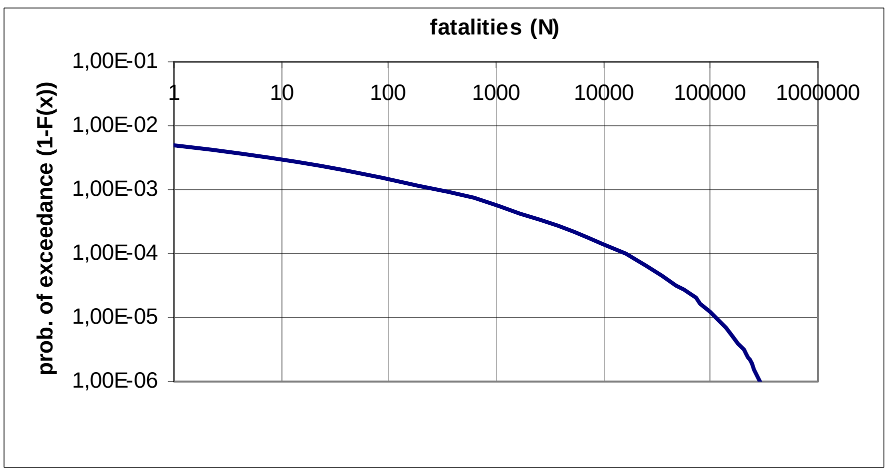

Figure 14: Probability of exceedance of a certain number of fatalities for an earthquake in the Tokyo area

Although this example is mainly intended to show the application of the general approach it has to be noted that several assumptions will have a major influence on the outcomes. Kanda and Nishijima (2004) state that the hazard curve is considered as conservative. In loss estimation only total loss of building is considered while partial collapse may also contribute to mortality. Also one general fragility curve is used for building collapse, while collapse will actually depend on the type of building. Finally, one constant mortality fraction is assumed in the calculation, while in fact it will depend on the floor of the building where persons are present and the operations of rescue services.

7 Concluding remarks

Based on the observations that the existing approaches of life estimation in different fields include similar steps, a general approach for loss of life estimation is proposed which can be used over different domains. The methodology provides a basis for more efficient and standardised consequence estimation for different fields. In order to achieve more realistic consequence estimations a further foundation of loss of life models based on past accidents is important. (Improved) recording and storage of data on loss of life and the use of this information in validation of the existing methods is recommended.

Estimation of loss of life often requires a multi-disciplinary approach, which expands outside the traditional engineering domain. For example, knowledge from toxicology is needed to establish dose response relations. Study of evacuation requires insight in psychological issues regarding human reaction to disasters. Further cooperation between involved disciplines is encouraged.

It has been shown how the approach is applicable in quantitative risk analysis for different case studies. Further applications could involve other engineering related sectors, such as naval and off-shore safety. Outcomes of consequence and risk calculations can be used in the decision process regarding the “acceptable” level of risk, for example by comparison with risk standards. Effectiveness of measures can be analysed by considering their reduction of loss of life. Comparison of the investments in risk reduction and the reduction of (expected) loss of life can be related to discussions on the (implicit) “value of human life”. Broader applications could be interesting. For example, application of the outcomes of consequence analyses can provide valuable information for risk communication and emergency management.

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