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A risk-based approach to land-use planning

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Abstract

The Seveso II-Directive requires that the objectives of preventing major accidents and limiting their consequences be taken into account by the Member States in their land-use policies and/or other relevant policies. This is to be achieved by ensuring adequate distances between industrial establishments and residential areas, areas of public use and areas of particular natural sensitivity or interest. A risk-based framework implemented in a computer program is presented which enables one to calculate adequate distances. The criterion used is a limit on the individual risk of death. The method is a simplified risk analysis which represents the plant, whose characteristics are normally unknown at the stage of land-use planning, by generic frequencies of release for process units and storage tanks. Their number depends on the size of the site to be allotted. The procedure is capable of addressing the siting of new establishments and, with due regard to the simplifications used, modifications to and new developments in the vicinity of existing establishments. Given the numerous assumptions, which have to be made, the framework represents a convention.

Keywords: Seveso II-Directive; Appropriate distances; Risk assessment; Siting of process plants

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1. Introduction

Article 12 of the Seveso II-Directive [1] requires that the objectives of preventing major accidents and limiting their consequences be taken into account by the Member States in their land-use policies and/or other relevant policies. They shall pursue those objectives through controls on:

(a) the siting of new establishments,
(b) modifications to existing establishments covered by article 10,
(c) new developments, such as transport links, locations frequented by the public and residential areas in the vicinity of existing establishments, where the siting or developments are such as to increase the risk or consequences of a major accident.

The objective is to maintain appropriate distances between establishments and residential areas, areas of public use and areas of particular natural sensitivity or interest. The rationale behind this requirement is the decrease of harmful effects of accidents with distance. Such a decrease may be expected for all causes of damage except in the case of travelling clouds of hazardous materials. Should the distance not be appropriate for an existing establishment technical measures may be taken to compensate this deficiency.

In any case, the question of what is appropriate requires interpretation. This is given here by an approach representing a framework of methods and criteria to be universally applied to the above-mentioned cases of land-use planning.

In order to create such a framework a risk-based approach is adopted. It accounts for the fact that land-use planning is not feasible, if it is solely based on maximum ranges and does not consider the low frequencies of occurrence of the underlying events. Table 1 provides some indications on extreme hazard ranges. However, it should be noted that the ranges given there may be even larger depending on the boundary conditions of the accident and the health criteria applied.

In order to introduce the framework the next section provides a brief overview of risk analysis for technical systems.

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Table 1
Observed hazard ranges (based on [2,3])

Toxic release: harmful health effects up to 3, 8, and 32 km
Missiles: up to 1200 m (Mexico city)
Explosions: ear drum damage up to 2 km (Toulouse), glass breakage up to 4.8 km, death up to 7 km
Fireball: radii up to 300 m were observed, injury by heat radiation from fireball up to 300 m (Feyzin), up to 400 m (Mexico city)
Vapour cloud fires: lethality ranges up to 2–3 km
BLEVE: blast wave caused extensive though minor damage within 500 m, window breakage up to 3 km (Feyzin)

2. Outline of risk analysis

Fig. 1 outlines a probabilistic risk assessment for a technical system. Basically it comprises three steps:

1. initiating events (due to component failures, human error, spontaneous chemical reactions or external causes, e.g. lightning impact) and event sequences (inside the plant),
2. characteristics and exposure sequences (outside the plant),
3. consequences and risk.

Accidents start with initiating events $D_1, \ldots, D_k$ (e.g loss of electric power, stirrer failure etc.), which cause time-dependent changes of the process parameters in the technical system. These are counter-acted by limiting and trip systems. The resulting event sequences are analyzed in a detailed risk analysis using fault trees and event sequence diagrams, also called event trees.

Numerous event sequences result from the analysis. They characterize different potential progressions of the accident. In order to reduce the amount of analysis, similar event sequences are binned forming categories $k_1, \ldots, k_n$. These categories represent the initiating and boundary conditions for the exposure sequences. For example, one category may represent a toxic release, another a boiling liquid expanding vapour explosion (BLEVE) etc. Each category occurs with an expected frequency which is the sum of the expected frequencies of the contributing event sequences.

The exposure sequences describe how the phenomena affect individuals outside the premises. For example, in the case of a toxic release atmospheric dispersion has to be treated in order to assess the dose to which an individual is exposed at a certain distance from the plant. This dose is then introduced into a probit equation (cf. [2] and Table 5) in order to obtain the probability for the consequence (e.g. injury or death).

Risk is then assessed by assigning the frequency of the category in question to the corresponding consequence. Such a detailed analysis produces results which are generally considered to be the “true” risk, although they can only be an approximation. For example, one cannot prove that all relevant accident sequences have been included in the analysis.

The effort required for a detailed risk analysis is not warranted for land-use planning. Additionally, when siting new establishments the details of the plants are generally not known. This precludes a profound analysis of the plant systems (“initiating events” and “event sequences” in Fig. 1).

Hence, a generic procedure was developed and implemented in the computer program GEBAUL. It draws extensively on experience with past accidents. This experience is represented, for example, by the:

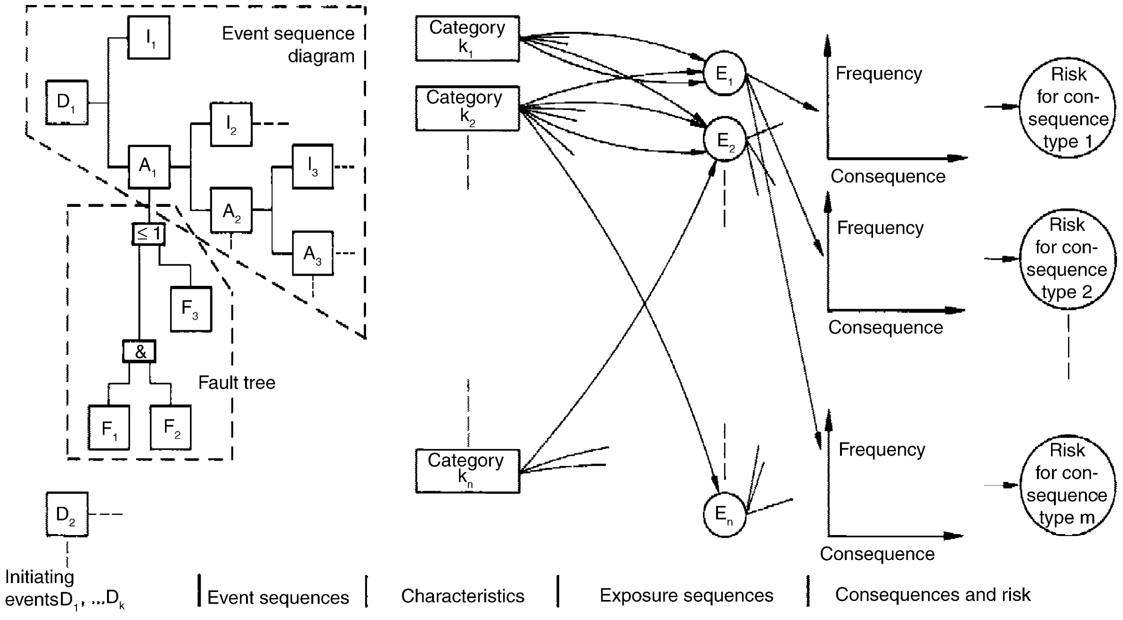

Fig. 1. Overview of a probabilistic risk analysis for a technical system [4].

Table 2
Indicative overview comparing a detailed risk analysis with the risk-based framework

Step	Detailed risk analysis	Risk-based framework
Initiating events and event sequences (inside the plant or due to external causes, e.g. lightning impact)	Comprehensive identification of initiating events, elaborate fault and event trees for all process units and storage tanks on the site	Generic frequencies of release from German records and from the literature for storage tanks, average numbers of units based on assumptions and the size of the site to be allotted
Characteristics and	Detailed investigation of the conditions of releases and the corresponding boundary conditions (e.g. leak sizes, locations, pressure differences), models for assessing the released quantities	Distributions of released quantities based on past liquid and gaseous releases of hazardous substances
exposure sequences	Modelling for dispersion, explosion, missiles, heat generation etc., taking into account site-specific meteorological, orographic and urbanistic conditions, e.g. quality of housing, and the effect of mitigating measures like evacuation etc.	Dispersion of toxic substances (airborne and heavier-than air) Explosion of released substances (TNT-model) BLEVE Missile generation Heat radiation from fireball (largely based on parameters derived from past accidents)
Consequences and	Conditional probabilities of harm to humans from the above phenomena using Probit-equations	Conditional probabilities of harm to humans from the above phenomena using Probit-equations
risk	Individual risk by combining release frequencies with the above conditional probabilities, societal risk by including population distribution and periods of presence in the impact range, etc.	Individual risk by combining release frequencies with the above conditional probabilities

- frequency of accidents,
- hazardous substances frequently used in the process industry,
- observed quantities of release,
- efficiency of vapour cloud explosions,
- flight ranges of missiles.

It must be noted, however, that the resulting method represents a convention, given the numerous assumptions which it necessarily implies. The procedure is not apt to assess the “true” risk. It only provides a risk-based figure. Apart from dealing with the siting of new establishments, it is suited to address modifications to existing establishments just as new developments in the vicinity of the establishment, as required by [1].

An indicative overview, comparing a detailed risk analysis with the generic procedure adopted here is provided in Table 2, a more detailed explanation is given in the following section.

3. The method

In general, the following hazardous phenomena may be expected in a process plant:

- explosions,
- fires,
- releases of toxic substances.

A multitude of event sequences and consequences is possible. For example, fires and explosions may occur within the enclosing boundary of the plant or be the consequence of a release. Hazardous substances may be present in the process during normal operation, result from deviations of process parameters from their nominal values (e.g. production of larger quantities of dioxin in Seveso) or be formed during accident progression, e.g. combustion gases of fires.

It is obvious that all imaginable event sequences can hardly be modelled even in a comprehensive risk analysis, leave alone in the present generic approach. Therefore, the treatment is limited to releases. The following phenomena, which are considered as representative, are dealt with:

- release of toxic substances,
- explosion of a released vapour cloud,
- BLEVE,
- vessel rupture with ensuing fireball,
- missile flight of vessel fragments.

Each of these phenomena contributes to risk according to its expected frequency of occurrence. The relevant parameters involved are considered to be random variables, i.e. variables which adopt certain values with specific probabilities. Hence, they are represented by probability distributions. These characterize the uncertainties deriving either from the stochastic character of the parameters or from insufficient knowledge of their values. An example of such a distribution is given in Fig. 2 along with quantities used to characterize it.

In what follows the above-mentioned steps of a risk analysis and the simplifications and assumptions made for the present purpose are addressed in detail.

3.1. *Initiating events and event sequences*

Contrary to a detailed risk analysis, no exhaustive investigation of potential initiating events and their expected frequencies of occurrence, of their progression inside the plant, their outcomes and the corresponding conditional

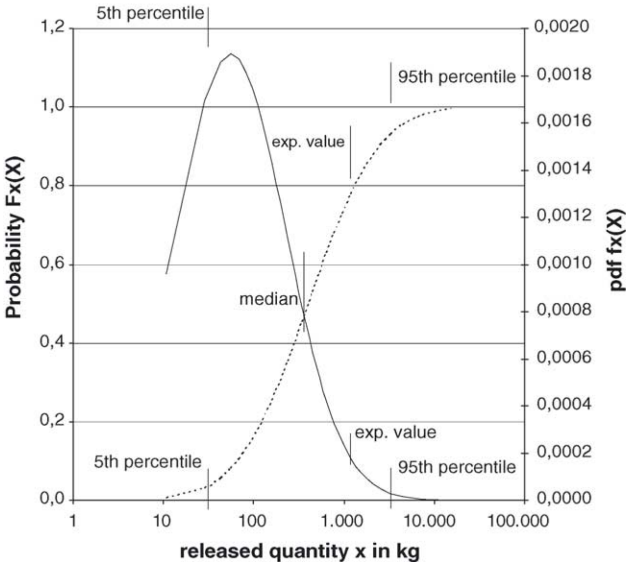

Fig. 2. Example of a probability distribution and probability density function (pdf) with indication of quantities used for its characterization. Ammonia (gaseous) - storage . . .. Probability—pdf.

probabilities is performed in order to arrive at the expected frequencies for the categories $k_1, \ldots, k_n$ of Fig. 1. Instead, generic frequencies for releases from process units and storage tanks are used.

3.1.1. Process units

The German data bank on accidents ZEMA [5] indicates that during the 10 years of its existence no accident with a fatality outside one of the 8100 Seveso plants covered by the data bank occurred. A Bayesian zero-failure analysis (cf. [6]) performed on this basis results in an expected value of $6.6 \times 10^{-6}\,\text{yr}^{-1}$ and plant for an accident with casualties outside the plant.

Assuming that approximately 10% of all accidents cause harm to man, a large release from a plant may be expected with a frequency of $6 \times 10^{-5}\,\text{yr}^{-1}$. In order to break this value down to process units, it is supposed that a Seveso plant comprises an average of 50 major process units. This leads to an expected frequency of $1 \times 10^{-6}\,\text{yr}^{-1}$ and process unit for a major release. The chain of arguments used to derive this figure suggests that it is an uncertain datum. Therefore, a lognormal distribution (cf. [7]) with an estimated (large) uncertainty factor of $K_{95} = 10$ is used to describe it.

If technical measures for upgrading become necessary because an existing establishment does not satisfy the distance requirements, the annual frequency of release is lowered by one order of magnitude. This is in line, for example with [8], where 10 is the smallest factor of credit proposed, if active protection measures are implemented.

In order to compile a generic plant based on the aforementioned considerations a reasonable assumption on the number of its process units has to be made. This number depends on the area to be allotted. Data from the process industry suggest a value of 0.00014 process units per m^2.

The expected annual frequency of a major release from a plant or establishment is then obtained as the product of the area it covers and the convolution of the distributions of the frequency of release and the number of process units per m^2.

3.1.2. Storage vessels

The relevant literature provides a number of values for the failure of storage vessels (cf. [2,9]). They are in good agreement with the ranges stated in [8]. Based on this a rectangular distribution (cf. [7]) between $10^{-7}\,\text{yr}^{-1}$ and $10^{-5}\,\text{yr}^{-1}$ is used for the failure rates of pressure vessels. The failure rates for atmospheric and refrigerated storage vessels are represented by a Gamma distribution (cf. [7]) with a mean of $1.9 \times 10^{-5}\,\text{yr}^{-1}$.

The number of vessels per m^2 is assessed as follows. The basis area of a vessel is assumed to lie between 20 and $2000\,\text{m}^2$ and 10–20% of the available site are supposed to be covered by vessels. Both quantities are described by rectangular distributions. Their convolution results in 3.5×10^{-4} vessels m^{-2}. Upgrading is treated as for process units.

3.2. Released quantities

The quantities potentially released in accidents are mainly obtained from [5,10]. They are considered to be random variables and hence described by probability distributions (cf. Fig. 2). This renders assumptions on hypothetical leak sizes, pressure differences and durations of discharge unnecessary. Table 3 gives examples for released quantities from process units and Table 4 for vessels. They also indicate the type of distribution resulting from a fit of the quantities released for any of the substances.

The shaded quantities are dominated by the corresponding gaseous releases and hence are not treated. Evaporation from liquid releases is calculated by simple models (cf. [2]) assuming an undisturbed evaporation process for 30 min. Since [5] makes no indication as to whether the release was liquid or gaseous, gaseous release is always assumed and the larger quantity of [5] and [10] is taken.

3.3. Joint distributions for expected frequencies and quantities of release

The existing empirical bases only provide separate values for the expected frequencies of release and the quantities released. However, experience shows that large releases are less frequent than small ones. One accounts for this by generating realizations from the distributions for both frequency and released quantity. The resulting values for the frequencies are ordered from high to low values and those for released quantities in the opposite direction. The corresponding couples of values (frequency and quantity) are then represented by bivariate lognormal distributions, which are used in the calculations.

Table 3
Examples for mean quantities of release from process units in kilogram

Data bank	EPA [10]				ZEMA [5]	
	Liquid	Type of distribution	Gaseous	Type of distribution	Gaseous or liquid	Type of distribution
Acrylonitrile	2207.9	2	3020.1	2	–	–
Ammonia	44932.8	2	1053.3	5	–	–
Bromine	1182.2	2	42.1	6	–	–
Chlorine	471.4	3	664.2	2	926.3	2
Hydrogen chloride	8840.0	2	529.8	2	–	–
Hydrogen cyanide	19.7	4	79.1	3	–	–
Cyclohexane	–	–	22451.2	2	–	–
Ethylene oxide	4375.6	2	554.1	2	–	–
Ethylene	–	–	19439.5	2	–	–
Hydrogen fluoride	461.7	2	419.5	2	–	–
Phosgene	6.7	6	69.3	2	–	–
Styrol	–	–	–	–	303.0	2
Sulphur dioxide	156.8	2	19888.3	2	–	–
Hydrogen sulphide	–	–	1030.3	5	–	–
Vinyl chloride	2580.2	2	765.6	2	–	–

Type of distribution (cf. [7]): 1, inverse Gaussian; 2, lognormal; 3, inverse γ; 4, Weibull.

3.4. Characteristics and exposure sequences

The detailed treatment of the initial and boundary conditions (characteristics) is replaced by using the quantities of release of Section 3.2. In the cases of atmospheric dispersion and missile flight initial heights of release are chosen randomly from reasonable intervals. The progression of exposure is dealt with by simple calculational models drawing as far as possible on observations. In particular, the following approaches are applied:

- fireball: empirical correlations (cf. [2]),
- dispersion of gases: VDI models for airborne [11] and heavier-than-air dispersion [12],
- explosion pressure wave: TNT equivalence model, probability distribution for efficiency based on findings from past explosions (cf. [2]),
- missile flight: observation-based models for spherical [13] and cylindrical [14] vessels.

3.5. Consequences and risk

The consequences of a release usually derive from the flammability, toxicity or explosibility of the materials involved. There are substances exhibiting several of these properties. This is accounted for by the conditional probability for the outcome in question, e.g. fire or explosion. Important features of the corresponding treatment are presented below.

3.5.1. Flammable substances

Empirical findings from releases of flammable substances reported in [2] lead to the event tree of Fig. 3 for the accident progression following a vapour cloud release.

Since a fireball is considered as the more severe consequence, flash fires, which are also possible, are neglected. Given the small probability for the cloud to drift away for

Table 4
Examples for mean quantities of release from storage vessels in kilogram

Data bank	EPA [10]				ZEMA [5]	
	Liquid	Type of distribution	Gaseous	Type of distribution	Gaseous or liquid	Type of distribution
Acrylonitrile	731.4	4	–	–	–	–
Ammonia	585.4	5	1977.2	3	–	–
Bromine	378.0	1	–	–	–	–
Chlorine	–	–	259.8	2	1104.0	6
Hydrogen chloride	14081.1	2	–	–	–	–
Cyclohexane[a]	–	–	–	–	27000.0	4
Hydrogen fluoride	4158.0	6	8118.4	2	–	–
Phosphorous trichloride	3854.4	2	–	–	–	–
Propane[a]	–	–	–	–	22076.3	6
Propylene[a]	–	–	–	–	9100.2	4
Sulphur dioxide	–	–	581.2	2	–	–
Hydrogen sulphide	–	–	155.0	5	–	–

Type of distribution (cf. [7]): 1, truncated normal; 2, inverse Gaussian; 3, lognormal; 4, γ; 5, inverse γ; 6, Weibull.

[a] From [2].

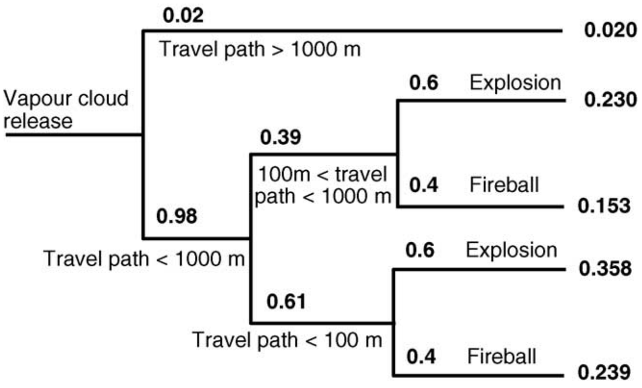

Fig. 3. Event tree for the accident progression following a vapour cloud release with corresponding conditional probabilities for the branches.

more than 1000 m from the point of release, i.e. 0.02, this phenomenon is not treated. Conservatively one assumes that an ignition always takes place.

3.5.2. *Toxic substances*

The release of a toxic substance is followed by atmospheric dispersion. This is assumed to be airborne unless the substance is heavier than air (1.2 kg/m^3) and the released quantities lie above a minimum threshold.

The following dispersion situations are considered with probabilities of their occurrence representative for Germany [15] given in parenthesis.

- unstable temperature stratification (0.107),
- neutral temperature stratification (0.062),
- stable temperature stratification (0.27),
- mean dispersion situation (0.561).

The "mean dispersion situation" describes neutral temperature stratification without an inversion layer whilst the category "neutral temperature stratification" includes an inversion layer. In order to arrive at the above probabilities the total probability for "neutral weather situations" was split up into 90% for the "mean dispersion situation" and 10% for "neutral temperature stratification".

All calculations assume puff releases, which lead to higher concentrations in the surroundings than releases of the same quantity spread over time. This makes hypotheses on the duration of the release unnecessary.

The following additional assumptions are made for the calculations:

- random variation of wind speed between 1 and 10 m/s using a rectangular distribution,
- random variation of the release height between 0 and 20 m using a rectangular distribution. If a volume source is specified the edge length of the corresponding cube is added (see below),
- in the case of airborne dispersion the program option of specifying a volume source is used; the volume of the release is then represented by a cube of equal volume (cf. [11]),
- with a probability of 1/3 a choice is made between the roughness lengths $z_0 = 0.5$, 0.8 and 1.2, which respectively represent slightly rough, fairly rough, and very rough terrains. The terms have the following meanings:
  - "slightly rough": relatively even terrain, only a few buildings and trees in the wider surroundings,
  - "fairly rough": uneven terrain; villages or small forests in the wider surroundings,
  - "very rough": urban areas and forests.

If a substance is both toxic and flammable, a probability of 0.9 is taken for no ignition, i.e. the event tree of Fig. 3 applies with a probability of 0.1. For releases of $m < 10000$ kg, $p_{\text{nig}} = 10^{-4} + 0.09999\,m$ is used for that probability.

3.5.3. *Harm to man*

Only harm to man is considered. In order to assess it, probit equations (cf. [2,16]) are used. These enable one to determine the conditional probability for a certain consequence, e.g. death, to occur following a certain causative factor like, e.g. peak overpressure or toxic dose. Table 5 gives some examples.

One then obtains the conditional probability of death due to the respective cause by calculating $\Phi(Y-5)$, where Φ denotes the standard normal distribution (cf. [7]).

3.5.4. *Risk*

Risk is assessed by multiplying the distribution of the frequency of release with that of the conditional probability for death. One then obtains the distribution of the frequency of death (individual risk) as a function of the distance from the source.

4. Processing of random variables

Most of the variables involved in the calculations are random (e.g. the efficiency of a vapour cloud explosion, wind speed etc.). Hence, they are treated using probability distributions. These represent data uncertainties. Additionally, there are phenomena like, for example, the initial energy of fragments after vessel burst, for which several accepted competing models exist. This fact is an expression of model uncertainties.

Both types of uncertainties are propagated through the calculations using the Monte-Carlo method (cf. [17]). This method is based upon repeating the entire calculations N times. Each of these repetitions is called a "trial". In each of these trials, values are assigned to all the random input variables. These values are realizations from their underlying probability distributions. In order to obtain these realizations quantities uniformly distributed on [0,1] and generated by using the algorithm by L'Écuyer are transformed to the corresponding distribution (cf. [18]). For non-random inputs, their corresponding point values are used.

Table 5
Examples of probit equations

Cause of death	Probit equation
Lung haemorrhage (p^0, peak overpressure in Pa)	$Y = -77.1 + 6.91 \ln p^0$
Heat radiation from fireball (q'', heat flux density in Wm^{-2}; t_d, duration of the fireball in s)	$Y = -14.9 + 2.56 \ln (t_\mathrm{d} q''^{4/3} \times 10^{-4})$
Exposure to chlorine (C, concentration in ppm; t, time of exposure in min)	$Y = -17.1 + 1.69 \ln \left(\int_0^\infty C(t)^{2.75}\,\mathrm{d}t\right)$
Exposure to ammonia (C, concentration in ppm; t, time of exposure in min)	$Y = -28.33 + 2.27 \ln \left(\int_0^\infty C(t)^{1.36}\,\mathrm{d}t\right)$
Exposure to hydrogen fluoride (C, concentration in ppm; t, time of exposure in min)	$Y = -25.87 + 3.354 \ln (Ct)$

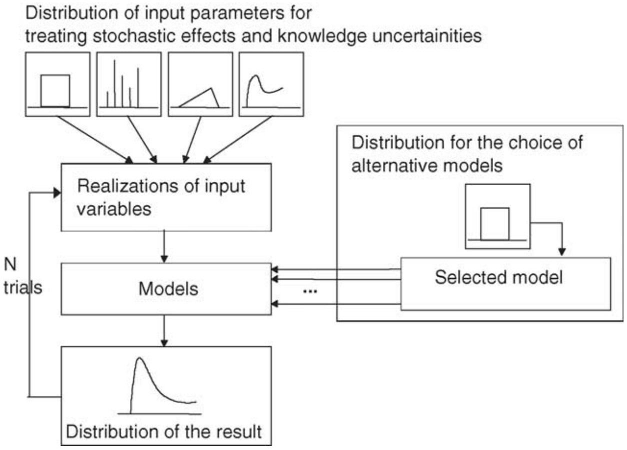

Fig. 4. Schematic representation of the Monte-Carlo evaluation.

The N trials provide a histogram, which is represented for ease of calculation by a lognormal distribution. Fig. 4 gives a schematic of the procedure.

5. Distances based on risk criteria and risk assessment

5.1. Risk criteria

In order to determine adequate distances, criteria on the level of risk to be tolerated are required. These exist in several countries, as shown in Table 6. The criteria are formulated in terms of point values. The results of the risk assessment, however, are obtained as probability distributions reflecting the uncertainties associated with the process of their determination. Therefore, based on the values of Table 6, a rectangular distribution between the bounds $b = 10^{-4}\ \mathrm{yr}^{-1}$ and $a = 10^{-6}\ \mathrm{yr}^{-1}$ is used as an uncertain "yardstick". The probability of excess, P_excess, is calculated as shown in [19]. The radius which leads to $P_\mathrm{excess} < 0.4$ is then considered as adequate.

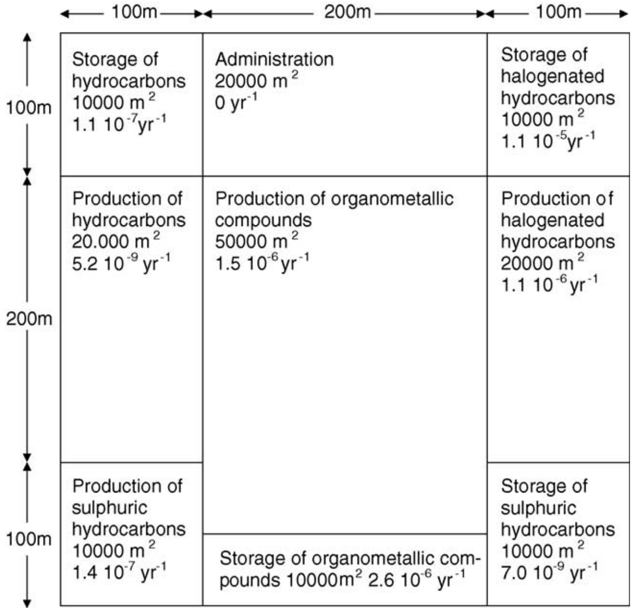

Fig. 5. Allocation of different industrial installations to a site and corresponding individual risks at a distance of 500 m.

5.2. Distances

As an example of one of the possible applications of the proposed method, Table 7 contains appropriate distances for some groups of plants, where the grouping and lead substances selected are based on [20]. The lead substances are considered to represent the corresponding type of plant. The effect of back fitting within the present framework is shown as well. The risk indicated is based on the criterion that the probability of exceeding the range of $10^{-4}\ \mathrm{yr}^{-1}$ to $10^{-6}\ \mathrm{yr}^{-1}$ is <0.4. On this basis, the indicated distances are considered to satisfy the requirement of adequacy of [1].

5.3. Planning of a site

Fig. 5 shows a site where different types of production and storage are to be built. Their allocation and the corresponding

Table 6
Criteria for individual risks in different countries

Country	Limit value for individual risk in $10^{-6}\ \mathrm{yr}^{-1}$
Netherlands	One for new plants, 10 for existing plants
Switzerland (canton Zürich)	10
Great Britain	<1, No remedial action; 100 – 1, remedial action observing the "as low as reasonably practicable (ALARP)" principle

Table 7
Appropriate distances and individual risk for several types of processes and storages

Type of plant	Lead substances	Distance (m) 1,000,000 m^2	Individual risk (10^{-6} yr^{-1})	Distance (m) 100,000 m^2	Individual risk (10^{-6} yr^{-1})
Production of hydrocarbons (linear or ring shaped, saturated or unsaturated, aliphatic or aromatic)	Acetylene, benzene, ethylene, toluene, hydrogen	100	0.8	100	0.07
Storage of hydrocarbons (linear or ring shaped, saturated or unsaturated, aliphatic or aromatic)	Acetylene, benzene, ethylene, toluene, hydrogen	150	12.4	150	1.2
Production of sulphuric hydrocarbons	Hydrogen sulphide	850	3.1	400	2.3
Storage of sulphuric hydrocarbons	Hydrogen sulphide	350	5.1	300	1.4
Production of basic pharmaceutics	Methanol	100	1.2	100	0.1
Storage of basic pharmaceutics	Methanol	400	22.0	400	2.2
Plants for distilling, refining or processing petroleum or petroleum products in refineries, petrochemical plants	Ammonia, propane (LPG), hydrogen sulphide	1500	7.4	200	2.1
Storage of substances related with plants for distilling, refining or processing petroleum or petroleum products in refineries, petrochemical plants	Ammonia, propane (LPG), hydrogen sulphide	750	17.5	400	6.8
After back fitting					
Production of hydrocarbons (linear or ring shaped, saturated or unsaturated, aliphatic or aromatic)	Acetylene, benzene, ethylene, toluene, hydrogen	100	0.08	100	0.007
Production of hydrocarbons (linear or ring shaped, saturated or unsaturated, aliphatic or aromatic)	Acetylene, benzene, ethylene, toluene, hydrogen	150	1.2	100	0.1
Production of sulphuric hydrocarbons	Hydrogen sulphide	400	2.4	100	0.3
Storage of sulphuric hydrocarbons	Hydrogen sulphide	300	1.3	100	0.9
Production of basic pharmaceutics	Methanol	100	0.1	100	0.01
Storage of basic pharmaceutics	Methanol	400	2.2	100	1.2
Plants for distilling, refining or processing petroleum or petroleum products in refineries, petrochemical plants	Ammonia, propane (LPG), hydrogen sulphide	200	2.4	100	0.1
Storage of substances related with plants for distilling, refining or processing petroleum or petroleum products in refineries, petrochemical plants	Ammonia, propane (LPG), hydrogen sulphide	400	6.9	150	2.5

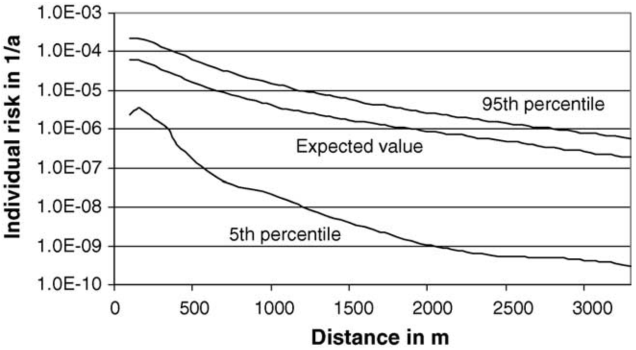

Fig. 6. Individual risk as a function of distance for the site of Fig. 5.

individual risk at a distance of 500 m are indicated as well. The total risk amounts to $1.6 \times 10^{-5}\,\mathrm{yr}^{-1}$. If the installations were back fitted the corresponding individual risk would drop to $1.8 \times 10^{-6}\,\mathrm{yr}^{-1}$. Based on the criteria for the Netherlands (cf. Table 5) the installation would be acceptable if it were existing and would require back fitting if it were a new one.

Fig. 6 shows the distance-dependent individual risk. The representation enables one to assess the impact of new developments in the vicinity of a site and the increase in risk deriving from an approach of residential areas, transport links etc. The indication of uncertainties enables one to put the results into perspective for decision-making.

6. Summary and conclusions

A framework was presented which permits one to consistently address land-use planning for process plants. It takes into account the expected frequency of major releases, which is low and therefore provides the justification for the deployment of such an industry. Important factors are addressed as, for example, the:

- type of the plant to be built,
- size of the site to be allotted,
- effect of back fitting,
- approach of urbanization.

These factors are of decisive influence on risk. Their inclusion enables one to plan the land-use accounting for prevailing and developing boundary conditions. Thus, for example, it is evident that a larger site entails an increase in risk if the same type of plant is considered as compared with a smaller one. Furthermore, it is possible to exclude the use of certain types of installations at a certain site in order to make plans match with existing distances. An application to other countries becomes possible if the expected frequencies for releases for Germany and the probabilities for different weather situations are replaced by values reflecting the situation in the country to be analyzed. It must be kept in mind, however, that the method represents a convention.

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