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Standard methods for land-use planning to determine the effects on societal risk

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Abstract

In the Netherlands, the individual risk and the societal risk are used in efforts to reduce the number of people exposed to the effects of an accident. In principle, the societal risk for each new land-use plan should be recalculated. Since this is proving increasingly cumbersome for planning agencies, several methods have been developed for SEVESO establishments and establishments for which in the Netherlands a generic zoning policy is used to determine the effects of new land-use plans on the societal risk. The methods give the uniform population density from a certain distance around the establishment at which the indicative limit for the societal risk is not exceeded. Correction factors are determined for non-uniform population distributions around the establishment, non-continuous residence times and deviating societal risk limits. Using these methods allows decision-making without the necessity of repeating quantified risk analyses for each alternative proposal.

Keywords: Land-use planning; Societal risk; SEVESO establishments

1. Introduction

The policy in the Netherlands to prevent major accidents is a two-tracked one [1]. Firstly, the chances of accidents occurring and their effects when they do occur are reduced as much as is reasonably practicable through measures taken at the source of risk. Secondly, the number of people exposed to the effects, should an accident occur, is reduced by a zoning policy. Two measures are used in defining these policies: the individual risk as a measure of the level of protection offered to each individual member of the public, and the societal risk as a measure of the disaster potential for the society as a whole. No new dwellings or vulnerable destinations, like hospitals and schools, are

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allowed within the individual risk contour of 10^{-6} a^{-1}. Less vulnerable destinations, like offices, are allowed in the zone between the individual risk contours of 10^{-5} and 10^{-6} a^{-1} [2]. An indicative limit for societal risk in the Netherlands is given as the limiting frequency for the occurrence of an event with N or more deaths:

$$F_{\mathrm{lim}}(N) = \frac{10^{-3}}{N^2} \tag{1}$$

The exponent (n) of 2 is the aversion factor for severe accidents with many casualties. This factor determines the risk aversion index $(\alpha = 1 + n)$ [3].

As the individual risk posed by a risk source can be expressed as risk contours (lines of equal risk on a map), a zoning policy for individual risk can be readily developed. Unfortunately, measures comparable to individual risk contours, such as societal risk contours, do not exist for societal risk. In principle, the societal risk for every new potential development will have to be re-calculated for a consistent implementation of a societal risk policy. Because this is proving increasingly cumbersome for planning agencies, several methods have been developed to determine the effects of new land-use plans on the societal risk. The methods are developed for SEVESO establishments, establishments for which in the Netherlands a generic zoning policy is applied (for example, warehouses with dangerous substances, liquid-gas filling stations and ammonia cooling systems) and for transport routes (road, rail, pipelines and inland waterways) [4]. The methods allow decision-making without the necessity of repeating quantified risk analyses for each alternative proposal.

This paper will describe the methods developed for SEVESO establishments (Section 2) and establishments with a generic zoning policy (Section 3). The methods give the uniform population density from a certain distance around the establishment at which the indicative limit is not exceeded. Correction factors are determined for non-uniform population distributions around the establishment, non-continuous residence times and deviating societal risk limits (Section 4).

2. SEVESO establishments

Under the Major Hazard Decree [5], 125 establishments in the Netherlands are required to prepare a safety report. The method developed to determine whether the societal risk limit is exceeded in a new land-use plan is valid for all kinds of SEVESO establishments, including LPG-storage facilities, oil refineries and other processing industries. The individual and societal risk of a SEVESO establishment is derived using a generic method [6]. Results must be presented in the form of risk contours (individual risk) and an F–N curve (for societal risk). At the moment, calculations show that for 58 of the 125 establishments there is a significant societal risk. Of these 58 establishments, eight show an exceedance of the societal risk limit.

The method developed is described in Ref. [7] and will be outlined here briefly, along with new available data. This method is based on the correlation between the Potential

Loss of Life (PLL), defined as the expectation value of the number of deaths per year, and the maximum level (E_{max}) to which the societal risk limit is exceeded:

$$E_{max} = \max\left(\frac{F(N)}{F_{lim}(N)}\right) \tag{2}$$

Theoretically, there is no correlation between these parameters. However, as a potential means for avoiding the necessity of re-calculating the risk for each proposed new housing development plan, an investigation has taken place to see if, in practice, a relationship between the level of exceedance of the societal risk limit and the PLL can be found.

The PLL can be calculated from both the individual and the societal risks as follows: let PLLI be the expectation value of the PLL calculated from the individual risk. The individual risk is a spatially distributed quantity $I(x,y)$. The population density $m(x,y)$ is also spatially distributed. Using these definitions:

$$\mathrm{PLLI} = \int\int I(x,y)\, m(x,y)\, \mathrm{d}x\, \mathrm{d}y \tag{3}$$

If the risk contours are circular and the population density depends on the distance to the risk centre only, this can also be written as:

$$\mathrm{PLLI} = 2\pi \int r I(r)\, m(r)\, \mathrm{d}r \tag{4}$$

The PLL can also be calculated from the societal risk. Let $F(N)$ be the frequency of accidents with N or more victims. Let PLLF be the expectation of PLL based on the societal risk and let $P(N)$ be the frequency of having precisely N victims. It then holds that:

$$\mathrm{PLLF} = \sum_{N=1}^{\infty} NP(N) = \sum_{N=1}^{\infty} N[F(N) - F(N+1)] = \sum_{N=1}^{\infty} F(N) \tag{5}$$

The results for PLLI and PLLF are not necessarily equal, since in the Netherlands the individual risk is calculated for an unprotected individual, whereas the societal risk is calculated by taking protection into account (e.g., by buildings).

Using Eqs. (2) and (5), the PLLF for an establishment can be correlated with the maximum exceedance (E_{max}) of the societal risk limit. The PLLF and E_{max} for the Dutch SEVESO establishments were calculated from the available safety reports. In Ref. [7], the limiting value (PLL_{lim}) is based on the in 1995 available safety reports of the Dutch SEVESO establishments. At that time this included 70 safety reports; for half of these establishments the societal risk calculated was significant. The results are depicted in Fig. 1. It can be seen that the relationship between PLLF and E_{max} follows an approximate straight line through $E_{max} = 1$ and $\mathrm{PLLF} = 10^{-4}$. Given the spread around the line, a conservative value for the limiting PLL would be $\mathrm{PLL}_{lim} = 10^{-5}$. This will give sufficient certainty that the societal risk limit in a later analysis will not be found to be exceeded. Recently, new information has become available. Safety reports are now

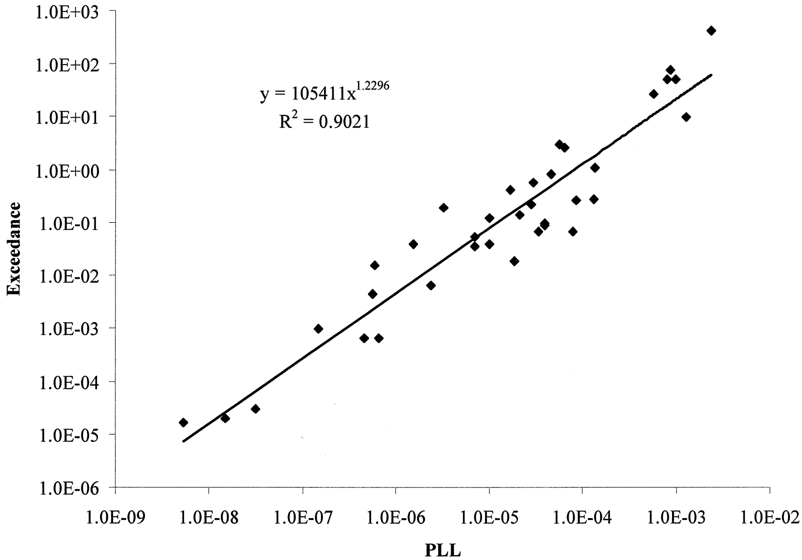

Fig. 1. Maximum exceedance of the societal risk as a function of PLL for the major hazard sites in the Netherlands (situation 1994).

available for all SEVESO establishments [8]. Further, most of the establishments for which the safety report was used to derive the first limiting value for PLL had to prepare an update of their safety report. On the basis of these data, the earlier derived limiting value of 10^{-5} can still be concluded to be valid (Fig. 2).

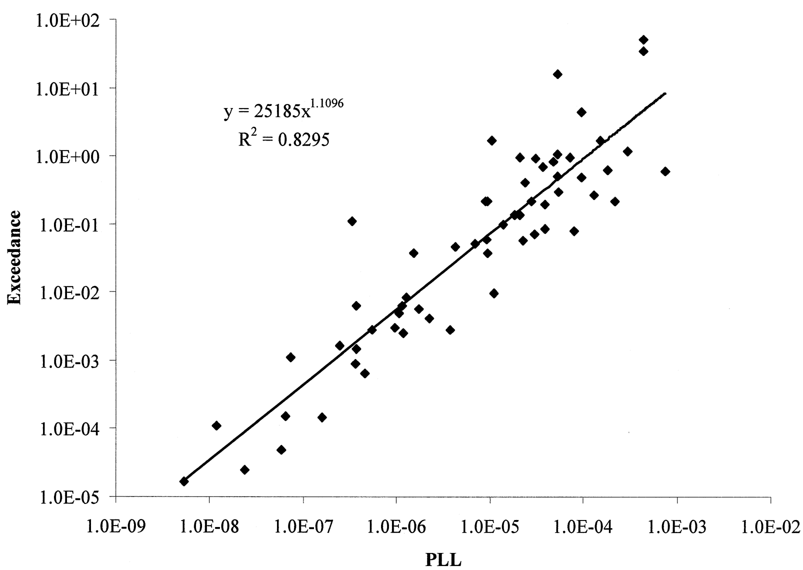

Fig. 2. Maximum exceedance of the societal risk as a function of PLL for the major hazard sites in the Netherlands (situation 1998).

In other countries, like the UK, other aversion factors (n) are used to limit the societal risk:

$$F_{\text{lim}}(N) = \frac{10^{-3}}{N^n} \tag{6}$$

It has also been investigated if a limiting value can be derived for different aversion factors from the data presented. The limiting PLL for another aversion factor (n) is equal to:

$$\text{PLL}_{\text{lim}} = 10^{-5}(N_{\text{max}})^{n-2} \tag{7}$$

Eq. (7) is only valid if: (1) the number of people (N_{max}) at which the maximum exceedance occurs is known, (2) all establishments give the maximum exceedance at the same number of deaths and (3) the number of deaths at which the maximum exceedance occurs is the same for all aversion factors.

Unfortunately, the maximum exceedance for all establishments does not occur for the same number of deaths. Furthermore, the number of deaths at which the maximum exceedance occurs is affected by the change in the aversion factor. Therefore, the limiting values for the aversion factors 1.5 and 2.5 are determined as examples (Figs. 3 and 4). With an aversion factor of 1.5, only two of the 125 Dutch SEVESO establishments would exceed the societal risk limit. From Fig. 3 it can be deduced that a conservative value for the limiting PLL would be 5×10^{-5}. If the aversion factor is 2.5, more than 20 establishments would exceed the societal limit. From Fig. 4, a conservative value for the limiting PLL can be deduced to be 5×10^{-7}.

With the value for the limiting PLL derived, a zoning distance can be calculated. Since the purpose of the current development is circumventing the need to repeat the

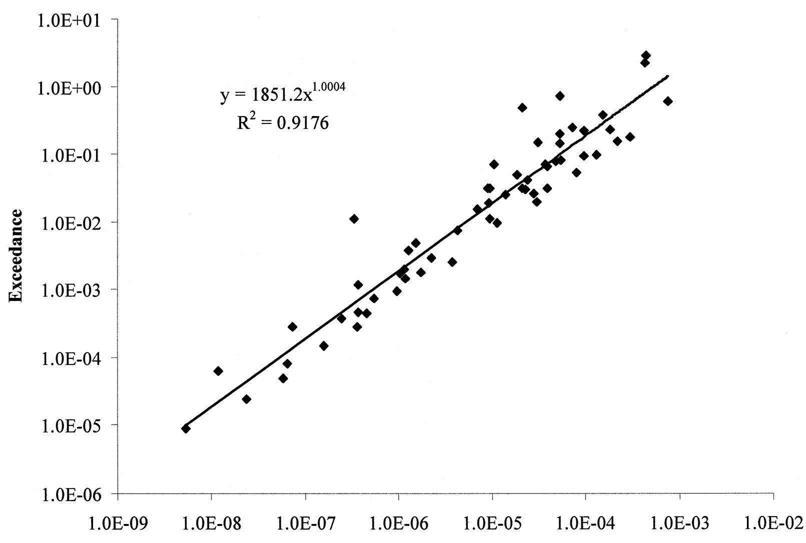

Fig. 3. Maximum exceedance of the societal risk as a function of PLL for the major hazard sites in the Netherlands (situation 1998) for an aversion factor (n) of 1.5.

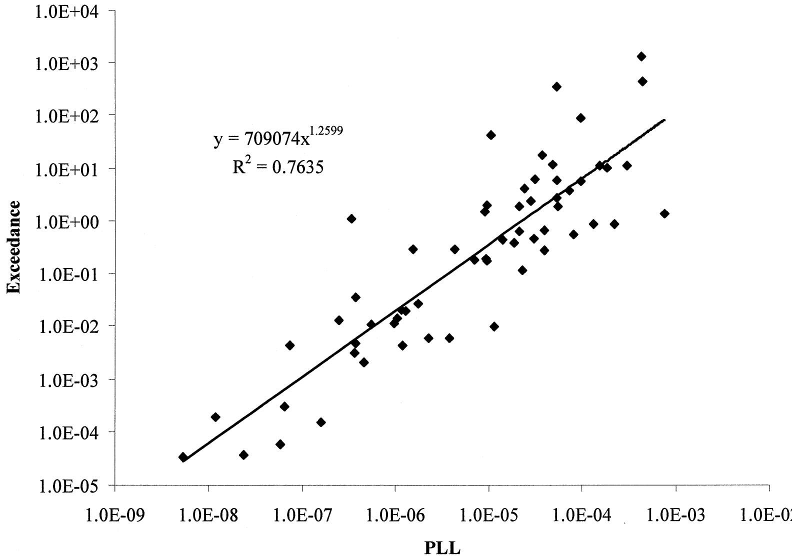

Fig. 4. Maximum exceedance of the societal risk as a function of PLL for the major hazard sites in the Netherlands (situation 1998) for an aversion factor (n) of 2.5.

complete risk analysis, the contribution of the additional PLL, PLL_{ad}, is calculated on the basis of the individual risk.

As the risk contours are assumed to be circular, which in practice, is usually shown to be true upon analysis of all risk contours of SEVESO establishments, the individual risk can be described as:

$$I(r) = I_o e^{-ar} \tag{8}$$

The additional PLL from a land-use plan, starting at a distance, R_l, from the establishment and having a constant population density, m_o, can now be derived from Eqs. (4) and (8).

$$\text{PLLI}_{\text{ad}} = 2\pi I_o m_o \int_{R_l}^{\infty} r e^{-ar} \mathrm{d}r = 2\pi I_o m_o e^{-aR_l}(aR_l + 1)/a^2 \tag{9}$$

With $\text{PLLI}_{\text{ad}} + \text{PLLF} < \text{PLL}_{\text{lim}}$, the necessary zoning distance for a pre-defined population density or the maximum population density for a pre-defined distance of the land-use plan to the establishment can now be derived by varying R_l respectively m_o.

The software application RORISC ('Spatial Planning and Risk') has been developed on the basis of the method described above [9]. Following are the required input for RORISC.

(1) The distance to the individual risk contours of 10^{-6} and 10^{-8} a^{-1} to derive the constants in Eq. (8). This information can be found in the safety report of the establishment under consideration.

(2) The PLL in the existing situation, which can be derived from the societal risk curve given in the safety report. In RORISC, there is a module which calculates the

PLLF from the F–N pairs of the societal risk curve (Eq. (5)). If the societal risk curve is not available and the societal risk is not negligible in the existing situation, then the PLL is derived using Eq. (4).

(3) The distance of the new land-use plan to the establishment and the population density for calculation of the additional PLL ($PLLI_{ad}$).

3. Establishments with a generic zoning policy

A generic zoning policy is used in the Netherlands for establishments like warehouses with dangerous substances, liquid-gas filling stations and ammonia cooling systems. The described method for SEVESO establishments is not applicable to establishments with a generic zoning policy. For most of these, the population density calculated is much lower than allowed. The limiting value for the PLL (PLL_{lim}) derived for SEVESO establishments is not valid for all different types of generic establishments and should therefore be derived separately. However, as for the generic establishments all different kinds of installations are well defined it is also possible to calculate the exact allowed uniform population density. Therefore so-called 'Distance Density Figures (DDFs)' have been developed for these establishments. In a DDF the maximum allowed uniform population density at which the indicative limit for the societal risk is just not exceeded, is given as a function of the distance to the hazardous establishment. The use of a DDF is explained in the flow chart in Fig. 5. First, it is checked whether the new land-use plan is not situated within the individual risk contour of 10^{-5} or 10^{-6} a^{-1}. Second, the maximum population density (Dmax) within the zone of the minimum distance to the establishment (Xmin) and the maximum calculated effect distance (Effmax) is determined. Third, it is checked whether the maximum population density in this zone exceeds the in the DDF given population density at the distance Xmin. The new land-use plan is allowed if the population density is not exceeded. Otherwise, the indicative limit will possibly be exceeded. In that case, further analysis is necessary. The calculation of the DDF is described in more detail in Ref. [10]. A brief description of the method used to determine the risk for the different kinds of installations is given, along with examples of DDFs.

3.1. Warehouses for hazardous substances

The total number of warehouses with hazardous substances in the Netherlands is estimated at 900 [11]. The risk analysis method for these establishments is described in Ref. [12]. The technical safety demands are prescribed by the Dutch CPR commission [13–15]. The risk of a warehouse is mainly determined by the toxic burning products (NO_x, SO_2 and HCl) produced during a fire. For warehouses with dangerous substances three protection levels are defined [13].

Protection level 1: (semi-)automatic extinguishing system or a company fire brigade;
Protection level 2: fire detection system, extinguishing water collecting system and preventive measures;
Protection level 3: preventive measures.

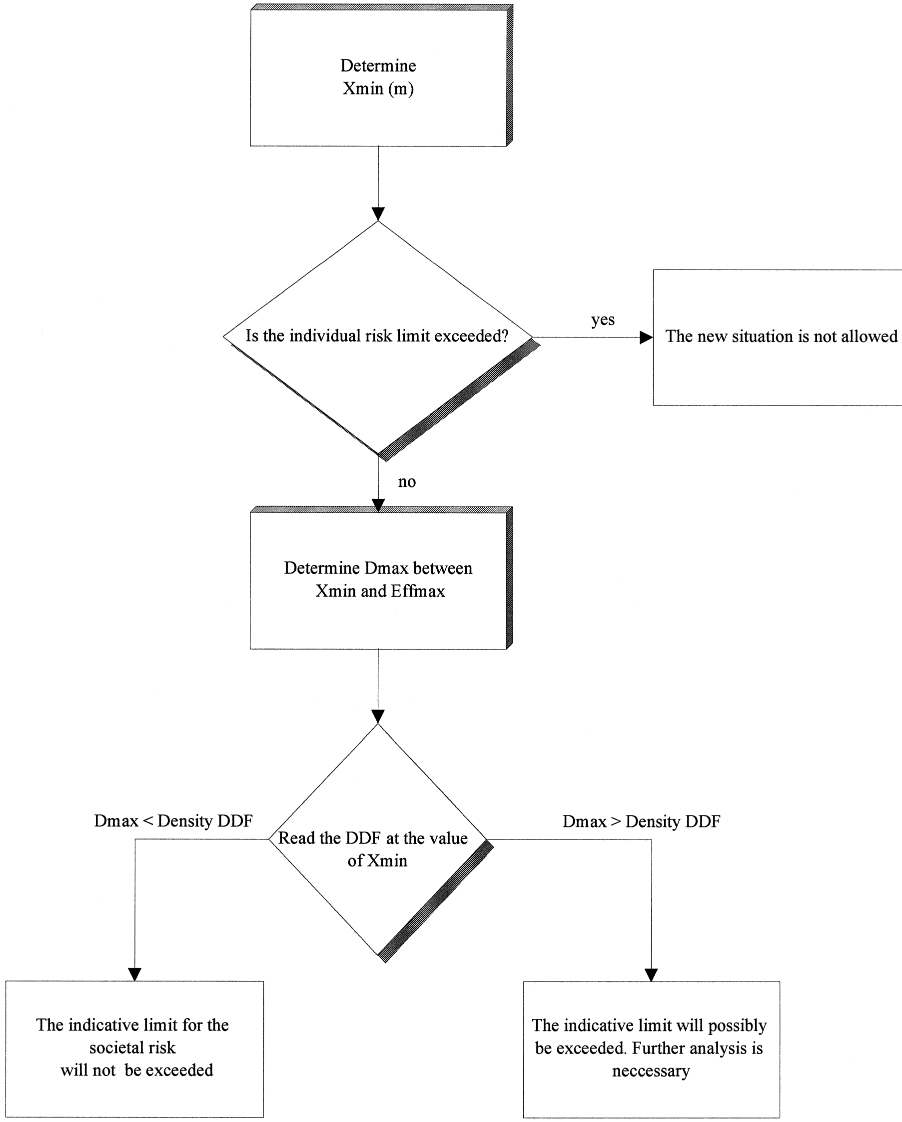

Fig. 5. Flow chart on how to use a DDF. Dmax, maximum population density in new situation, ha^{-1}. Effmax, maximum effect distance, m. Xmin, minimum distance between the existing or planned situation and the establishment, m.

The protection level of a warehouse depends mainly on the flammability and the hazard classification of the products stored in the warehouse. The generic zoning distances are derived for the different fire extinguisher systems and the area of the warehouse. For most warehouses under protection level 1, no DDF is derived as the population density from the individual risk contour of 10^{-5} a^{-1} is more than 300 persons ha^{-1}. For warehouses under protection levels 2 and 3, DDFs are derived. Although the flammability and toxicity of the substances in these warehouses is less than those of the substances stored in warehouses under protection level 1, the quantity of toxic burning products produced during a fire is greater, since the probability of high burning areas is higher. Fig. 6 presents the calculated DDF for a warehouse under protection level 3. If new dwellings are planned at a distance of 250 m from a warehouse under protection level 3 with a maximum population density of 60 persons ha^{-1}, this land-use plan will be allowed because the dwellings are not situated within the individual risk contour of 10^{-6} a^{-1} (situated at a distance of 235 m) and the planned population density is less then the maximum allowed population density (100 persons ha^{-1}, Fig. 6).

3.2. Liquid-gas filling stations

The total number of liquid-gas filling stations in the Netherlands is estimated at 2500 [11]. The risk analysis method for these establishments is described in [16]. The technical safety demands are laid down by the Dutch CPR commission [17,18]. For most liquid-gas filling stations, the stationary LPG vessel is situated underground. Therefore the risk is fully determined by the scenario, 'Boiling Liquid Expanding Vapour Explosion (BLEVE) of the truck'. As a BLEVE has a circular-effect zone, the number of deaths allowed in an accident where the societal risk limit is just not exceeded can be easily derived from:

$$N = \sqrt{\frac{10^{-3}}{F_{\mathrm{BLEVE}}}} \tag{10}$$

As the frequency of a BLEVE (F_{BLEVE}) is estimated at 2×10^{-6} a^{-1} [19], the maximum number of deaths allowed is 22. In the current risk-analysis method for

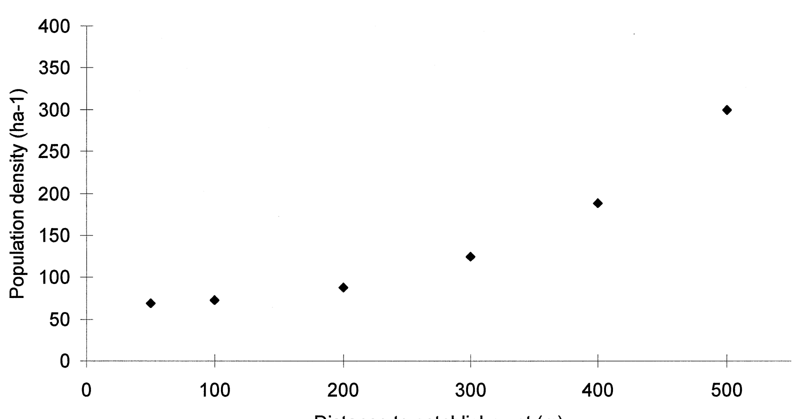

Fig. 6. DDF for a warehouse (protection level 3).

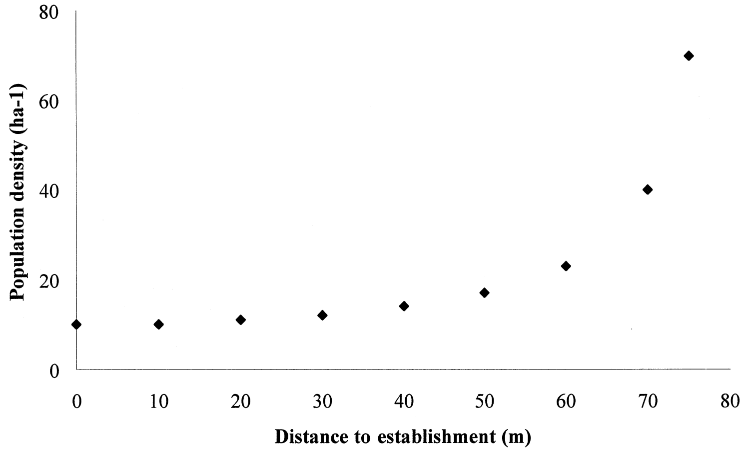

Fig. 7. DDF for liquid-gas filling stations.

gas-filling stations [16], the probability of death for a BLEVE is given for two zones. The first is the fireball zone ($\approx$ 80 m) in which the probability of death is equal to one. The second is the heat radiation zone (between 80 and 170 m) in which the probability of death is assumed to be equal to 0.01 [16]. The DDF can now be easily derived from this information (Fig. 7).

3.3. Ammonia cooling systems

The total number of ammonia cooling systems in the Netherlands with an inventory of more than 400 kg ammonia is estimated at 440 [11]. The risk analysis method for these establishments is described in Ref. [20]. The technical safety demands are prescribed by the Dutch CPR commission [21]. The generic policy is followed for

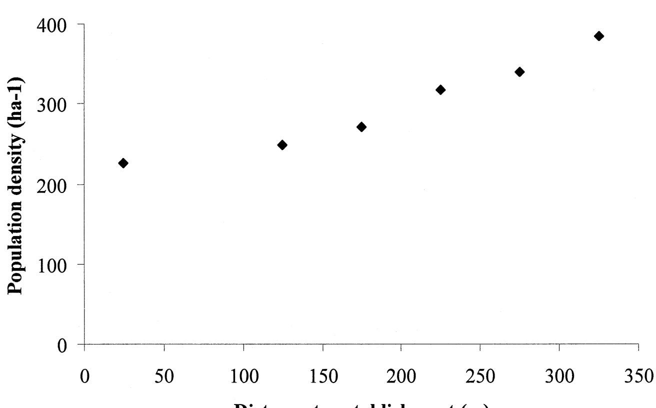

Fig. 8. DDF for an ammonia cooling system of 5000 kg.

installations up to 10 tons. Larger systems are not described by a generic system, these systems being fairly rare. The total number is estimated at 10–20, and the generic scenarios from Ref. [20] are not applicable for this kind of systems. The allowed population density from the individual risk contour of 10^{-5} a^{-1} for installations inside a building and those with a block valve on the liquid vessel, or for systems with an inventory of less than 3000 kg, is more than 300 persons ha^{-1}. Therefore, no DDFs are calculated for these systems. Fig. 8 shows the DDF for an installation situated outside a building having an inventory of 5000 kg and no block valve on the liquid vessel.

4. Density correction factors

In the development of the methods for SEVESO and generic establishments the societal risk limit is defined by Eq. (1), in which the population density is assumed to be uniformly distributed around the establishment and the population continuously present. Correction factors are derived for different societal risk limits, population distributions and non-continuous residence times.

The uniform population density (m_{360}) around an establishment results in an F–N curve for which at F–N pair F_1, N_1 the indicative limit is just not exceeded, i.e. $F_1 \times N_1^2 = 10^{-3}$. If the population is only present in one sector, with angle φ, and under the assumption that the wind rose is uniformly distributed, the total frequency of the scenarios which contributes to the societal risk decreases with a factor $x = 360/\varphi$. As the shape of the F–N curve is not affected the indicative limit will now just not be exceeded at the F–N pair F_2, N_2, i.e. $F_2 \times N_2^2 = 10^{-3}$. As $F_2 = 1/x \times F_1$, N_2 can now be derived with $N_2 = \sqrt{x} \times N_1$. As the population density and the number of deaths are linear correlated, the same correction factor may used for the correction in the population density (m_φ):

$$m_\varphi = \sqrt{\frac{360}{\varphi}}\, m_{360} \tag{11}$$

The relation given in Eq. (11) is not valid for establishments with only circular-effect zones, like liquid-gas filling stations. For gas filling stations only the BLEVE scenario, with a circular-effect zone, is of importance. So the total frequency of the scenarios contributing to the societal risk does not decrease as a result of the presence of the population in certain sectors. The allowed population density in the sector can therefore be derived from:

$$m_\varphi = \frac{360}{\varphi} m_{360} \tag{12}$$

For other societal risk limits with the same aversion factor of 2 ($F \times N^2 = C$), the maximum allowed uniform population density can be derived from Eq. (1).

$$m_C = \sqrt{\frac{C}{10^{-3}}}\, m_{10^{-3}} \tag{13}$$

As stated in Section 2, it is only possible to determine the allowed population density if the number of deaths for which the societal risk limit is exceeded is known. Therefore, no general correction factor can be derived for other aversion factors.

If the population is not expected to be permanently resident, for example, in the case of offices, the maximum allowed population density, m_T, can be derived from the allowed population density as in continued population presence, m_{24}.

$$m_T = \sqrt{\frac{24}{T}}\, m_{24} \tag{14}$$

5. Conclusions

For both SEVESO establishments and those establishments in the Netherlands for which a generic zoning policy is used, methods have been developed to determine the effects on the societal risk of a new land-use plan. The methods allow decision-making without the necessity of repeating quantified risk analyses for each alternative proposal. They give the uniform population density at a certain distance around the establishment at which the indicative limit is not exceeded. Correction factors are determined for non-uniform population distributions around the establishment, non-continuous residence times and deviating societal risk limits.

Nomenclature

a	a constant characterising the decrease inindividual risk at distance, m^{-1}
E_{max}	maximum exceedance of the societal risk limit
F_{BLEVE}	frequency of the BLEVE scenario at a liquid-gas filling station, a^{-1}
$F(N)$	frequency of N or more deaths, a^{-1}
$F_{lim}(N)$	limiting frequency at N (or more) deaths, a^{-1}
I_o	individual risk at the risk centre, a^{-1}
$I(x,y)$	individual risk at position x, y, a^{-1}
$I(r)$	individual risk at a distance r from the risk source, a^{-1}
m_o	population density, m^{-2}
$m(x,y)$	population density at position x, y, m^{-2}
$m(r)$	population density at a distance r from the risk source, m^{-2}
$m_{10^{-3}}$	allowed population density for the limiting value of 10^{-3} a^{-1} for one or more deaths, m^{-2}
m_C	allowed population density for the limiting value of C a^{-1} for one or more deaths, m^{-2}
m_{24}	allowed population density for a continuous presence, m^{-2}
m_T	allowed population density for a non-continuous presence, m^{-2}
m_φ	allowed population density with a sector angle of φ, m^{-2}
m_{360}	allowed population density with a sector angle of 360°, m^{-2}

N	number of deaths
N_{max}	number of deaths at maximum exceedance of the societal risk limit
n	aversion factor for the societal risk
$P(N)$	frequency of precisely N deaths, a^{-1}
PLL	expectation value of the number of deaths per year, a^{-1}
$PLLI_{ad}$	additional PLL through a new land-use plan, a^{-1}
PLL_{lim}	limiting PLL, a^{-1}
PLLI	PLL calculated from the individual risk, a^{-1}
PLLF	PLL calculated from the societal risk, a^{-1}
r	distance to centre of risk source, m
R_1	distance of new land-use plan to centre of risk source, m
T	duration of presence, h

Greek letters

α	risk aversion index
φ	angle of sector, degrees

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