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The third spatial dimension risk approach for individual risk and group risk in multiple use of space

Shahid Suddle[a], Ben Ale[b,*]

[a] Stadsgewest Haaglanden, P.O. Box 66, 2501 CB, The Hague & Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands
[b] Delft University of Technology, Safety Science, P.O. Box 5015, 2600 GA Delft, The Netherlands

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Abstract

Buildings above roads and railways are examples of multiple use of space. Safety is one of the critical issues for such projects. Risk analyses can be undertaken to investigate what safety measures that are required to realise these projects. The results of these analyses can also be compared to risk acceptance criteria, if they are applicable. In The Netherlands, there are explicit criteria for acceptability of individual risk and societal risk. Traditionally calculations of individual risk result in contours of equal risk on a map and thus are considered in two-dimensional space only. However, when different functions are layered the third spatial dimension, height, becomes an important parameter. The various activities and structures above and below each other impose mutual risks. There are no explicit norms or policies about how to deal with the individual or group risk approach in the third dimension. This paper proposes an approach for these problems and gives some examples. Finally, the third dimension risk approach is applied in a case study of Bos en Lommer, Amsterdam.

Keywords: Transport of hazardous materials; Multiple use of space; Risk analysis; Infrastructure; Urban planning

1. Introduction

As a consequence of an ever-growing population, land is becoming more and more scarce, especially in urban areas. This has led to the development of design and construction techniques that make intensive and multiple use of the limited space possible. In the last decade, the space available above transport infrastructure – such as roads and railway tracks – and existing buildings has been exploited at a growing rate in city centres. The new development strategies regarding space in urban areas pay particular attention to these issues. In The Fifth National Policy Document on Spatial Planning of The Netherlands [1] the need of space and spatial quality is designated a primary concern for the government in The Netherlands. With a population density of 475 people/km^2, a particular concern is to preserve the remaining "empty" areas as long as possible if alone to provide recreational area's for the inhabitants of the congested cities.

Accordingly, future projects preferably are to be realised within the present urban contours, utilising existing urban spaces more efficiently and effectively. This policy is characterised by the key-words intensification, combination and transformation. The policy is aimed in using the urban areas as intensely as possible, among other by combining and layering functions and at the same time transform the inner city surroundings into an "agreeable" environment, although what this means is hardly defined. The expected advantages are maximum use of limited space, reduction of travel and commuting time and saving the already limited area of "green" space in The Netherlands, which has been proven to contribute significantly to the perception of good quality of the cities that it surrounds.

This spatial planning policy, however, with its aim to intensify the use of space, may come into conflict with the intentions set out in the Fourth National Environmental

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[*] Corresponding author.
E-mail address: b.j.m.ale@tbm.tudelft.nl (B. Ale).

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Policy Plan, regarding the protection of the population against undue hazards and risks. If the use of space is being intensified near locations where hazardous activities are taking place (e.g. industrial activities and transport routes or storage of hazardous materials), any accident may result in increasing serious consequences [2]. Already protecting all members of the population in The Netherlands against undue risks as defined in the policy document“Coping with Risks” [3] has not always proved feasible in practice [4]. Intensifying the use of inner-city space may further reduce separation distances, thereby increasing the risks.

The Fourth National Environmental Policy Plan indicates that in situations where existing acceptability criteria may be exceeded the choice between further spatial development and accommodating the risk generating activity [5] has to be made explicitly. Unfortunately a number of locations where current criteria are already exceeded [6], such as nodes for the transport of hazardous materials, are also the locations for which the Fifth National Policy Document on Spatial Planning of The Netherlands desires intensification, combination and transformation (encircled in Fig. 1).

Projects using land in multiple ways are generally complex. In these locations large numbers of people are potentially exposed and interactions are involved between several sources of risk. Due to the complexity and interrelationships in such a project, a small accident, like a fire in a building or on infrastructure, which is covered by a building, can easily lead to a major disaster.

Therefore, safety is one of the critical issues in such projects during construction as well as in the exploitation stage (see, e.g. [7]). Major accidents all over the world, particularly cases in which a great number of casualties were involved, have an influence on the local perception of risk [8]. Hence, safety issues in multiple use of space projects are “double” sensitive and thus “double” important. Several projects have been realised in the past without proper attention to safety issues [9]. This was the reason for undertaking a Ph.D. research project at Delft University of Technology, carried out by Suddle [7]. Probabilistic risk analyses can be undertaken to assess the safety level and to investigate what safety measures are needed to realise these projects within the boundaries of acceptable risk. Such a risk analysis should consider the construction stage and when the building is in use, for four different cause–consequence relationships, which are presented in Fig. 2 as arrows [10].

For the purpose of this paper four categories of risk are distinguished, which differ in the kind of threat, the source and the target as follows:

- Risk category 1: External safety and risks from the building in relation to the infrastructure beneath (e.g. falling elements and fire);
- Risk category 2: External safety and risks from the infrastructure towards the building (e.g. release of toxic gasses, fire, explosions and collisions against building structure);

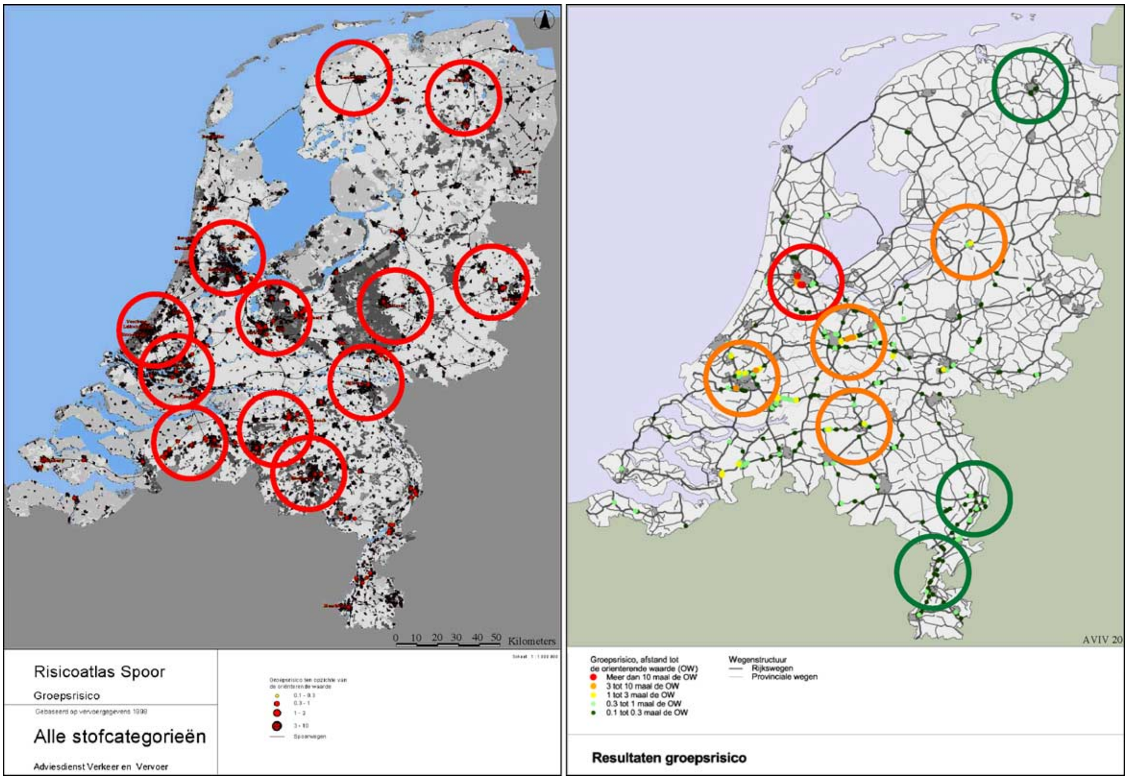

Fig. 1. Locations where acceptance criteria for risk in The Netherlands are exceeded (railways (left) and roads (right)) are encircled (source: DHV and AVIV, respectively).

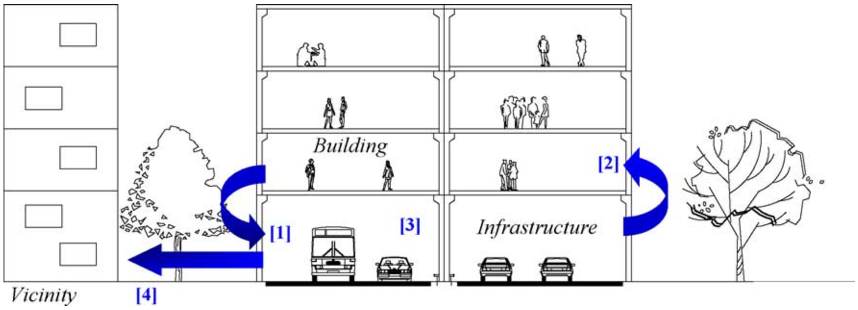

Fig. 2. The four risk interaction categories in multiple use of space projects [10].

- Risk category 3: Internal safety and risks from the structures enclosing the infrastructure (e.g. explosions, fire, explosions and collisions against building structure);
- Risk category 4: External safety and risks from the infrastructure towards the vicinity (e.g. release of toxic gasses, fire, explosions and collisions against building structure).

The criterion for acceptability of individual or localised risk is usually depicted as contours on a – two-dimensional – map, as demonstrated [11]. However, when doing risk analysis for multiple use of space, different functions are layered [12], introducing a third spatial dimension [13]. In considering the limits for risk acceptance in multiple and intensive use of land, where different functions are layered, the third spatial dimension, must be taken into account.

Another instance where individual risk varies in the third dimension – i.e. in height – is in case of flood hazard. Generally, the individual risk can be given for persons behind a river dike in which is assumed that the houses are homogenous and consist two stories. It has to be noted, however, that in some cases, especially people living in a high-rise building do not have the same individual risk.

In these circumstances it may also be useful to consider the risk in three rather than in two dimensions. As dealing with the third dimension safety system when doing risk analysis adds considerably to the complexity, this is not done in the traditional models for consequence analysis and frequency estimation. Therefore, additional methods are needed for the calculation of risk in the third dimension.

2. Qualitative risk analysis

A qualitative insight into the problem can be gained by using Failure Mode and Effect Analysis (FMEA) techniques

Table 1
An example of a section of the FMEA for safety of people during the exploitation (see [15])

Failure mode	Failure cause	Effect of failure
Risk category 1: External safety and risks from the building in relation to the infrastructure beneath		
Fire in building	Short circuit Cigarettes Cooking facilities Terrorism	Costs, time loss, loss of quality, fatalities
Explosion in building	Gas leak	Costs, time loss, loss of quality, fatalities
Falling objects	Montage failure Throwing out of window	Costs, fatalities
Collapse building	Explosion infrastructure	Costs, time loss, loss of quality, fatalities
Risk category 2: External safety and risks from the infrastructure towards the building/risk category 3 internal safety and risks from the structures enclosing the infrastructure/risk category 4 external safety and risks from the infrastructure towards the vicinity		
Collision (against building structure)	Inattention Distraction High speed Overtaking	Costs, fatalities
Fire at infrastructure	Traffic accident Leakage of flammable materials Terrorism	Costs, time loss, fatalities
Explosion at infrastructure	Leakage of flammable materials Terrorism	Costs, time loss, loss of quality, fatalities
Release of toxic gasses	Leakage of toxic materials of vessels	
Electrocution	Short circuit	Costs, fatalities
Derailment	Defective track	Costs, time loss, fatalities

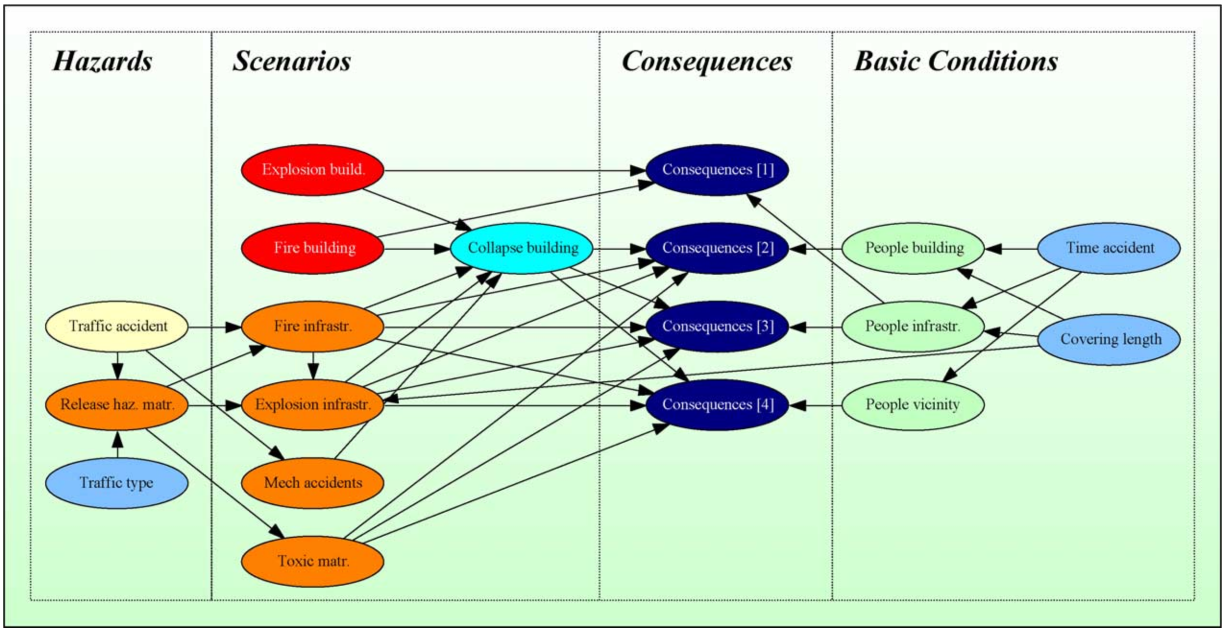

Fig. 3. Schematic Bayesian network for building above roads for exploitation stage.

for the four risk interrelations given above: the construction and exploitation of a building over a motorway. A section of the FMEA with its major hazards is presented in Table 1. The interactions found can be arranged in an influence diagram (Fig. 3). It appears from the FMEA that the risk for people during the exploitation stage, either in the building above the infrastructure or at the infrastructure or in the vicinity, depends largely on the hazards taking place on the infrastructure or the hazards taking place in the building. Although Table 1 might indicate that the interrelation of hazards on the infrastructure to the building (risk category 1) are the same as the interrelation of hazards between the structures enclosing the infrastructure (risk category 3), it should be noted that the risks are not of the same magnitude. They have different consequences and probabilities and work in different areas.

The hazards posed by the infrastructure, which could be a road or a railway track, can be grouped into four classes: traffic accidents (mechanical load on the structure of the building), fires, leaks of toxic substances and explosions (see also [13,14]). The hazards in the building are mainly fire, explosions and in some cases (with a very low probability of occurrence) falling objects.

In principle the scenarios that could occur on the infrastructure remain the same when the infrastructure is covered. The consequences, however, may differ widely with regard to their impact on structures above and beside the infrastructure, between the situation where when it is covered by a building or not. The possible collapse of the building above the infrastructure is a crucial phenomenon in the risk analysis for the group and individual risk. The collapse of the building above the infrastructure may cause fatalities in the building above the infrastructure and on the infrastructure itself. Therefore, the individual risk varies across the vertical. So, if the probabilities of collapse due to scenarios can be determined, the risk can be presented in the third spatial dimension.

3. Three-dimensional approach of individual risk contours

3.1. Two- and three-dimensional individual risk contours

In urban planning the limits of the areas where developments are allowed are – among other – determined by the individual and societal risk of existing hazardous installations. Similarly risks posed by line infrastructure for the transport of hazardous materials limit the area where further development is possible. Even in the past the inhabitated buildings are planned far away from hazardous installations and hazardous installations are planned at some distance from the city. Line infrastructure for the transport of hazardous materials mostly is used also for the transport of people and therefore often passes through densely populated urban areas. Because in the past, new buildings were never planned above hazardous installations or transport infrastructure, a three-dimensional approach of risk contours was not necessary. In the two-dimensional approach, the individual risk depends on the distance and is displayed in the form of iso-risk contours on a geographical map. The individual risk as used in The Netherlands is not characteristic for any person, but for the location for which it is calculated. Thus, the individual risk contour maps give information on the risk of a location, regardless whether people are present at that location or not (see, e.g. [16,17]).

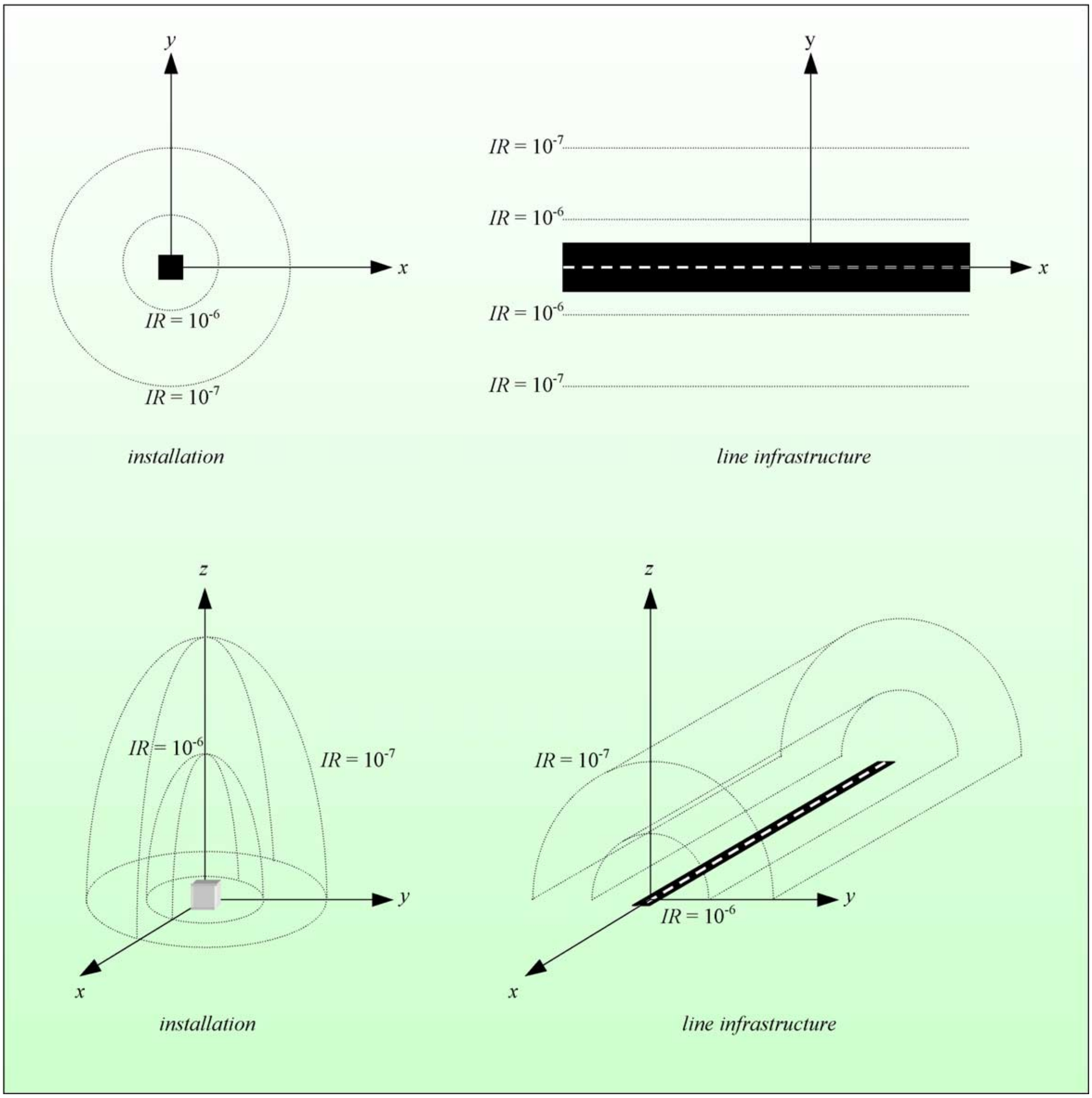

Fig. 4. Schematic two- and three-dimensional individual risk contours for an installation and line infrastructure [10].

The schematic risk contours for a hazardous installation and a transport route are shown in Fig. 4. Due to the lack of space in combination with a new awareness of quality of the built-up environment, new concepts for urban planning are considered in which space is used more intensively. The possibilities of using the land more than once by building over line infrastructure are studied and applied. Accordingly, the development of an approach for the third dimension are inevitable. In general, three-dimensional individual risk contours for installations will have the shape, in open-air, of a half ellipsoid, as presented in Fig. 4 [10].

These risk contours are related to the intensity of combustion caused by a flame [18]. A similar but transposed figure for line infrastructure is also drawn. It should be noted that it is possible that the contours do not close in the vertical, resulting in vertical cylinders rather than ellipsoids. Such may be the case if a building is realised above the hazardous installation and if the risk is posed by scenario's involving the potential collapse of structures in which people are present. The general equation of an ellipsoid whose centre is the origin, and whose axes correspond to the *x*, *y* and *z*-axis is:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{1}$$

In the same way, one may outline the three-dimensional risk contour approach for line infrastructure, which is a half a cylinder. The general equation of a cylinder is (with $a \to \infty$):

$$\frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \tag{2}$$

For both examples, the height of the risk contour depends on the nature and on the quantity of hazardous materials produced in the installation, or transported over the infrastructure. In most cases, the height (z) of the individual risk

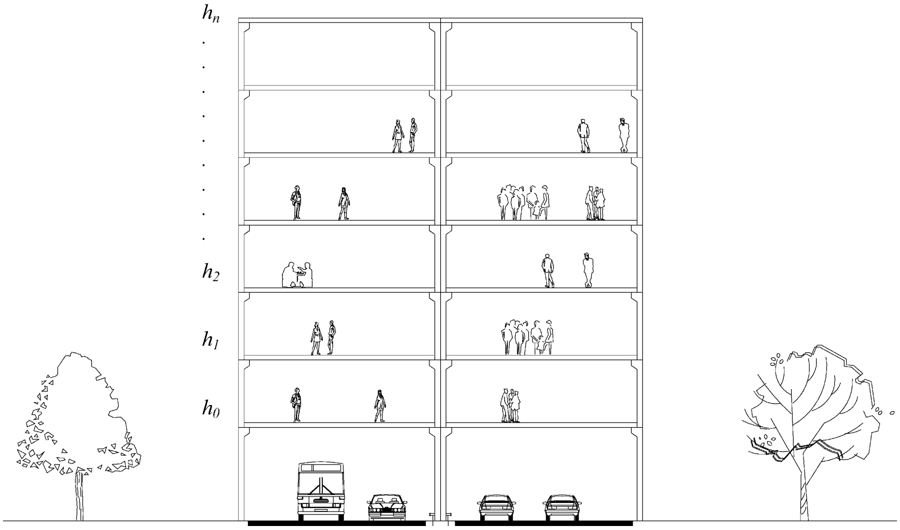

Fig. 5. Basic conditions of storeys of building above infrastructure.

contour is bigger than its width (x, y). However, as indicated, the integrity of the structure may have a large effect on the shape of these contours. A tool to calculate the effect of a scenario is Computational Fluid Dynamics (CFD). CFD calculations are often used to calculate the effects of fires and explosions in and around complex structures such as oilrigs and tunnels. The output of the CFD calculations is a three-dimensional description of effects, which can be translated into a probability of fatality or other damage where necessary.

3.2. Basic conditions

The realisation of buildings above infrastructure can influence the shape and the surface area of the cross section of the individual risk contour. In order to analyse the height of the risk contour in multiple use of space, the individual risk can be examined in a risk analysis. In this research, Bayesian networks were used [19]. The individual risk has to be analysed per storey of the building above infrastructure (h_0, h_1, . . ., h_n), as presented in Fig. 5.

The consequences of accidents on the infrastructure dominate the safety of people in the building. These accidents, however, all have a different impact. As mentioned earlier, the accidents on infrastructure can be grouped into four dominant classes: collisions (mechanical load on the structure of the building), fires, leaks of toxic substances and explosions [14]. These accidents can also be the starting points of others. A fire for instance can cause an explosion and vice versa. The release of toxic gasses almost never initiates other events. It is, therefore, important to explore the effects of releases of toxic gasses separately from the release of explosive materials on infrastructure. Moreover, to determine the effect of fire on the individual risk on each storey, the fire on infrastructure scenario is explored separately from the previous scenarios. In order to set up a (methodological) risk analysis, the most important factor is whether the building collapses due to an accident.

3.3. Programming in Bayesian networks

A quantitative risk analysis is done for the main scenarios. Bayesian networks are used for the quantitative risk analysis as presented in Fig. 6. These networks represent the relations between the events on the infrastructure and the building. These relations are quantified in (conditional) probabilities, as presented in Appendix A. The (change of) individual risk

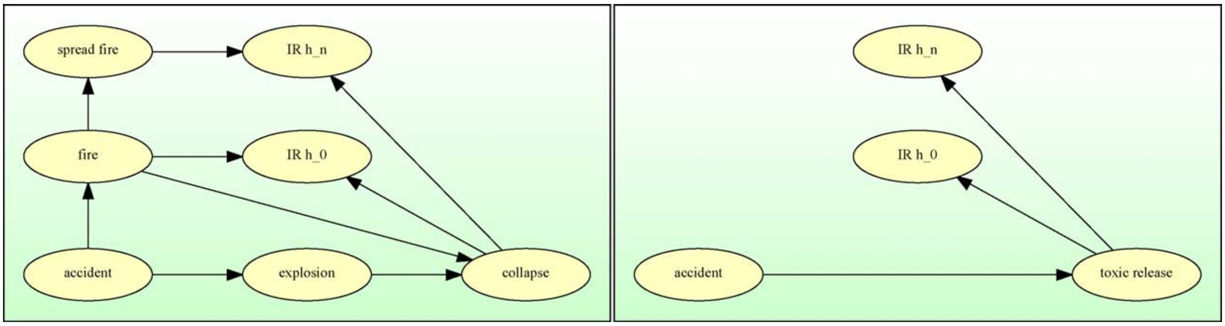

Fig. 6. Bayesian networks; explosions on infrastructure (left) and release of toxic gasses (right) on infrastructure.

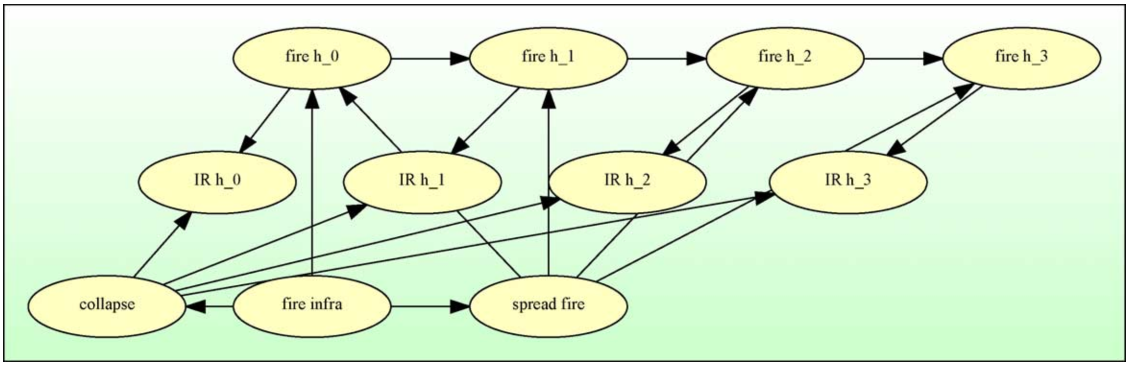

Fig. 7. Bayesian network: fire on infrastructure.

for each storey of the building is considered in these networks. An accident on the infrastructure may cause an explosion, which may cause the collapse of the building straight away or may cause a fire followed by the collapse of the building. This results in a variation of the individual risk per storey. In the network, the node explosion is divided into three classes: a BLEVE, a deflagration and a detonation, because the effects on the building will be different for each of them. An accident on the infrastructure may also lead to the release of toxic gasses, which affects the individual risk in the building as well.

Fig. 7 presents the scenario “fire on the infrastructure”. The intensity of fire on the infrastructure varies between 20 MW (passenger cars), 100 MW (busses/trains) and 300 MW (trucks/trains). The higher the intensity of the fire, the higher the probability that it will spread to upper storeys. An even higher fire intensity can lead to the collapse of the building. The assumed conditional probabilities that a building may collapse due to an accident can be found in Appendix A. In order to keep the example simple only the events occurring on the infrastructure are assumed (see Table 2, first row).

3.4. Results of the risk analysis per storey

The results of the risk analysis are presented in Table 2. Table 2 lists the individual risk per storey and the ratio of individual risk per storey (IRh_i) in comparison with the individual risk at the infrastructure (IRh_{-1}). The ratio $\mathrm{IRh}_i/\mathrm{IRh}_{-1}$ presents the increase or decrease of the individual risk on the considered storey (IRh_i) compared to the individual risk at the infrastructure (IRh_{-1}).

When considering the scenario of an explosion possibly combined with fire, the individual risk on the top storey (h_n) is almost as high (in some cases higher) as on the covered infrastructure. This “relative increase” is due to the risk of collapse of the building, which has a dominant influence. If the building collapses, one may assume that a great number of fatalities will occur in the building (e.g. 99%). Explosions, collisions with the building structure and fires can initiate the collapse of the building. One should note that functional and structural measures to prevent a collapse by traffic accidents or fires can be taken, but measures to stop a detonation are much more difficult to take and are in disproportionably expensive [20].

The results of Table 2 are graphically presented in Figs. 8 and 9. In these figures, the increase or decrease of relative risk contours is depicted. The arrows indicate a change from the base values (solid lines), which are assumed to be the vertical section of the cylinder of Fig. 4 below-right and the new values after the building is constructed above the infrastructure (dashed lines). In the case of a release of toxic gasses on infrastructure, the individual risk contour decreases rapidly. This is because the effects of toxic gasses are for the greater part restricted to the infrastructure when it is covered (see Fig. 8). The toxic gasses can only reach the open-air and

Table 2
Results of the risk analysis

Risk level	Explosion		Release of toxic gasses		Collisions affecting the building structure		Fires	
	IRh_i	$\mathrm{IRh}_i/\mathrm{IRh}_{-1}$	IRh_i	$\mathrm{IRh}_i/\mathrm{IRh}_{-1}$	IRh_i	$\mathrm{IRh}_i/\mathrm{IRh}_{-1}$	IRh_i	$\mathrm{IRh}_i/\mathrm{IRh}_{-1}$
Infrastructure	10^{-9}	–	10^{-8}	–	10^{-6}	–	1×10^{-6}	–
h_0	10^{-9}	1	10^{-10}	0.01	7×10^{-7}	0.7	7.1×10^{-7}	0.71
h_1	10^{-9}	1	10^{-10}	0.01	7×10^{-7}	0.7	6.7×10^{-7}	0.67
h_2	10^{-9}	1	10^{-10}	0.01	7×10^{-7}	0.7	6.2×10^{-7}	0.62
h_3	10^{-9}	1	10^{-10}	0.01	7×10^{-7}	0.7	5.7×10^{-7}	0.57
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
h_n	1×10^{-9}	1	10^{-10}	0.01	7×10^{-7}	0.7	10^{-7}	0.1

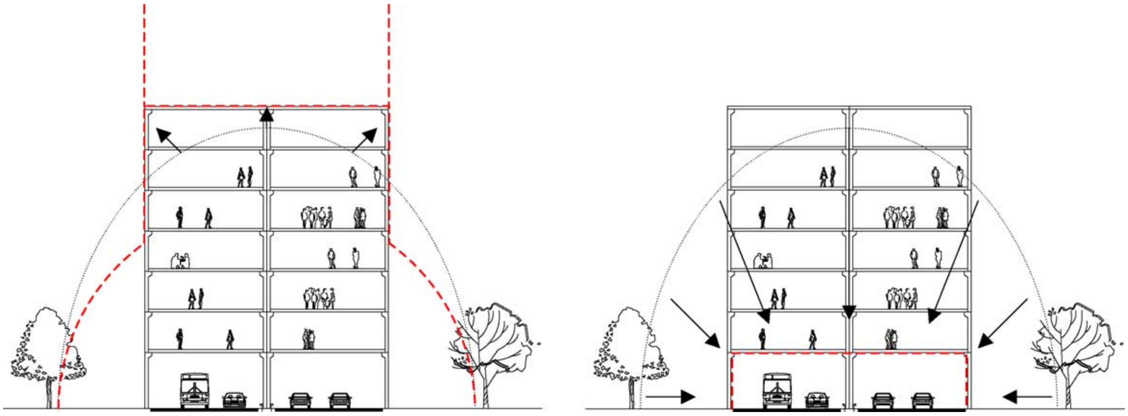

Fig. 8. The influence of the individual risk contour: fire and explosions (left) and release of toxic gasses (right).

the building at the ends of the tunnel. It is important to note that the three-dimensional cross-sectional approach must be linked to the two-dimensional ground level approach in order to really be three-dimensional. When considering the fire scenario on infrastructure, the individual risk contour decreases with a factor 10 within five/six storeys. Collisions with the building structure (e.g. derailing trains or traffic accidents) can cause a mechanical load on the structure that can lead to the collapse of the building. So, for the individual risk contour, this scenario ranges between the explosion on infrastructure scenario and the fire on infrastructure scenario (see Fig. 9).

3.5. Evaluation of the height of individual risk contour

Considering the previous, it may be concluded, that, when realising buildings above infrastructure, the height of the individual risk contour can be influenced indeed. But it has to be noted that the (internal) risk on the infrastructure will increase. The shape of the individual risk contour depends on a number of aspects (see Section 5.1 and further):

- The amount of explosive and toxic materials transported on the infrastructure:

  If the transport of explosive and toxic materials is prohibited, the individual risks will almost be confined to the infrastructure.
- The measures to protect the building from the main four scenarios (explosion, release of toxic gasses, collisions with the building structure and fires) can be divided into functional and structural measures.

Assessing risks of scenarios separately with a three-dimensional approach emphasises the fact that intensifying the use of space does not a priori mean that the overall risk will increase.

4. Results of three-dimensional group risk

4.1. Group risk

The societal/group risk is calculated with the risk analysis Bayesian network model of Fig. 3 for three different covering lengths. The major input data of that model can be found in Appendix A. The covering length of the infrastructure means the longitudinal length of the infrastructure covered by a building, as defined in Fig. 14. The group risk is depicted in the FN-diagrams per risk category (Fig. 10). The FN-diagrams of Fig. 10 based on the input data of Appendix A show that the risks from the building towards the infrastructure (risk category 1) are almost negligible. This is because only two scenarios can appear in the building, namely fire and in a few cases an explosion. In contrast, the risks from the

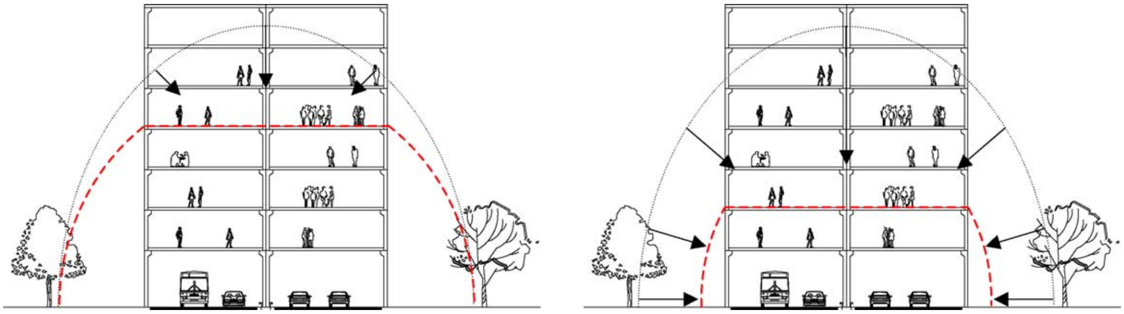

Fig. 9. The influence of the individual risk contour: collisions with the structure of the building (left) and fire on the infrastructure (right).

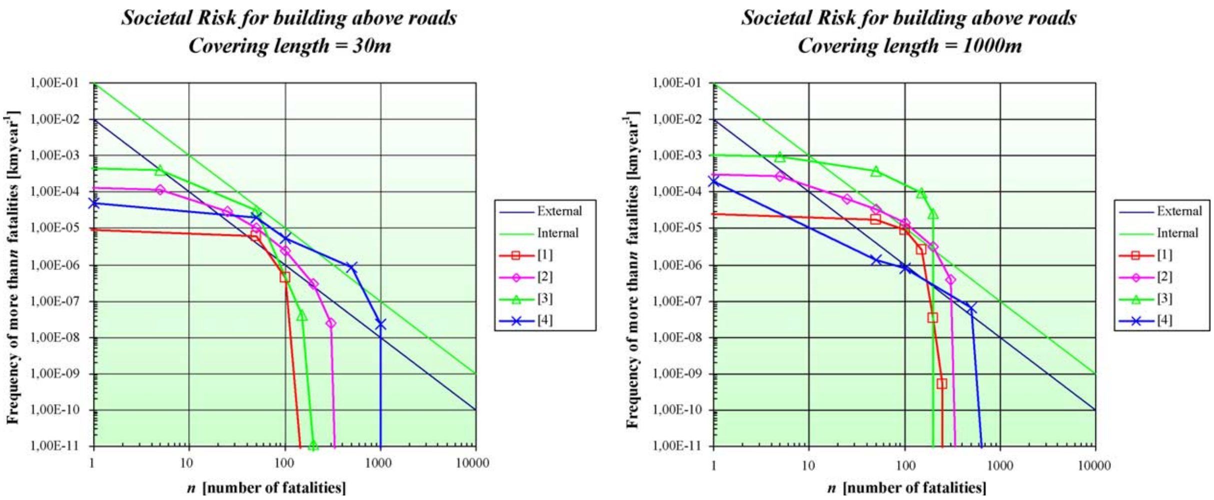

Fig. 10. Societal risk for building above roads with a covering length of 30 m (left) and 1000 m (right).

infrastructure towards the building above the infrastructure (risk category 2) are relatively high. The building above the infrastructure is the main reason for internal risks (risk category 3) in the tunnel. The reduction of risk for the vicinity (risk category 4), when considering a small covering length, is almost the same as when the infrastructure is not covered. However, the risks for the surroundings due to transport of hazardous materials can be decreased by covering the infrastructure for a larger distance (see Fig. 10, right), while the risk increases in the tunnel (risk category 3).

4.2. Expected number of people killed

If we correlate the $E(N_\mathrm{d})$, the expected loss of human lives per kilometre per year, with the covering length, remarkable results are obtained (Fig. 11). Although the relation is not of a linear type, it can be observed that the $E(N_\mathrm{d})$ for the surroundings (risk category 4) decreases, if the covering length of the infrastructure increases. In contrast, the $E(N_\mathrm{d})$ for the people at the infrastructure (risk category 3) inflates rapidly in case of an increase in the covering length of the infrastructure. Both the $E(N_\mathrm{d})$ of risk category 2 and risk category 1 enlarges slowly in case of an increase of the covering length of the infrastructure [7].

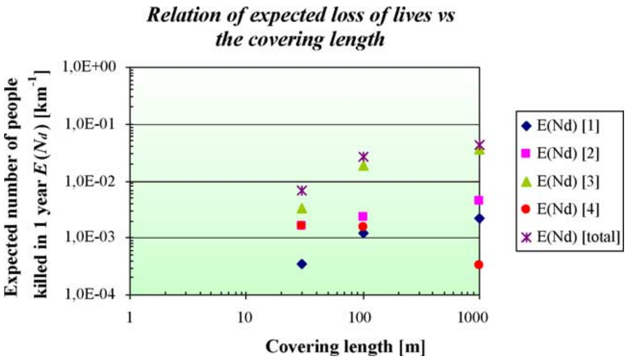

Fig. 11. Relation of expected loss of lives vs. the covering length of the infrastructure.

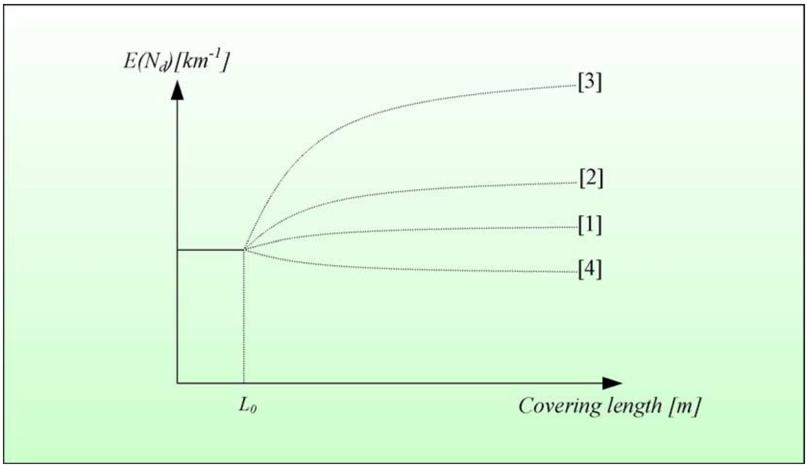

Fig. 12. Schematic relation of the expected loss of lives vs. the covering length of the infrastructure.

This phenomenon is schematically presented in Fig. 12, which is applicable both to the realisation of buildings above roads and railways. This figure shows that from a minimum covering length L_0 of the infrastructure, the expected loss of human lives per kilometre per year ($E(N_d)$) splits up into three additional risk categories (1, risks of the buildings above the infrastructure to the enclosed infrastructure; 2, risks of the infrastructure to the building above; 3, internal risks within the covered infrastructure). In fact, the risk towards the vicinity (risk category 4) already exists. It should be noticed that these results are comparable to the study presented by RWS of Hoeksma [21], in which the $\Delta E(N_d)$ increases with 30% if the infrastructure is covered compared to a road which is not covered.

5. Influencing building parameters

5.1. Introduction

Given the fact the that transport of hazardous materials is allowed in such areas, the building and infrastructure parameters can be influenced by their configuration. This will result in the variation of both the shape of the (individual) risk contour and the group risk for the building above the infrastructure and for the vicinity. The main influencing (functional) building and infrastructure parameters are the width and height of the covered infrastructure, possibly combined with the length of the covered infrastructure and the height level of the infrastructure. These influencing parameters form a main part of the functional measures. By implementing functional measures, effective results can be achieved. The configuration of the functional design of the building most definitely affects the risks of scenarios, e.g. configuration in the ratio L/D (explained in Section 5.2) and fire.

5.2. The effect of the width and height of the tunnel

In situations like Fig. 13, the height of the covered infrastructure depends on the height of the lowest storey of the building h_0. The width of the covered infrastructure depends on the span l of the building.

These two parameters form the basis for the possible scenarios at the infrastructure. The section area D can be defined as the average of the height and the width of the tunnel: $(h_0 + l)/2$. Suppose h_0 is designed at a minimum of 4 m and if $l = 12$ m, then $D = (12 + 4)/2 = 8$ m. For the present, we suppose, in this study, that the probability of the occurrence of a detonation is higher if $L/D > 10$ (see also Baker et al. [22]. It should be noted that additional (field) research is necessary to determine the exact probabilities. Since $L/D < 10$, the limit for the covering length $L \leq 80$ m (in order to prevent a detonation scenario). In order to comply with the criterion of $L/D < 10$, one may decrease the covering length L or increase the section area D. Implementing a big diameter (a high level for the lowest storey h_0 and a larger span l) in the design of the building leads to smaller probabilities for the detonation scenario and in case of fire on the infrastructure, the consequences are smaller (Fig. 13).

5.3. The effect of the length of covered infrastructure

Multiple use of space becomes interesting when the infrastructure is covered for long distances [13]. This is, however, not always realisable because of urban and spatial limits, and safety considerations, e.g. a detonation scenario. In order to comply with the already mentioned assumed criterion of $L/D < 10$, one may realise individual buildings with a short covering length (see Baker et al. [22]). Note that the space between two buildings should be more than the covering length of one building, because only then the flame cannot spread to the next building. The probability of an accident on the infrastructure is related to the covering length of the infrastructure, while the consequences of an explosion increase rapidly with the length of the tunnel, as discussed by Berg et al. [23]. The effect of the covering length of infrastructure for the main scenarios is presented in Table 3. One can read that a small covering length of infrastructure is positive regarding the explosion scenario. Any advantages

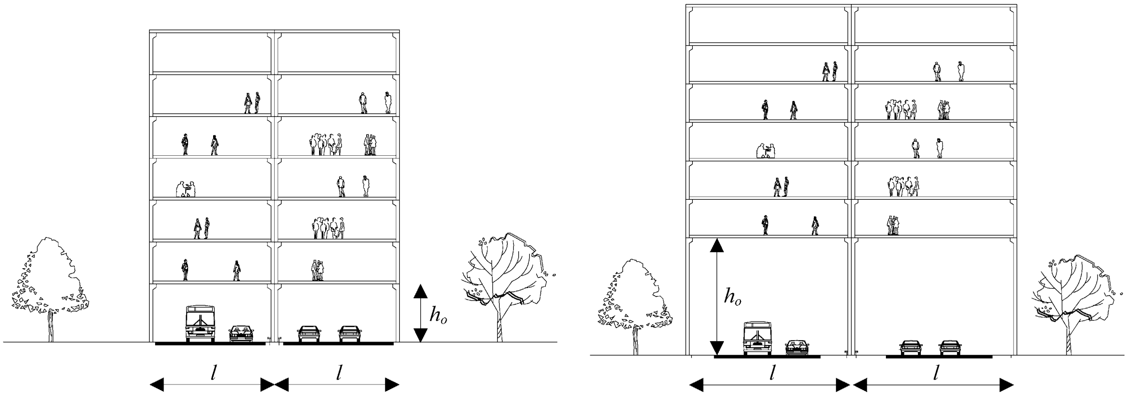

Fig. 13. The height of the lowest storey of the building and the width of the building: standard variant (left) and the variant with a higher lowest storey and a larger width (right).

Table 3
The effect of the covering length of infrastructure on the damage to the building above the infrastructure and the vicinity [7]

Covering length	Explosive materials	Release of toxic gasses	Collisions against structure building	Fires
Large: ratio $L/D > 10$	–	+	–	+
Small: ratio $L/D \leq 10$	0	0	0	0

regarding toxic gasses are, however, not seen by a small covering length of the infrastructure (Fig. 14).

In case of the prohibition of the transport of explosive materials, one can cover infrastructure for longer distances. When the infrastructure is covered for long distances by a building, some hazards can be limited to the covered infrastructure. In this regard, both the individual and the group risk for the surroundings can decrease in comparison to the building above infrastructure. Both the individual and group risk increase for the surrounding area at both ends of the building, which could be disturbing for buildings located near the tunnel ends. This decrease and increase must be compared with each other in order to determine whether the risk increases when building above infrastructure. An example of the shield that is formed by a covering of the infrastructure for toxic gasses is shown in Fig. 15. This is, however, not valid for small coverings.

5.4. *The effect of the height level of the infrastructure*

Four different levels of height for infrastructure can be distinguished: underground, subsurface, ground level and elevated. In Fig. 15, these different positions in height are drawn for railway infrastructure. The effect of the height of the infrastructure for the main scenarios is shown in Table 4. The higher the level of the infrastructure, the higher the risks for the building above the infrastructure. If the infrastructure is located underground, the effect of the hazards on the building and surroundings is much smaller than if the infrastructure is elevated (Fig. 16).

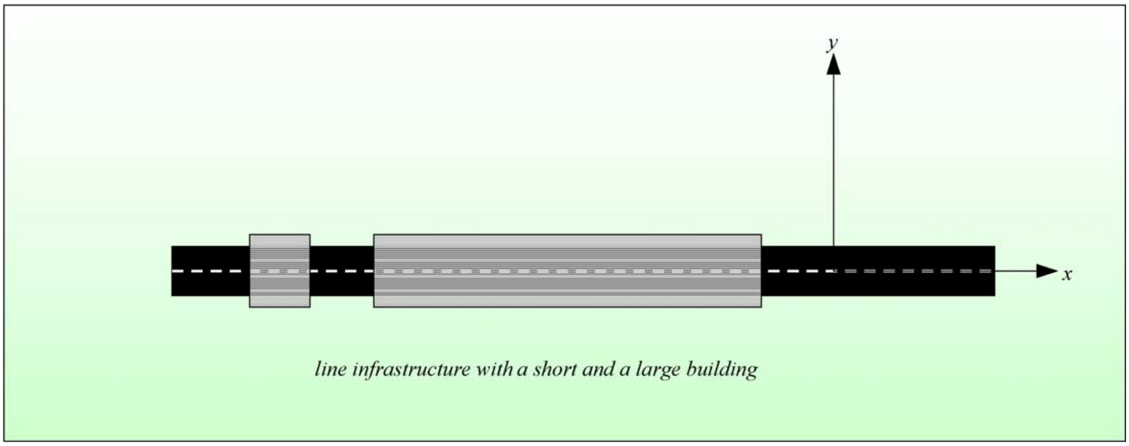

Fig. 14. A short (left) and a long (right) covering length of infrastructure.

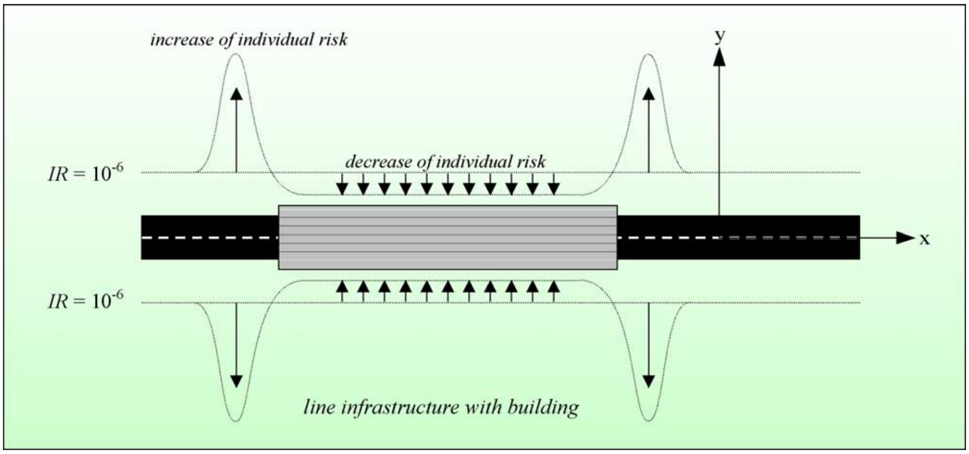

Fig. 15. Local decrease and increase of individual risk by enclosing infrastructure for toxic gasses.

Table 4
The effect of the level of infrastructure on the damage to the building above the infrastructure and the vicinity [7]

Level of infrastructure	Explosive materials	Release of toxic gasses	Collisions against structure building	Fires
Underground	0	0	0	0
Subsurface	+	+	0	0
Ground level	+	+	+	+
Elevated	++	++	+	++

6. Case study Bos and Lommer

6.1. Introduction

The Bos en Lommer office development is part of the development scheme, which centres on the Bos en Lommerplein and the surrounding area. The aim of this redevelopment programme is to span the gap between the eastern and the western flank of the A10 motorway and to provide the neighbourhood with a new heartbeat. The development lies close to the S104 exit on the A10 motorway to the west of Amsterdam. Accessibility by car, tram and train is excellent for this area. The buildings form a bridge between the eastern and the western side of the A10 ring road and comprise part of a plan for a new shopping centre with residential accommodation above. The focal point of the shopping centre will be the market square underneath, where an underground car park will be situated to serve shoppers and office workers. The buildings have a total floor space of 20,000 m^2 distributed over two buildings of six floors each of 9000 and 11,000 m^2, respectively. The fifth floor has been designed as a set-back level with balconies. Commercial functions were planned for the ground floor of the building first (employment agency, travel agents, etc.). The buildings line the outside of the bridge such that the motorway is less apparent on the section in between the buildings, so doing justice to the commercial activities on the ground floor. Large entrance halls finished in natural stone are sited at either side of the bridge, designed primarily in glass. The depth of the buildings is approximately 15 m (adapted from http://www.multivastgoed.nl). The construction of this project started in 2001 and was finished in end of 2003 (Figs. 17 and 18).

6.2. Input parameters

The covering length of the buildings is about 90 m [21]. Hoeksma [21] also presents some basic probabilities of

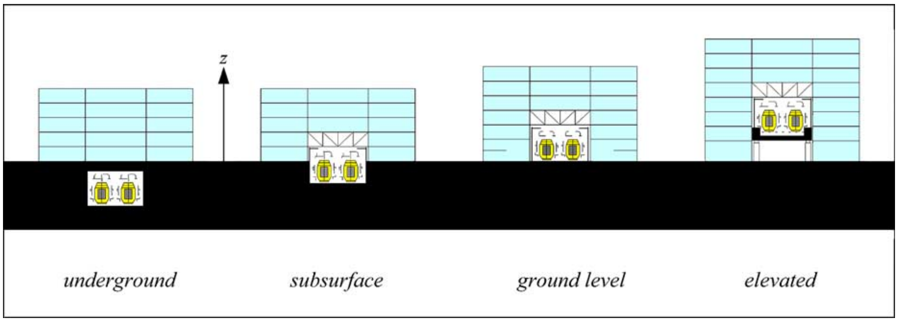

Fig. 16. Several height positions of infrastructure [12].

Fig. 17. Map of Bos and Lommer.

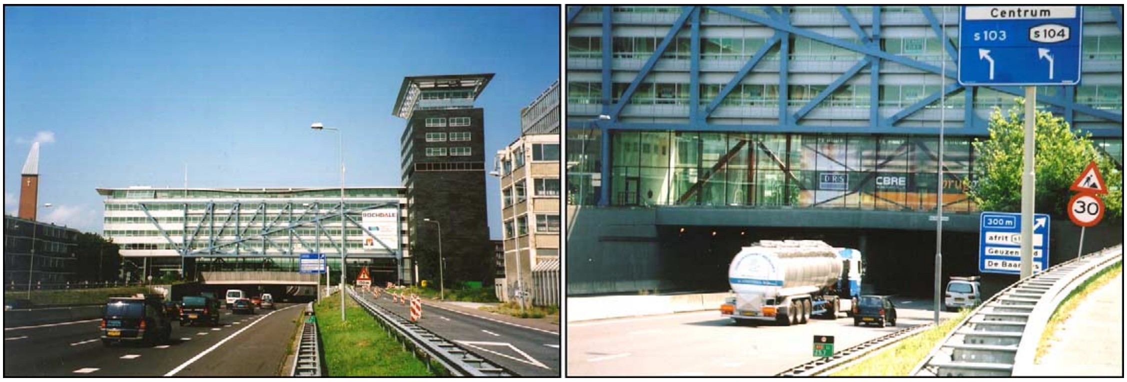

Fig. 18. An impression of the Bos en Lommer Office buildings with transport of hazardous materials.

events that may occur on the infrastructure. The number of vehicles passing per day is 159,000 of which 8% is heavy truck traffic. This means that the number of trucks passing per day is equal to 12,720 and thus 4,642,800 per year. In the analysis, it is assumed that 50% of the truck traffic is non-flammable. Furthermore, Hoeksma [21] provides the quantities of transport of hazardous materials in 1996, i.e. transport of flammable liquids: 12,438 wagons of fuel (heptane) and 24,063 wagons of diesel (pentane). According to Hoeksma [21], toxic liquids and toxic gasses are not transported. The transport of flammable gasses is set to be 3664. The average number of people working in these buildings is approximated 800 during the day. The study of AVIV [24] describes that the population density in the vicinity suffers from large fluctuations, from which the average population density for the vicinity can be determined: this is assumed to be about 5.0×10^3 persons/km^2. According to [24], the fraction of hazardous materials can be derived for the motorway A10 Bos and Lommer Amsterdam as well. Table 5 shows the quantity of transport of hazardous materials for the input parameters of the risk analysis. The suggested parameters will be used as input for the quantitative risk analysis. The result of the risk analysis is presented in the next section for the individual, group and economical risk. The input parameters for the QRA of Bos en Lommer are presented in Table 5:

6.3. Results risk analysis

The Bayesian network of three is used for the risk analysis. First, the individual risk, IR, is computed. Subsequently, the group risk, GR, is determined, from which the number of people killed $E(N_\mathrm{d})$ per year is derived. The consequences, C_fi, are assumed per scenario.

6.3.1. Individual risk

The individual risk can be divided into IR for people present on the infrastructure and IR above the covered infrastructure, which is about 2×10^{-5} and 2×10^{-6}, respectively (see Fig. 19). Table 6 presents the individual risk for the buildings above the infrastructure (per unit building), where the conditional probability of a person being killed due to an "average" scenario is presented.

This means that the risk slightly exceeds the criterion for the individual risk acceptance. From this, the schematic risk contour in the third dimension (see Section 3.1), can be depicted in the cross section. It is assumed that the shape of the contour is a rectangle.

Table 5
Input parameters for the case Bos en Lommer QRA

Input parameters for case Bos en Lommer	
Characteristics of the road	
Type of road	3 × 2 lane motorway
Number of vehicles passed per day	159000
Ratio of traffic type on the road	91% cars 8% truck traffic 1% busses
Transport of hazardous materials per year	36501 LF trucks 3664 GF trucks
Ratio transport of hazardous materials per year	0.122807 not hazardous traffic 0.729123 LF 0.14807 GF
Covering length (m)	79.5
Frequency of an accident	8.30×10^{-8}
Maximum people in the covered infrastructure	100
Characteristics of the building above the road	
Function of the building	Offices
Floor space of the buildings (m^2)	20000
Length of the building (m)	79.5
Width of the building (m)	85
Height of the building (m)	20
Maximum people in the building	800
Characteristics of the vicinity	
Population density (persons/ha)	50

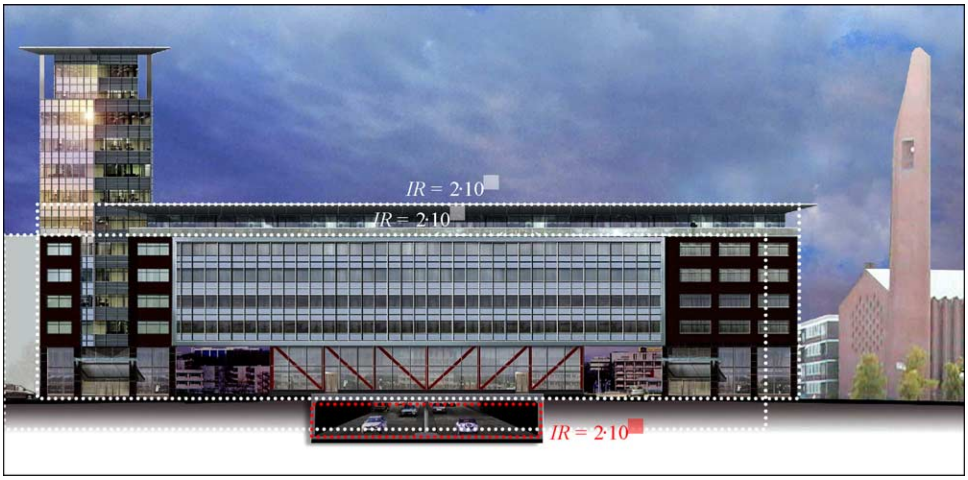

Fig. 19. The (schematic) IR contours in the third dimension for Bos and Lommer building (source artist impression: www.multivastgoed.nl).

Table 6
The individual risk (death/year/km) for Bos and Lommer

Covering length	80 m		
Scenario *i*	P_{fi}	C_{fi}	*R*
(1) Collisions with the structure of the building	1×10^{-6}	0.1	1×10^{-7}
(2) Fires	2×10^{-5}	0.07	1×10^{-6}
(3) Leak of toxic substances	0	0.5	0
(4) Explosions	3×10^{-7}	1	3×10^{-7}
ΣIR (per year/km)			2×10^{-6}

6.3.2. *Group risk*

Likewise, the group risk can be determined for the Bos and Lommer buildings. The FN-curve for this project is presented in Fig. 20.

6.3.3. *Expected number of people killed*

From the group risk, the expected number of people killed per year can be determined per risk category. The expected number of people killed per year $E(N_{\rm d})$, 1; $E(N_{\rm d})$, 2; $E(N_{\rm d})$, 3; $E(N_{\rm d})$, 4 are, respectively, 1.4×10^{-4}, 1.2×10^{-4}, 2.4×10^{-3} and 4.5×10^{-4}. The total expected number of people killed per year $E(N_{\rm d})_{\rm tot}$ is thus equal to 4.2×10^{-3}. Note that the $E(N_{\rm d})_{\rm tot}$ depends primarily on both risk categories 3 and 4.

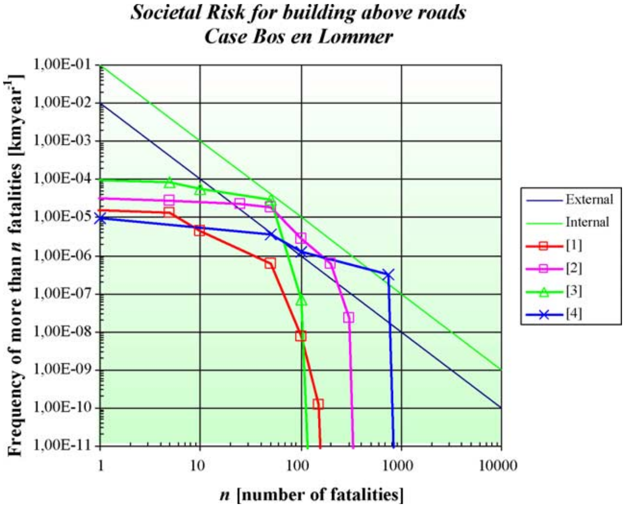

Fig. 20. The group risk for the Bos and Lommer building and the vicinity per risk categories 1–4 of Fig. 1.2 of chapter 1.

7. Conclusions and discussion

A three-dimensional risk assessment approach for both individual and group risk in the exploitation stage is highlighted in this paper. Without such an approach, quantifying the risks of the building over the infrastructure becomes almost impossible. Because in multiple use of space the building and the infrastructure (two different functions) are layered, a three-dimensional risk approach is an effective method to visualise the risks from the infrastructure to the building above the infrastructure and visa versa. The methods used presently by decision-makers for QRA are not applicable for layered functions and the risks for buildings above infrastructure cannot be expressed in the situation without taking the height into account. The method discussed in this paper enables the decision-makers to consider the risks in the height direction, perpendicular to the ground surface. The advantage of introducing the individual contours in the third spatial dimension is that effects of different hazardous materials can be depicted separately. The method shows that intensifying the use of space does not a priori mean that the overall risk will increase. The introduction of this methodology is an important contribution to the risk analysts and for engineers working in order to realise future multiple and intensive use of space projects.

Lack of spaces forces designers to explore the possibilities of building over infrastructure. Rules and regulations for the third dimension in risk analysis have, however, not been developed yet. Generally, accepted computer models for calculation of the risk also lack a three-dimensional approach.

The third dimension of the risk contour of infrastructure can be set up as a half cylinder. When this infrastructure is covered, the risk contour changes. The changes of the risk have been indicated for four representative calamities: fire, mechanical loads, toxic gas release and explosions. A possible collapse of the building is dominant in the risk analysis. If a collapse can be prevented, a covering of infrastructure can be safer for individual risk for surroundings and the building. Further development of the methods will enable a systematic a more appropriate evaluation of these risks than the flat plane approach, which is employed dominantly to date.

Appendix A

The input parameters for risk analysis model with the Bayesian networks of this paper are presented in this appendix. Details on these conditional probabilities can be found in the thesis of Suddle [7].

A.1. Basic conditions

A.1.1. Covering length of the infrastructure

Different covering lengths of the infrastructure imply different consequences. Accordingly, three different classes are considered as variable-outcome in the QRA, namely 30, 30–100 and 100–1000 m.

A.1.2. People present in different areas

First of all, people present in the covered infrastructure, the building above it and the vicinity depends on the time of the day and thus the time of the occurrence of an accident. The time of the occurrence of an accident can be divided into three classes: working hours, night and rush hours, following from the distribution per day, respectively, 0.3333 (8/24), 0.5834 (14/24) and 0.0833 (2/24) (Table A.1).

The number of people in the building above the infrastructure depends of course on the covering length (and the height) of the building, given a function of that building. For the considered case, the function of the building is set to be an office building and the height of the building is 50 m. For the number of people in the building above the infrastructure during the day, the distribution is presented in Table A.2. In the risk analysis, it is assumed that during the night, 1% of the persons in the building above the infrastructure are present (which corresponds with a office building).

The number of people present at the infrastructure (beneath the building) during the working hours and rush hours is modelled as presented in Table A.2. It is assumed that during the night, 10% of the number of people during the day is present in the tunnel.

For the considered case of chapters 3 and 4, the population density in the vicinity is set to be 7.5×10^3 persons/km^2.

Table A.1
Input parameters for the case of Section 3

Input parameters for case Bos en Lommer	
Characteristics of the road	
Type of road	2 × 2 lane motorway
Number of vehicles passed per day	1000000
Ratio of traffic type on the road	84% cars 15% truck traffic 1% busses
Transport of hazardous materials per year	36501 LF trucks 3664 GF trucks
Ratio transport of hazardous materials per year	0.14 remaining category 0.60 LF 0.05 LT 0.20 GF 0.01 GT
Covering length (m)	Variable (30, 100, 1000)
Frequency of an accident (vehicle/km)	8.30×10^{-8} (motorway) 3.60×10^{-8} (outside built-up area) 5.90×10^{-8} (inside built-up area)
Maximum people in the covered infrastructure	Variable
Characteristics of the building above the road	
Function of the building	Offices/residence
Floor space of the buildings (m^2)	Variable (5000, 20000, 200000)
Length of the building (m)	Variable (30, 100, 1000)
Width of the building (m)	20
Height of the building (m)	50
Maximum people in the building	Variable (200, 500, 2000)
Characteristics of the vicinity	
Population density (persons/ha)	75

Table A.2
The covering length of the building and the assumed number of people present in the building above the infrastructure and on the infrastructure, homogeneous distribution ($h = 50$ m)

	Covering length		
	0–30 m	30–100 m	>100–1000 m
Number of people present in the building above			
5–50	0.06	0	0
50–100	0.09	0	0
100–200	0.2	0.05	0
200–300	0.4	0.15	0
300–400	0.2	0.8	0.2
400–500	0.05	0	0.8
Number of people present at the infrastructure			
0–10	0.999	0	0
10–50	0.001	0.75	0
50–150	0	0.25	1

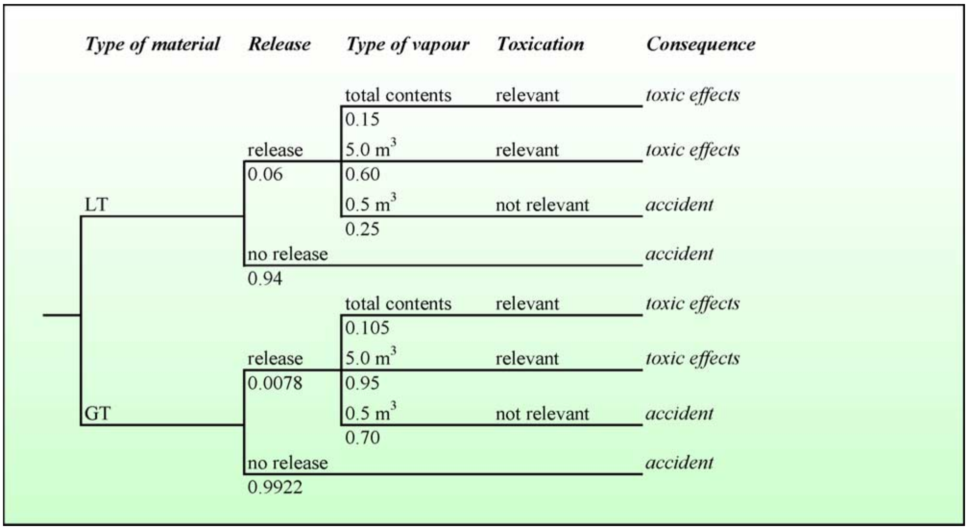

Fig. A.1. Following up scenarios and conditional probabilities of release of LT and GT [25].

A.2. Hazards

A.2.1. Following up scenarios of LT, GT, LF and GF

The following up scenarios of LT, GT, LF and GF can easily be found in literature (cf. [25]). The following up scenarios of release of LT/GT and LF/GF, which are given, respectively, in Figs. A.1 and A.2, are used in the Bayesian network model of Fig. 3.

A.3. Collapse of building above infrastructure due to critical scenarios

A.3.1. Covering length of infrastructure and the explosion scenario

Assumptions are made for conditional probabilities of the explosion scenario versus the covering length of the infrastructure (see Table A.3). Because marginal research has been

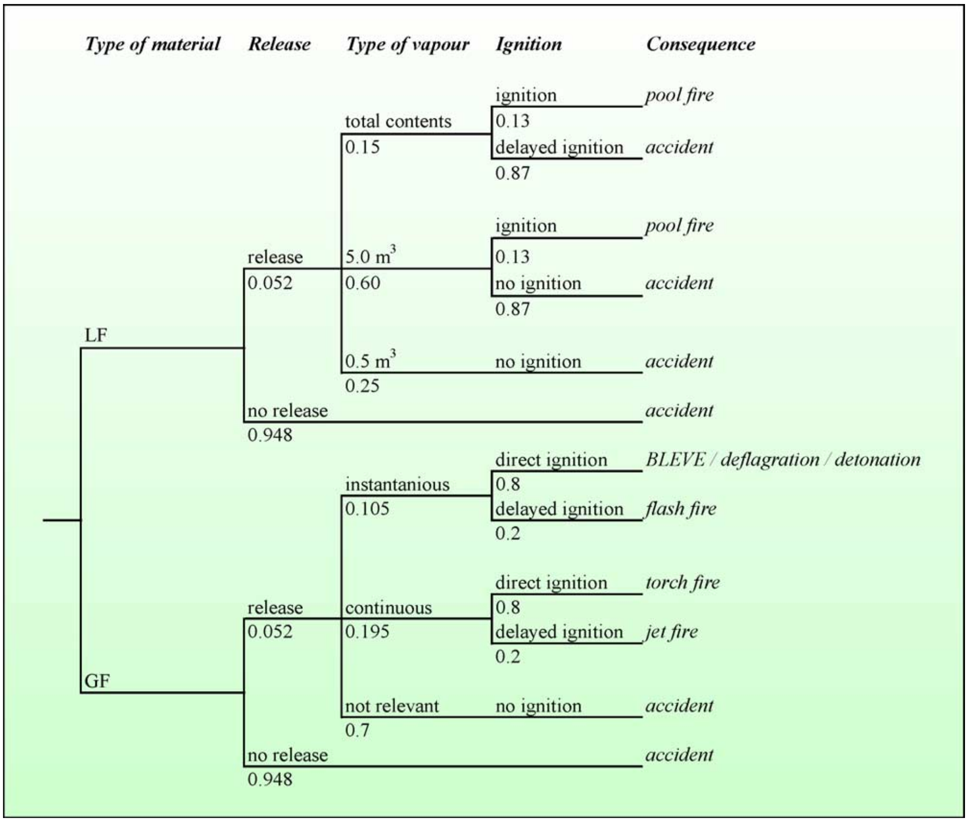

Fig. A.2. Following up scenarios and conditional probabilities of release of LF and GF [25].

Table A.3
The assumed conditional probabilities of the explosion scenario and the covering length of the infrastructure

Scenario	Covering length		
	0–30 m	30–100 m	> 100–1000 m
Deflagration	0.40	0.50	0.10
BLEVE	0.60	0.49	0.19
Detonation	0	0.01	0.71

Table A.4
The probability of fire occurrence in the building per year for different functions (adapted from Holborn et al. [27])

Purpose group	Probability of fire occurrence (year^{-1})
(1) Residential other	0.067
(2) Residential institutional	0.021
(3) Entertainment	0.0038
(4) Industrial and storage	0.0035
(5) Assembly and recreation	0.0077
(6) Shop and commercial	0.0030
(7) Office	0.0017
All	0.0038

Table A.5
Conditional (assumed) probabilities given the fact that a fire spreading to the building above the infrastructure from the infrastructure and visa versa

Fire on infrastructure	5 MW	20 MW	300 MW
P (no spread to building)	0.999	0.79	0.69
P (spread 5 MW)	0.001	0.20	0.2
P (spread 20 MW)	0	0.01	0.1
P (spread 300 MW)	0	0	0.01

done on this specific topic, these probabilities are determined by (in house) engineering judgement. According to Berg et al. [23], if the ratio *L*/*D* is more than 10, the probability of a detonation in the pipe/tunnel will increase rapidly. Berg et al. [23] does not provide specific conditional probabilities. In order to carry out a QRA, it is assumed that the probability of a detonation is much higher in case of a covering length of 1000 m, instead of a covering length of just 80 m. Additionally, it is assumed that the probability of collapse of the building above the infrastructure for the deflagration, BLEVE and detonation scenario is, respectively, 0.5, 0.95 and 0.99, since no probabilities were found in literature. Note that in order to determine these probabilities accurately, one should set up many scale models and conduct a lot of experiments, which is not the scope of this study. The obtained results from these scale models may differ totally, since one may also assume that the conditions for occurrence of a detonation are not easy to realise. These probabilities are particularly assumed for the set up of the QRA.

A.3.2. Fire in building and covered infrastructure and fire spread

The probabilities of fire on infrastructure due to an accident can be found in [26], which are presented in Fig. A.3, are used in the Bayesian network of Fig. 3.

The probabilities of fire occurrence in buildings per year, investigated by Holborn et al. [27] is used in the risk analysis model (Table A.4).

When a small or big fire occurs on infrastructure (under the building) as a consequence of an accident (with or without transport of hazardous material), it is important to know the probabilities of fire spread to the building and visa versa.

In Table A.5, the conditional probabilities are ranked per type of fire applicable for the risks that a building forms towards the infrastructure below, and visa versa. These

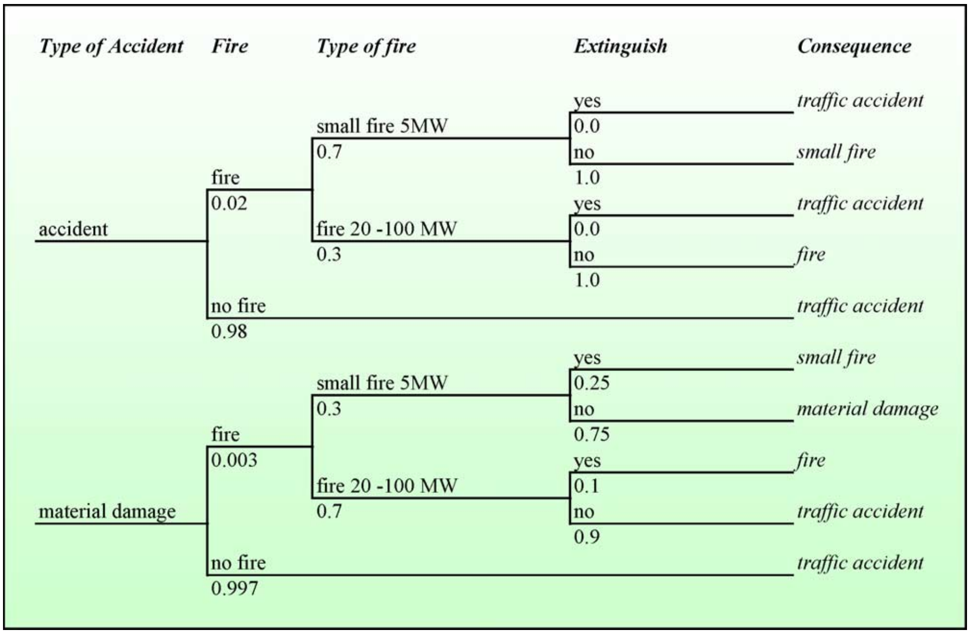

Fig. A.3. The probabilities of fire on infrastructure due to an accident [26].

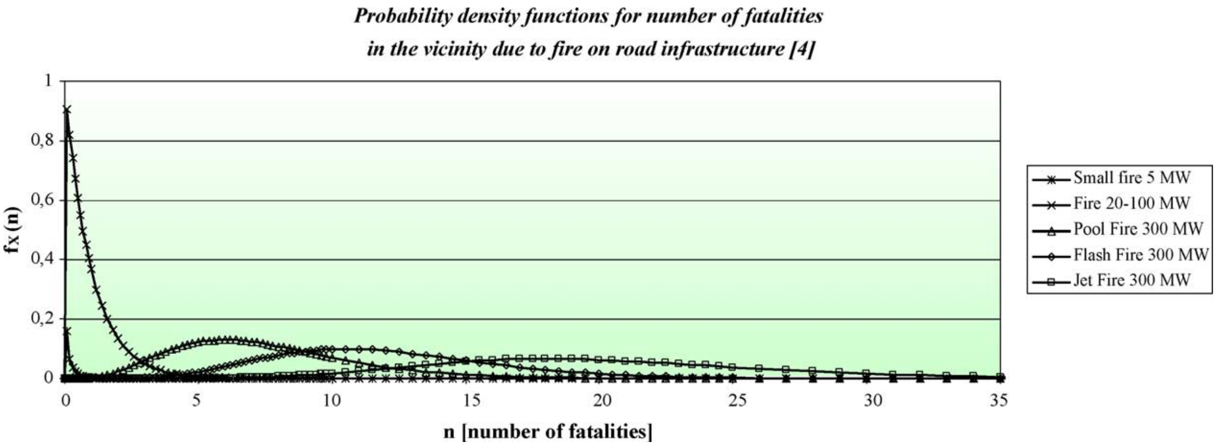

Fig. A.4. The assumed probability density functions for number of fatalities in the vicinity due to fire on the covered road infrastructure (population density of 7.5×10^3 people/km^2, risk category 4, adapted from Heilig [15]).

Table A.6
Assumed probabilities given the fact that the building collapses due to fire spread to the building above the infrastructure

Fire on infrastructure	5 MW	20 MW	300 MW
P (no collapse of building)	1	0.999	0.1
P (collapse of building)	0	0.001	0.9

probabilities are estimated for the QRA by engineering judgment. The assumptions about these probabilities are based upon the fact that the higher the intensity of the fire, the higher the probability that it will spread to higher storeys. Besides, high fire intensity spread can lead to a collapse of the building (Table A.6). Even low fire intensity on the covered infrastructure can grow to high fire intensity, since the building above the infrastructure can act as combustion material if the fire is not extinguished in time. Considering the scope of this study, this phenomenon is not considered in the QRA. The presented probabilities are taken into account in the risk analysis, even though the fire could spread to the whole building above the infrastructure. Note that, generally these probabilities depend on the geometry of the building.

A.3.3. Collisions affecting the main structure of building above

The assumed probabilities for the collapse of the building, given that the vehicle hits the main structure of the building due to an accident is assumed as presented in Table A.7.

Table A.7
The assumed conditional probabilities for the collapse of the building given a vehicle type (given that the vehicle hit the main structure of the building above the infrastructure)

Collapse/no collapse	Vehicle type		
	Cars	Truck traffic	Busses
P (no collapse)	1	0.99	0.999
P (collapse)	0	0.01	0.001

A.4. Consequences on infrastructure, building and vicinity

A.4.1. Fatalities

The fatalities in the covered infrastructure, the building above it and in the vicinity have been determined by a gamma distribution function per scenario by Heilig [15]. Heilig [15] presents the αs and the βs per probability density function per scenario. In order to determine the number of people killed in a specific area per scenario, the average number of people in the covered infrastructure, the building above it and in the vicinity has been determined, along with the effect distance of a particular scenario. An example of a gamma distribution function for the number of fatalities due to fire on the road infrastructure is presented in Fig. A.4.

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