Physical Safety

in

Multiple Use of Space

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Physical Safety in Multiple Use of Space

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This dissertation is dedicated to

my Beloved Grandfather Hazrat Baba-Ji Sakhi Saif Ullah Noori Al-Quadri Noshahi,

my lovely Father Sahibzada Inayat Ullah Suddle & my lovely Mother Razia Begum Suddle

You seek knowledge from books. What a shame! …
You are an ocean of knowledge hidden in a dewdrop.
(The Sufi Path of Love: The Spiritual Teachings of Rumi, pp. 64)

Contents

List of Symbols

$1 - F_N(n)$	=	complementary cum. distribution function in one year	[-]
α	=	monetary value per fatality	[cost unit]
α_j	=	(monetary) value per considered loss	[cost unit]
β_i	=	policy factor	[-]
$A_{building}$	=	the footprint of the building above the road	[m^2]
$A_{outside1}$	=	area of the risk zones	[m^2]
A_{person}	=	the area of the footprint of a person	[m^2]
γ	=	the slope of the *FN* curve	[-]
$C_0(y)$	=	the investment in a safety measure	[money]
C_f	=	consequence of the unwanted event	[fatalities or money]
C_{fi}	=	consequence of failure *f* as a result of an event *i*	[fatalities or money]
C_i	=	the (imaginary) acceptable probability for $n = 1$	[-]
C_j	=	damage cost in year *j*	[money]
C_{tot}	=	total costs	[money]
ΔC_{fi}	=	consequence reducing action	[fatalities or money]
D	=	average diameter of a tunnel	[m]
$E(N_d)$	=	is the expected number of people killed in one year	[-]
$E(N_d \mid \mathrm{F})$	=	expected number of fatalities given a failure in one year	[-]
f_N	=	probability density function	[-]
GR	=	group risk	[$year^{-1}$]
h	=	the height of the building	[m]

h_o	=	the height of the lowest storey of the building	[m]
IR	=	individual risk	[$year^{-1}$]
j	=	the number of the year	[-]
k	=	the risk aversion factor	[-]
l	=	the span of the building above infrastructure	[m]
L	=	covering length of infrastructure	[m]
M	=	(effect of) a safety measure	[-]
n	=	number of fatalities in one year in one accident	[-]
N	=	the number of people killed in one year in one accident	[-]
N_A	=	number of the independent locations	[-]
N_{pi}	=	number of participants in activity i	[-]
paX_i	=	parents of X_i	[-]
$P_{d\|fi}$	=	probability of being killed conditional upon the occurrence of event i and failure of the structure	[-]
P_f	=	probability of failure	[$year^{-1}$]
P_{fi}	=	probability of failure f as a result of an event i	[$year^{-1}$]
$P_{Fj}(y)$	=	the failure in year j	[-]
$P(D\|B)$	=	probability that D occurs given that B occurred	[-]
PLL	=	potential loss of life	[fatalities per year]
$P(N>n)$	=	probability of more than n fatalities in one year	[-]
ΔP_{fi}	=	probability reducing action	[$year^{-1}$]
QRA	=	quantitative risk analysis	[-]
q_{v10}	=	the q_{v10} ratio	[ls^{-1}]
r	=	real rate of interest	[-]
R	=	risk	[fatalities per year or money per year]
R_w	=	weighted risk	[$year^{-1}$]
ΔR_i	=	risk reducing effect of a measure	[fatalities or money $year^{-1}$]
SR	=	societal risk	[$year^{-1}$]
U	=	the entire domain of $\{X_1,X_2,\ldots,X_n\}$	[-]
(x,y,z)	=	Cartesian (rectangular) coordinates	[m]
y	=	decision parameter	

1

Introduction

1.1 Background and Research Problem

As a consequence of an ever-growing population, land is becoming more and more scarce, especially in urban areas. The economic growth causes additional pressure on scarce land. Therefore, a shortage of land across The Netherlands and in most countries of Western Europe 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 (VROM (2001)) a key concern is expressed: there is a need for space and spatial quality. Accordingly, future projects are to be realised within urban contours with the intent to utilise existing urban spaces more efficiently and effectively and at the same time providing better spatial quality. Therefore, the main strategies regarding space for future developments are *intensification, combination* and *transformation*. Projects of this nature arise from the lack of free building sites within inner city areas, and government policy dissuading construction outside city conurbations. Optimising the amount of buildings constructed within the city can save the limited green areas that remain. Apart from the expected commercial benefits of construction on prime city locations, multiple use of space has social benefits as well. Moreover, it adds spatial quality and has environmental advantages. However, the Dutch spatial planning policy, which aims to intensify the use of space, may come into conflict with the intentions set out in the Fourth National Environmental Policy Plan, which states that additional space is sometimes necessary to guarantee external safety.

Because the use of space is being intensified near locations where potentially dangerous activities are realised (e.g. industrial activities and transport routes or storage of hazardous materials), any accident may cause serious consequences (Ale (2003)). Besides, the protection of all members of the population in The Netherlands, which, as indicated in the policy document "Coping with Risks" (VROM (1989)), should be subject to a death risk of not more than one in a million (10^{-6}), has not always proved feasible in practice, as concluded in the document of RIVM (2003) "Coping rationally with Risks".

In order to control these risks, the Fourth National Environmental Policy Plan assumes that in such situations a choice must be made between spatial development, and accommodating the risk generating activity (V & W / VROM (2003)). As a consequence, the safety issue becomes an extra difficulty in The Netherlands. Unfortunately, several places are characterised by exceeding the acceptability and tolerability criterion of safety (RIVM (1998)), which can be a difficulty for the government and local municipalities. Remarkably, these areas, in which transport of hazardous materials takes place, are exactly the areas for which the Fifth National Policy Document on Spatial Planning of the Netherlands desires intensification, combination and transformation (encircled in figure 1.1). According to some studies (e.g. TCE (2003)), the transport of hazardous materials has continually increased over many years. Needlessly banning transport of dangerous goods may create unjustified economic costs (OECD (2001)). Moreover, it may force operators to use more dangerous routes - such as through densely populated areas - and thus increase the overall risk.

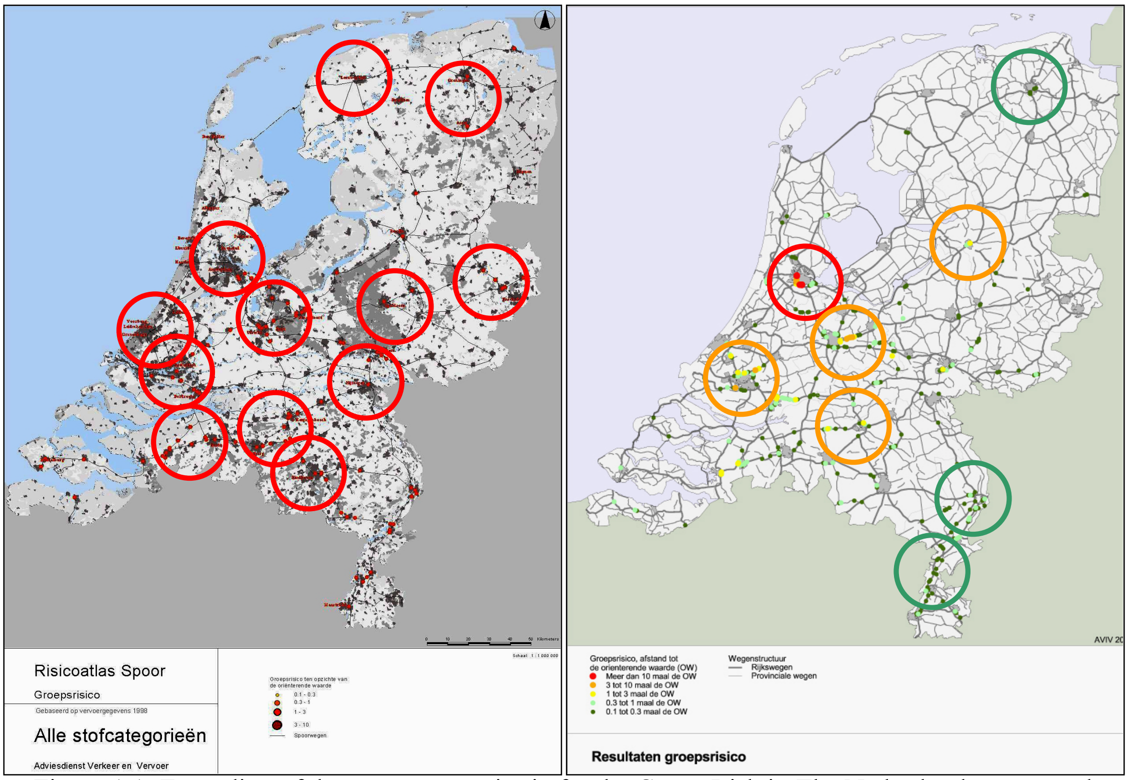

Figure 1.1: Exceeding of the acceptance criteria for the Group Risk in The Netherlands on several locations for railways (left) and roads (right) are encircled (Source: DHV and AVIV respectively).

Many international studies, for instance ARAMIS (Accidental Risk Assessment Methodology for Industries in the framework of SEVESO II directive), showed that the social relevance of safety and environment in relation with urban planning and the production and transport of hazardous materials is a national issue (see http://aramis.jrc.it).

Focussing on the locally project scale, it can be stated that that projects using land in multiple ways are generally complex. The safety considerations in multiple use of space projects should be considered as the utmost important issue and therefore should not be underestimated. Usually, a large number of people and several multiple risk interactions are involved. Due to the complexity and interrelationships of such a project, a small accident, like a fire in the building or on the covered infrastructure, 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 (Suddle (2002[A; E])). Aside from the safety considerations in such projects, there are more crucial points: engineering, finance and organisation (Wilde (2001)) on which little research has been undertaken (Wilde & Suddle (2002)).

Major accidents all over the world, particularly cases in which a great number of casualties were involved, have an influence on the perception of safety (Vlek (1995)). Calamities in The Netherlands - such as the Bijlmer plain crash in Amsterdam in October 1992, the explosion of the firework depot in Enschede in May 2000 and the fire in Cafe 't Hemeltje in Volendam in December 2000 - led nationally to both social and political disruption. Internationally, fires in tunnels and the attack on the WTC on September 11th 2001, increased the attention for safety and created a sensitised public opinion regarding safety issues. Hence, safety issues in multiple use of space projects are "double" sensitive and thus "double" important. At the same time, there is a growing awareness of the lack of knowledge on how to deal with physical safety in multiple use of space projects, especially in The Netherlands (Suddle (2002[C])). In this regard, a congress was organised at Delft University of Technology in July 2002 to map the safety issues in multiple use of space projects (Suddle (2002[C])). One of the main conclusions addressed the lack of knowledge on how to deal with physical safety in such projects.

Despite the unfamiliarity with safety issues, such projects have been realised in the past (Vamberský *et al.* (2002)). However, safety problems have occurred during construction (Meijer & Visscher (2001); Suddle (2001[A])). In the future, because of an increasing demand for space, buildings will often be realised above transport routes (of hazardous materials). Therefore, it is very important to develop a methodology for assessing and optimising physical safety in multiple use of space projects. For this to happen, it is essential to balance the effects and the costs of safety measures that may be applied in such projects.

1.2 Research Objectives and Scope of the Work

This overview sets out the main objective of the research underlying this Ph.D. thesis:

A framework for the design of physical safety aspects in multiple use of space projects.

From this, it becomes evident that defining *multiple use of space,* and both assessment, and optimisation of *physical safety* will play a central role in this work.

- *Multiple use of space*

So as to draw up the theoretical framework of this research, it is desirable to define the concept multiple use of space. Therefore, it is reasonable to go into the basic conditions of multiple use of space. What are the motivations for applying multiple use of space, despite the complexity of such projects? There are a range of definitions and types of multiple use of space. In this dissertation, multiple use of space is restricted to realising buildings above roads, railway tracks and existing buildings in already densely populated areas.

- *Physical safety*

Another significant element in the theoretical framework is the criteria for acceptability of risk, an expedient to objectify physical safety. When a risk assessment is done for the construction or exploitation stage, it is quite customary to have acceptability and tolerability criteria regarding risk. Besides, optimising safety implies that human risks may be compared with economical aspects. From an ethical point of view it is however not always possible to achieve this. Ethical problems can arise when 100% safety is not feasible from an economic point of view. It is therefore vital to describe different angles of safety (Suddle & Waarts (2003)), especially because safety is a wide notion.

In this research, physical safety aspects in multiple use of space will be assessed, rather than social safety aspects, which were executed by Durmisevic (2001) for spatial perception aspects in underground spaces. Additionally, in most studies (V & W (1997); VROM / V & W (1996); CIB (2001); Keulen *et al.* (2001[A & B]); Kleef *et al.* (2001); Kruiskamp (2002); MAVIT (2002); Frantzich (1998); Wiersma & Molag (2001)) physical safety is assessed for urban planning near hazardous installations and beside infrastructure or in either buildings or tunnels / underground spaces separately (two-dimensional safety system). However, neither studies nor methodologies can be found in literature assessing the physical safety and safety measures for combinations of buildings constructed over infrastructure - a three-dimensional safety system - in densely populated areas. It is surprising that most studies treat physical safety aspects separate from financial deliberations instead of discussing relations or comparisons between (non-)safety related aspects and economic consequences, all of which are strongly desired by decision makers. For this, it is essential to widen the knowledge of the safety element into multiple decision-making elements to optimise safety measures. Besides, on the basis of law there are no explicit norms for the safety of such projects (Suddle (2001[B])). So, one may conclude there is a gap in significant (scientific) knowledge about how to deal with physical safety in multiple use of space, even though it is necessary for decision makers, as well as for people involved in the design stage of such projects.

- *Optimisation*

The optimisation of physical safety can be considered to be the effectiveness of safety measures in multiple use of space. On one hand, an optimal level of safety is required, but on the other hand investments in safety measures, which reduce the risks of potential accidents, should be minimised. In order to compare different risks, such as investments, economical losses and the loss of human lives, in one dimension, both investments and risks could be expressed solely in money (Suddle & Waarts (2003)). However, ethical aspects are involved in such comparisons and should therefore be carefully considered. Only considering these ethical aspects is the proper way to validate decision-making about risks. In this thesis, the approach of the optimisation is not only based on effects of economical and human risks of measures, but also an integration of non-safety related aspects in these projects is desired. Therefore, these measures will be considered from different angles, such as the structural, functional and urban point of view.

The RIVM (2003) survey encourages four issues to cope with risks in a rational matter; (1) the cost-effectiveness analysis as the basis for ascertaining measure taking; (2) to consider the extent of voluntariness in the risk acceptance; (3) to draw the users into the discussion at an early stage and (4) the role of the scientist as a facilitator in stead of the mathematician. In this thesis, issues (1), (2) and (4) will serve as an instructional background when dealing with safety measures, since issue (3) is more a management action in practice and thus beyond the scope of this study.

Finally, it should be remarked that to present a framework of physical safety in multiple use of space as completely as possible, many scientific fields and disciplines in this research are taken into account i.e. urban development and planning, risk perception, psychology, chemical technology, toxicology, fire engineering, explosion engineering, impact mechanics, economics and so on. Unfortunately, calculations and estimations in this research contain many uncertainties in these areas and thus may contain large errors. It is often the lack of resources (time and money) that results in uncertainties, thus these are epistemic uncertainties and might be greatly reduced by increasing the resources. As was already noted, the results of this study may vary from calculations based on particular field researches. However, the purpose of this study is to research the combination of these fields in order to present an overall methodology, rather than research particular field objectives independently. Besides, the lack of expertise, time, and recourses makes the exact research in each field nearly impossible. If one likes, one may refine each field more deeply. This will be highly appreciated.

1.3 Method

In this thesis, probabilistic risk analyses will be undertaken to assess the safety level and to examine the required safety measures that are needed to realise these projects. When doing this risk analysis, the results have to be checked for compliance with the risk acceptance criteria. If the results do not comply with these risk acceptance criteria, to be divided into criteria on an *individual* and on a *social* basis, extra measures can be taken to reach a certain level of safety. These measures have to be economically viable (Suddle (2003[C])). Note that the risk acceptance criteria are targets, rather than the conditions to ensure complete safety. The risk analysis, which will be done for several case studies, should examine the construction stage and when the building is in use, for four different situations (figure 1.2) (Suddle (2002[G])):

- 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);
- 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).

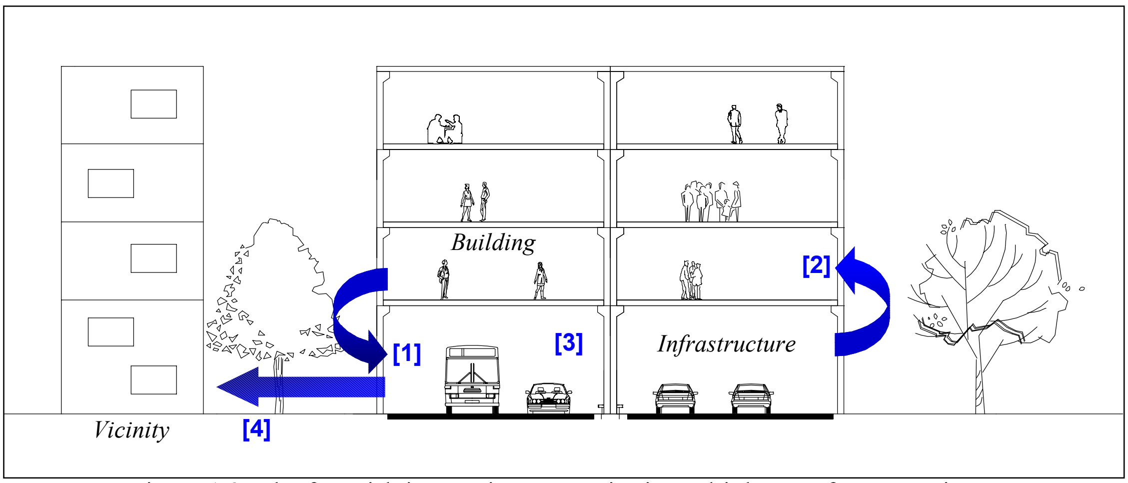

Figure 1.2: The four risk interaction categories in multiple use of space projects.

In order to determine the effect of formulated measures on both human and economical risks, one should integrate and verify these measures by this risk analysis. In general, these measures are implemented to reach a certain level of safety. This will be done for several case studies to verify the risk analysis models, and to determine the effectiveness of safety measures. These measures, which are normally part of the safety chain, will be integrated in the architectural and functional design of the building (if possible), while normal safety measures are only a cost-raising factor. From a decision point of view, it is a necessary strategy to balance costs and benefits of such measures and their contribution to physical safety.

Besides, the criterion for acceptability of individual or localised risk is usually depicted as contours on a - two-dimensional - map (Ale *et al*. (1996)). However, when doing risk analysis for multiple use of space, different functions are layered (Wilde (2002)), introducing a third spatial dimension (Suddle *et al*. (2004)). In this regard, it may be concluded that considering the limits for risk acceptance in multiple and intensive use of land, the third spatial dimension, when different functions are layered, will be treated.

Additionally, present risk analysis models, such as fault trees and event trees, that are mostly used for land use engineering (Berrogi (1999)), are sometimes not transparent for conducting risk analysis in multiple use of space. Therefore, in order to determine whether this will be well ordered, the performance of risk modelling with Bayesian Networks techniques will be explored. However, the Bayesian Networks have hardly been used for this purpose, until now. Friis-Hansen (2000), who used Bayesian Networks as a decision support tool in marine applications, showed the possibilities of the use and the effectiveness of such networks for risk analysis. Hence, risk analyses, which are performed in this research, are done with Bayesian Networks (using software HUGIN EXPERT 7.0), instead of traditional consequence and fault trees.

Finally, it should be noted that the risks of the demolition stage of the Life Cycle Analysis of multiple use of space projects are not considered in this thesis.

1.4 Outline of the thesis

The content of this Ph.D. dissertation is as follows:

Chapter 2 will give more detail on the background of multiple use of space projects. This chapter is concerned with the question why buildings are realised above roads, railways and existing buildings. This chapter forms the theoretical framework for this research.

Chapter 3 provides a theoretical background regarding the relation between safety and risk. In this chapter the relation and comparison between non-safety related aspects and risk is described. The criteria for acceptability and tolerability are formulated and compared with economical aspects. In this chapter, different risk analysis models will be described.

Chapter 4 deals with a methodology for the assessment of safety during the construction stage using Bayesian Networks. In this chapter, the aspects that mainly influence the safety during construction and the risk assessment of third parties of such projects are analysed. Furthermore, some safety measures for the construction stage are proposed, and their effect on safety and economical risks is shown.

In *Chapter 5* the level of safety during the exploitation stage is examined by a probabilistic risk analysis using Bayesian Networks and checked for compliance with the individual and societal risk acceptance criteria. The third spatial dimension is worked out for both individual and group risk in this chapter. In this chapter, human risks are analysed and compared with economical aspects as well.

Once an image of the safety system is obtained, safety measures can be formulated and their effect can be determined within the risk analysis (*chapter 6*). It is interesting to see which kind of measures are effective on safety and economical aspects and how the relation between human risks and economical aspects can be constrained.

Chapter 7 gives an overview of how to deal with these measures in such projects and how and to weigh them with non-safety related elements. In this chapter, two case studies are analysed on this point. First, the buildings over the motorway A10 West, Bos en Lommer in Amsterdam, are analysed. Second, the tunnelling and covering of the railway track in Delft is studied.

Finally, *chapter 8* contains an overall conclusion of the study as well as recommendations for further research, which are based on the obtained results.

In figure 1.3, an overview of the outline of the thesis is given. The figure also shows the relation between the chapters.

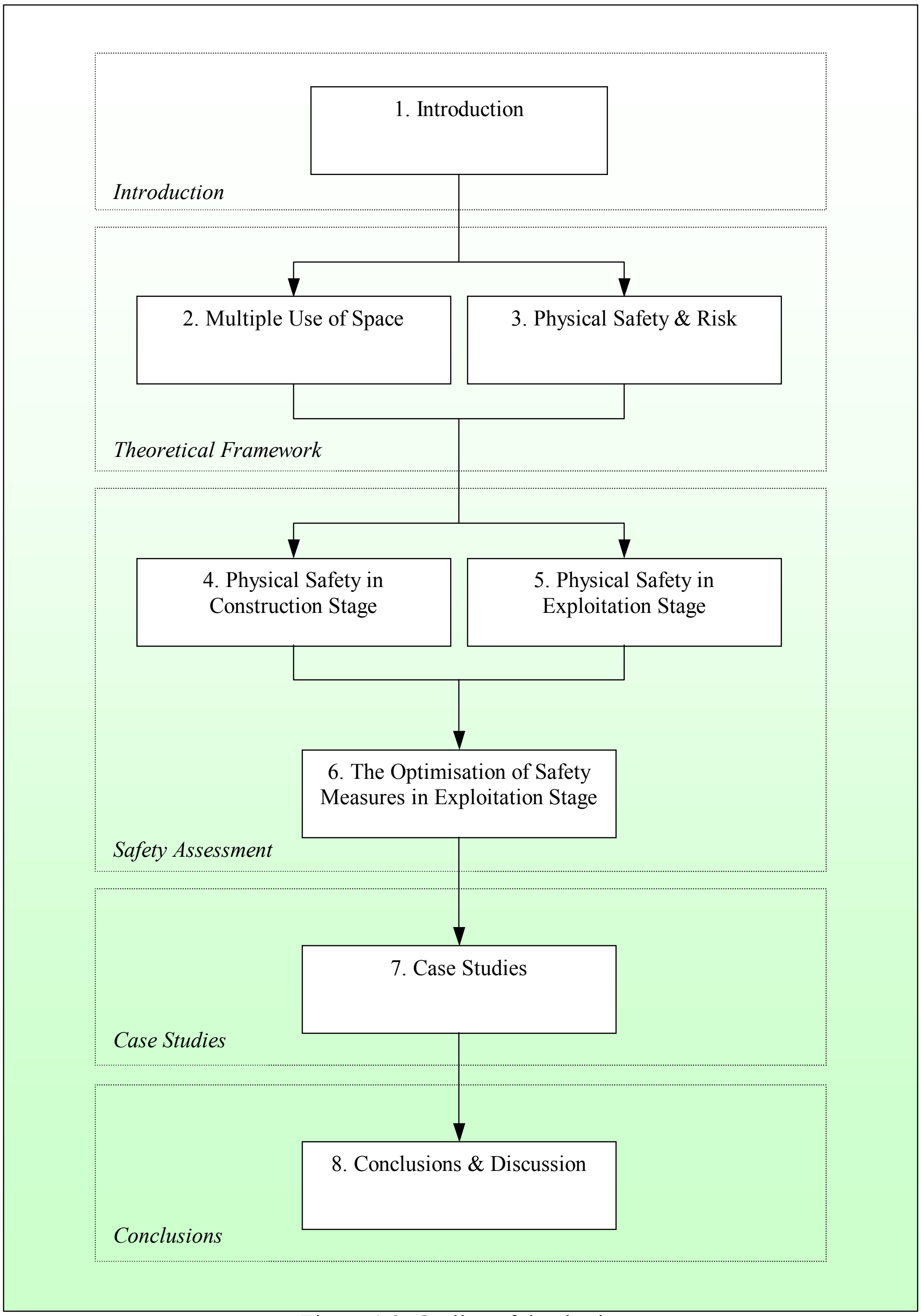

Figure 1.3: Outline of the thesis.

2

Multiple Use of Space

The combination of growing prosperity and the awareness of spatial quality leads to a rising need for space. Intensifying the available space by means of multiple use of space, is one solution to satisfy and fulfil this need (Jansen & Südmeier (1999)). There have already been a number of different multiple use of space projects realised in The Netherlands. Buildings above roads, railway tracks and existing buildings are examples of such projects. It is, however, not likely that the concept of multiple use of space is automatically applied, particularly not in urban areas that are not featured by the lack of space. Still, examples of such projects can be found in some cities across Europe. Having this all in mind, the following question arises: Under which condition is the concept of multiple use of space applied in certain cities across Western Europe? In this chapter, the main question is treated from the perspective of both lack of space and its quality in urban areas.

2.1 Driving forces behind multiple use of space

In order to answer the question, why multiple use of space has been applied in some cities, one has to focus on the driving forces behind multiple use of space. Priemus *et al*. (2000) and Harts *et al*. (1999) took three scenarios for future social decors into account; Divided Europe, European Co-ordination and Global Competition, following from studies of CPB (1997). These scenarios differ from one another by the input for the driving forces with regard to demographic, socio-economic, socio-cultural, technological and environmental developments. These driving forces are basic ingredients for the application of the concept multiple use of space (Priemus *et al*. (2000) and Harts *et al*. (1999)).

According to Hooimeijer *et al.* (2001) multiple use of space is associated with spatial quality, a definition of a subjective perspective (table 2.1). Hooimeijer *et al.* (2001) suggests that spatial quality depends both on social interests and aspects of spatial quality. In addition, all parties concerned have their own conceptions about spatial quality. This means that spatial quality is a debatable performance criterion.

Table 2.1: Spatial quality depends both on social interests and aspects of spatial quality (Hooimeijer *et al.* (2001)).

Aspects of spatial quality	**Social interests**			
	Economical	**Social**	**Ecological**	**Cultural**
Users value	Allocation-efficiency Accessibility External effects Multi-purpose	Access Distribution Interest Choice	Safety, Nuisance Dry out Shred	Freedom of choice Variety Meeting
Experience value	Image Attractiveness	Inequality Solidarity Safety	Space, calmness Beauty Health	Singularity Beauty Contrast
Future value	Stability / flexibility Agglomeration Cumulative attraction	Surrounding Cultures of poverty	Supplies Ecosystems	Heritage Integration Renewal

The aspects of spatial quality, presented in the matrix above, join social interests with design requirements; demand of space is a balance between economical, social, ecological and cultural interests (Perrels (1999) & Puyleart (1999)). The social interests suggested by Hooimeijer *et al.* (2001), are roughly the same as the driving forces behind multiple use of space. In order to realise multiple use of space projects, a governmental stimulation, which depends on cultural aspects (Wilde (2002)), is preferable (see section 2.3.5). The (local) government can contribute to the quality of spatial structure. Yet, this quality mainly depends on the market.

According to Chapin & Kaiser (1979) and Vliet (2000), the market consists of an *activity system*, a *developing system* and an *environmental system*. The government can be considered to be a part of this market. Actors of the *activity system* determine the demand of space. Individuals, companies, and governmental sectors are the actors of the activity system. Actors in the *environmental system*, such as biotic and a-biotic processes in nature, determine the supply of space. The *developing system* generates spaces to be developed for use. Multiple use of space can be considered as a part of this market. In that respect, the developing system functions as a tool for equilibrium between demand (activity system), and supply (environmental system) of space. Basically, spatial planning depends on the political planning process, which controls the use of space to serve the public interests in The Netherlands (Vliet (2000)).

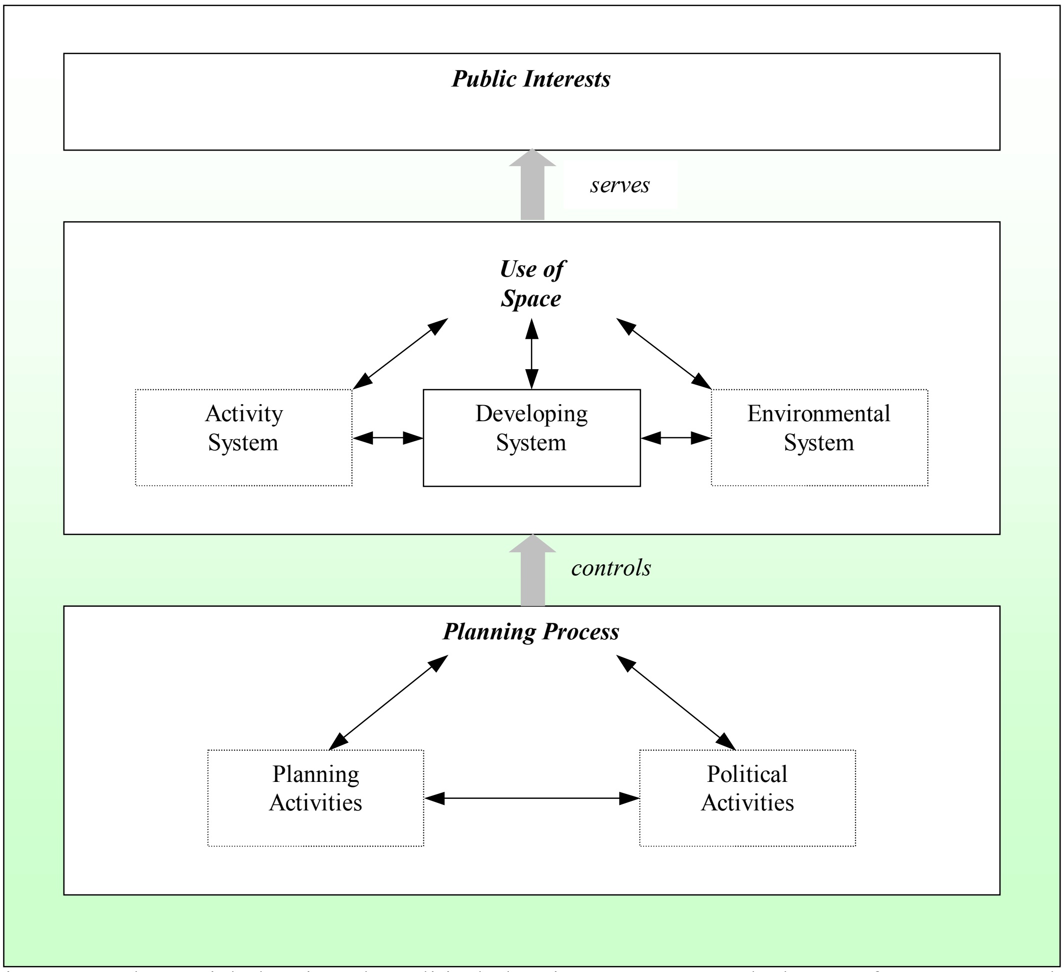

Figure 2.1: The spatial planning: the political planning process controls the use of space to serve the public interests (Vliet (2000)).

2.2 Examples of multiple use of space projects

2.2.1 History of multiple use of space projects

Examples of multiple use of space projects can be found all throughout history. The Ponte Vecchio (1245 - 1335AD) is one great example of such a project, where buildings were constructed on the bridge crossing the river in Florence (Italy). All through the centuries, city centres have been featured by a shortage of space. As a result of accelerating developments in city centres, this shortage has rapidly increased. Nowadays in The Netherlands e.g., one demands different quality aspects of space as well. Therefore, it is preferable to realise projects at attractive locations in city centres. Hence, realising buildings above roads, railway (stations) and even existing buildings is an option to satisfy both the demand of spatial quality and the lack of space in city centres. These developments will be treated in the following sections.

2.2.2 Buildings above roads

In The Netherlands, several multiple and intensive use of space projects have already been completed (see e.g. VROM (2000[A & B]); www.multiplespaceuse.com).

Examples of such projects are the buildings situated over the motorway ”Utrechtse Baan” in The Hague and The NewMetropolis in Amsterdam. Both examples were developed because of a lack of space in the city. Besides, the motorway Utrechtse Baan was an obstruction in the inner city, dividing the city into two parts. After the realisation of buildings over the Utrechtse Baan these divided parts were connected again.

Figure 2.2: Buildings situated over the motorway in The Netherlands; the ”Utrechtse Baan” in The Hague (left) and NewMetropolis in Amsterdam (right).

2.2.3 Buildings above railways

In Rijswijk, an office building and a residential building have been constructed over the railway. Since the railway divided the city into two parts, Rijswijk station was developed and realised to solve this problem. Besides, the tunnelling and the covering of the railway track resulted in a reduction of noise hindrance, which was a barrier to people who lived near the railway track. Applying multiple use of space contributed to spatial quality as well. If more buildings are realised above and near railway tracks, public transport can (locally) be stimulated (Wilde (2002)).

Figure 2.3: Railway station Rijswijk in The Netherlands covered by buildings; residential building (left) and an office building (right).

2.2.4 Buildings above buildings

Two examples of buildings realised above existing buildings can be found in Rotterdam and The Hague. In Rotterdam, the World Trade Centre has been constructed above an existing hall. The WTC was realised because of the combination of, lack of space, and a unique possibility to be established in the city centre. Similarly, in The Hague, the Dorint Hotel was built above the existing Congress Centre, because the owner of the Congress Centre decided to do this at a later stage, during the exploitation stage of the Congress Centre.

Figure 2.4: Buildings realised above existing buildings in The Netherlands; the World Trade Centre in Rotterdam (left) and Netherlands Congress Centre in The Hague (right).

2.2.5 Multiple use of space in Europe

Projects, which apply multiple use of space are also seen created in Europe, America and Asia (www.multiplespaceuse.com). An example of such a project in Europe is presented in figure 2.5. In Europe, many projects are realised above motorways and railway stations. An example of this is: in the UK, where several railway stations are covered with buildings. Considering the growth of the world population, one may expect that in the future, the lack of space will enlarge all over the world. Therefore, such projects will exist more often in the future.

Figure 2.5: Multiple use of space projects: Building above railways in Rive Gauche, Paris, France (left) and building above roads in London, United Kingdom (right).

2.3 The concept multiple use of space

2.3.1 Introduction

Kreukels & Vliet (2001) conclude in their international study about multiple use of space, that an absolute and even a relative lack of space, except in few urban areas, is not decisive for applying the concept of multiple use of space. This study also presents the fact that a specific quality is characteristic for each country; in The Netherlands, significant importance is attached to spatial quality resulting in a lack of space.

One may assume that both quality and quantity of space is different for each country. The combination of quality and quantity of space can be regarded as *spatial perception* (Suddle (2002[F])). Moreover, factors such as economic, cultural, social and environmental aspects are main factors influencing the application of multiple use of space (Nijkamp *et al*. (2003)). According to Kreukels (1997) and Kreukels & Vliet (2001) major issues for multiple use of space are:

1. Economic, social and ecological values or combinations of these values are decisive for the inception of efficient and multiple use of space;
2. These economic, social and ecological standards or combinations of them are decisive for cultural and social values of the users and for private parties in real estate and the infrastructure sector;
3. A (national and local) government can be an initiator of multiple use of space projects.

2.3.2 Multiple and intensive use of space

The multiple use of space has been characterised with several descriptions and views (Jansen & Südmeier (1999); Priemus *et al*. (2000); Harts *et al*. (1999); Vliet (2000); Wilde (2002); Hoeven (2001); VROM (2000[A]); Nova Curra (2000); Delft *et al*. (2000); Nijhof (1998)). In order to analyse multiple use of space in objective and technical terms, Wilde (2002) restricted these definitions as following:

- 2nd dimension: mixed use of space; different functions next to one another in a particular space;
- 3rd dimension: multiple use of land; different functions layered in a particular space;
- 4th dimension: multiple use in time; a set amount of floor area is used for different functions at different points in time.

Intensive use of space can be measured by density, like the amount of floor area that is realised per km^2 of building surface. Projects of intensive use of space do not automatically include multiple use of space. Intensive use of space is furthermore partly defined by culture. Dobbelsteen & Wilde (2004) presented the restricted and technical definitions in the following relations:

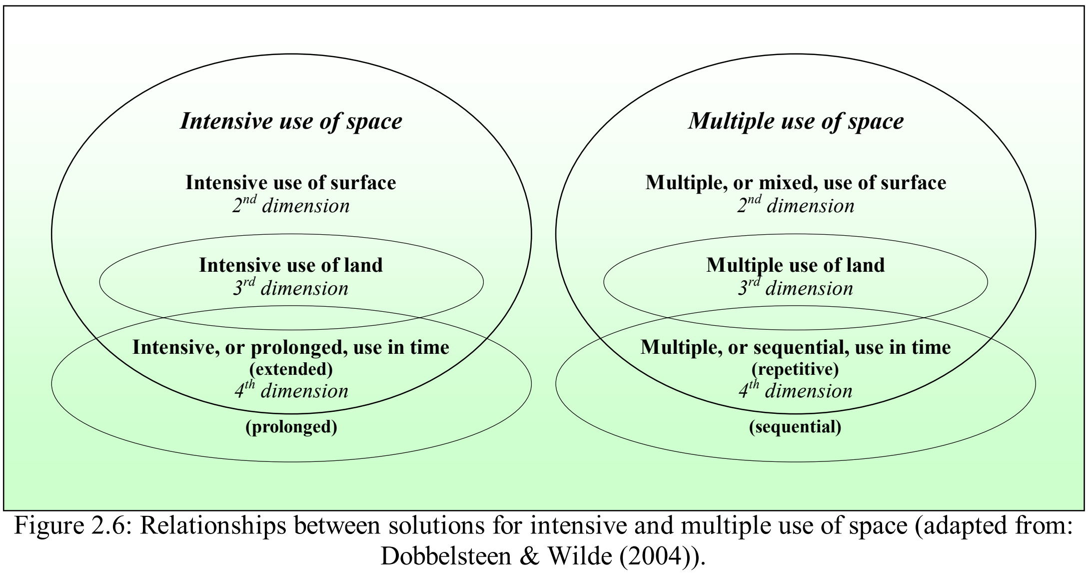

Figure 2.6: Relationships between solutions for intensive and multiple use of space (adapted from: Dobbelsteen & Wilde (2004)).

When considering multiple use of land (multiple use of space in the 3rd dimension), variations in covering the infrastructure originate from the footprint of the building (short or long covering length) and several height positions of the infrastructure (see figure 2.7 and figure 2.8). The footprint of the building over the infrastructure is depicted in the infrastructure direction x and the perpendicular direction y. The height is presented in the z direction, in which four different levels of height for infrastructure can be distinguished: underground, subsurface, ground level and elevated (Wilde (2002)).

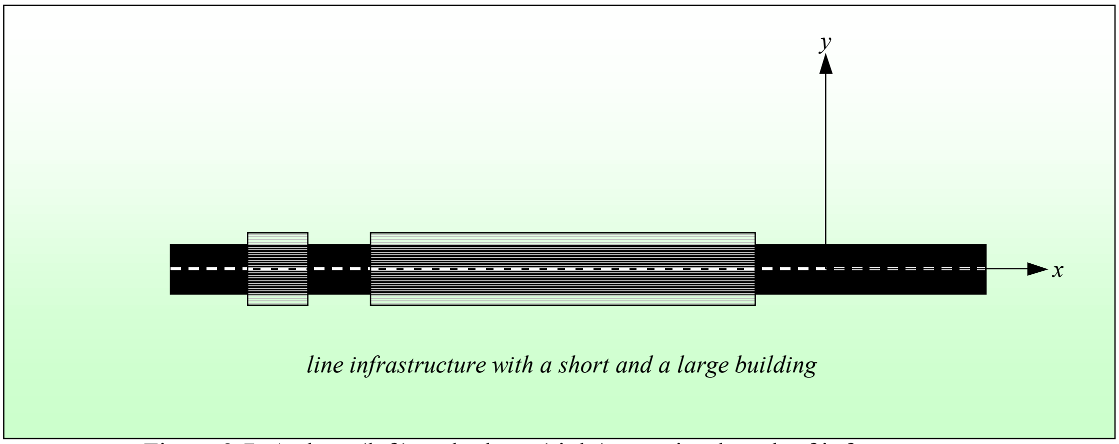

Figure 2.7: A short (left) and a long (right) covering length of infrastructure.

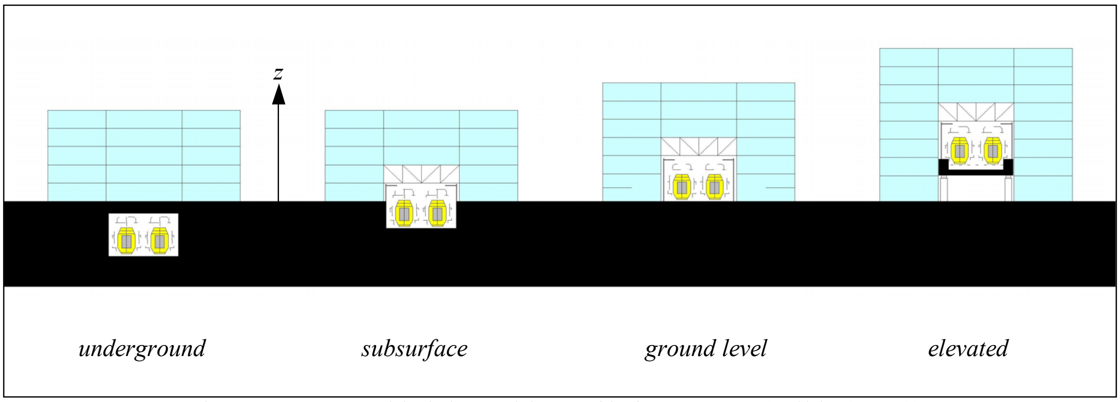

Figure 2.8: Several height positions of infrastructure (Wilde (2002)).

2.3.3 *Model for the applying of multiple use of space regarding spatial perception*

Considering the previous traditional theorems regarding multiple use of space, a model for the concept multiple use of space regarding spatial perception can be deduced (figure 2.9). When considering spatial perception, this model gives an approach of "when the concept is applied in certain cities". An extensive description of this model is presented in Suddle (2002[F]). First, the model starts with social interests and developments, which can be divided into terms of economic, ecological, cultural or social, on a national scale, as mentioned by Hooimeijer *et al.* (2001) (see section 2.1). Mostly, these developments are combinations of each other. In terms of both quality and quantity of space, these developments determine the demand of space locally, which can be considered as *spatial perception* specific for each country. Quality of space concerns the spatial demands set on the quality of the maintained space, which is actually the early mentioned environmental system. Quantity of space contains the available and undeveloped land in urban areas, which can be used for multiple use of space.

In case of an insignificant demand for space, one will not apply multiple use of space; therefore it is not of importance. But if the demand for space is high, one will reconsider space in urban areas. When reconsidering the space in urban areas, four types of scenarios for redivision of space are possible. Private parties, such as real estate developers and parties from the infrastructure sector, and the national and local government determine these scenarios for redivision.

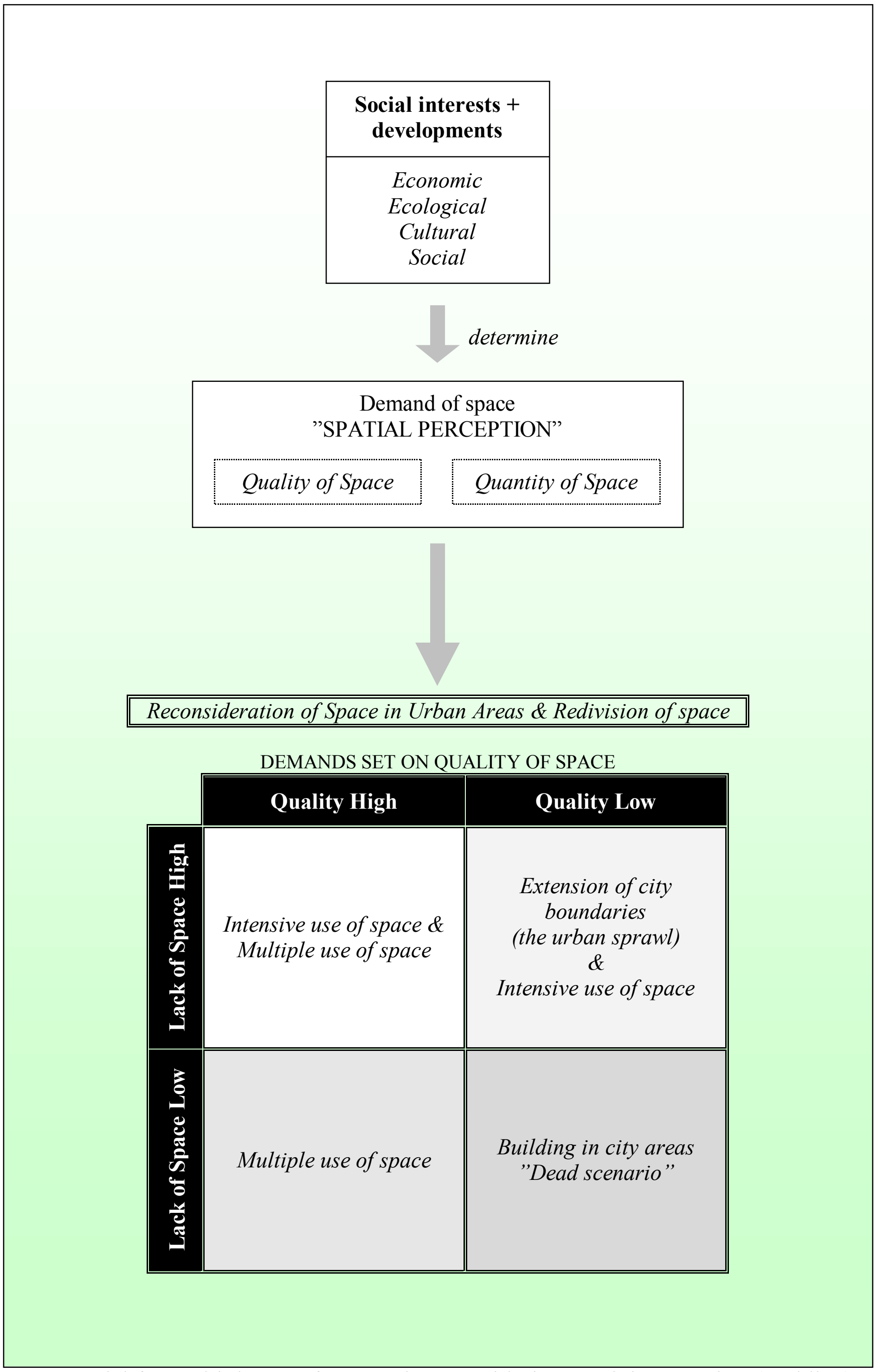

Figure 2.9: Model for multiple use of space when considering spatial perception (Suddle (2002[F])).

2.3.4 Scenarios for the redivision of space

When descriptions about space and the possible scenarios are considered from a *spatial perception* point of view, one may define and tackle the reconsideration of space in urban areas as follows:

1. *Demands set on quality high, and lack of space high*: This scenario is characterised by high demands sets on quality and a lack of space. Such circumstances will often appear in the future. This scenario is featured by a real lack of space in urban areas. Consequently, one will utilise the available space effectively and efficiently. Intensifying the available space is an option to solve the problem of high lack of space by means of high-rise buildings. If this is not possible, one can apply the concept of multiple use of space. Realising projects in the 3rd dimension (multiple use of land) is a logical solution and could therefore be more than attractive. As a consequence, the available space will be used intensively. Examples of such project are buildings realised over the Utrechtse Baan in The Hague.

2. *Demands set on quality high and lack of space low*: According to this scenario, multiple use of space will not appear automatically, because there is no sign of lack of space in urban areas. Yet, one attaches great significance to both aspects of spatial quality and the question about the redivision of space. As mentioned earlier, typically, there are examples of projects in which multiple use of land is applied in case of no lack of space. The reasons for applying multiple use of space in such circumstances could be; prestige, accessibility, attraction, local interests, or ambition. This scenario demonstrates that a lack of space is not always the reason for applying multiple use of space. All types of multiple use of space are possible for application. If one switches over to the 3rd dimension of multiple use of space, it will be realised purely for prestige and a (local) economic, sustainable city (Dobbelsteen *et al.* (2002)), social and physical interests and benefits. An example of such a project might be the Buraj Al Arab Hotel in Dubai (United Arab Emirates).

3. *Demands set on quality low and lack of space high*: This scenario also regards a real lack of space in urban areas. However, the spatial quality is insignificant and the social interests are subordinate as well. Hence, one will reconsider land at the boundaries of the city and one will continue constructing new projects at the boundaries of cities, also called ”urban sprawl”. In some cases, if one likes to develop in urban contours, one may consider to intensify the available space by e.g. high rise buildings.

4. *Demands set on quality low and lack of space low*: This scenario can be called the ”dead scenario” in which nothing remarkable will happen. One can build anywhere. After all, there is land enough and the economic situation of the country is below the normal level.

One has to consider that these scenarios are not the only basic motivations for the application of multiple use of space. The analysis should be combined with social, and economical values and developments of a considered area.

2.3.5 Parties and government

Obviously, multiple use of space is not only a matter of spatial perception. A large number of actors are involved by reconsideration and redivision of space in urban areas. Parties and the governments are the two main actors playing an important role when sentiments of social developments and an increasing demand of space can be found. These private parties originate from the developing system (see section 2.1).

When reconsidering space in urban areas, these real estate parties could gain profits, so they can make pre-investments, while parties of the infrastructure sector have to make investments. In order to initiate such large-scale and expensive projects, the government should act as a catalyst in this process by initiating and facilitating the projects (Wilde & Suddle (2002)). The national government can desire space and spatial quality, e.g. the Fifth National Policy Document on Spatial Planning of the Netherlands (VROM (2001)). The local governments, such as municipalities, benefit from the position of its city being strengthened internationally and a certain level of urban vitality is provided by means of redeveloping their inner city efficiently. The main purpose of realising such a project is, in principle, to stimulate local economic, social, ecologic, and cultural advantages. In addition to these advantages, one can increase spatial quality. Subsequently, social developments can make progress.

2.4 Critical issues multiple use of space

Realising projects, which carry out the concept of multiple use of space, especially the 3rd dimension, i.e. building over roads, railways and existing buildings, is extremely complicated. The critical issues in such projects can be subdivided into four different categories (Wilde (2001): (1) engineering; (2) safety; (3) finance; (4) organisation. Multiple use of space projects can only be realised successfully, if these categories are managed in detail (V & W (2001); Tanja & Wijnen (2001)). If one pays attention to aspects of engineering, safety, finance and organisation during the design process of a project, one may avoid problems during both the construction and the exploitation stage. Regarding the complexity of multiple use of space projects, one can assume that building above infrastructure is expensive. Financial support may be recommendable for the stimulation of such projects. The organisation of such projects is difficult as a result of several participants involved in such projects. Engineering such projects is rather complicated, because no standard structures can be applied and construction techniques differ from normal projects (Alphen & Vamberský (1999)). Moreover, it is recommendable that the infrastructure below the building must be maintained in use during the construction stage.

2.5 Conclusions

This chapter illustrates the application of multiple use of space regarding spatial perception in Western Europe, which can be divided into the quality and quantity of space. It may be concluded that a lack of space is not always the reason for applying multiple use of space (Kreukels & Vliet (2001)), a large range of motivations may lead to multiple use of space projects. One may consider that applying multiple use of space is a solution to many obstructions in cities; it is an effective instrument to add to sustainability (Wilde (2002); Dobbelsteen *et al.* (2002)). Synergistically, an additional advantage of multiple use of space near railway stations can be the stimulation of public transport (Wilde (2002)). Multiple use of space provides (local) economical improvement (Priemus *et al.* (2000)), also including cultural, social and environmental improvements. Remarkably, these are also the driving forces behind multiple use of space. One should note that realising such projects e.g. constructing buildings over roads, railways and existing buildings, is extremely complicated. The critical issues of such projects, which are of significant importance, have been outlined. One of the prime considerations of these projects is the safety issue, which will be treated in the next chapters of this thesis.

3

Physical Safety

Safety, and risk assessment are characterised by aspects, like subjectivity and objectivity. In this chapter, relations between safety and risk are described. Risk analysis is an important tool to quantify risks objectively. An essential element in risk assessment is risk evaluation. When a risk analysis is performed, it is important to realise that decision making about risks is very complex, and not only technical aspects but also economical, environmental, comfort related, political, psychological and societal acceptance are aspects that play an important role. In order to balance safety measures with aspects, such as political, social, and psychological aspects, a weighted risk analysis methodology is proposed here. This chapter provides a theoretical background regarding the scope of safety assessment in relation to the decision-making in multiple use of space projects, which will be used in this dissertation.

3.1 Safety & Risk

3.1.1 Introduction

Safety is a wide notion. Vrouwenvelder *et al*. (2001) defined safety as the state of being adequately protected against hurt or injury, free from serious danger or hazard. If the philosophy of safety is considered, safety can be classified into *social safety* and *physical safety* (Durmisevic (2002); Hale (2000); Suddle (2002[A]); Voordt & Wegen (1990)). Social safety constitutes mainly of the (perception) behaviour among persons. Crime incentive factors, spatial factors, institutional factors and social factors of an area are characteristics of social safety (Durmisevic (2002)).

As mentioned in chapter 1, social safety aspects are beyond the scope of this thesis and therefore will not be discussed further. In contrast, physical safety contains both the probability of a person being killed or injured by *natural hazards*, such as; bad weather, an earthquake, floods and the probability by *man-made hazards*, like traffic, calamities by transport of dangerous materials, calamities by nuclear reactors etc. It should be noted that several effects of failure like cost increase, time loss, loss of quality, environmental damage, also form a part of physical safety. In some cases, like fire or terrorism, it is difficult to classify the safety. The subdivision within physical safety divides into *internal safety,* and *external safety* (see e.g. Vrijling *et al*. (1998)). The following subdivision, here ranked according to increasing benefit to the persons at risk is frequently found (Suddle (2002[G])):

Figure 3.1: Subdivision of safety (Suddle (2002[G])).

<table>
<tr><th colspan="3">Safety</th></tr>
<tr><td>Social Safety</td><td colspan="2">Physical Safety</td></tr>
<tr><td rowspan="2">Crime incentive factors
Spatial factors
Institutional factors
Social factors</td><td colspan="2">Natural & Man-made hazards</td></tr>
<tr><td>Internal
Users
Passengers
Personnel</td><td>External
Third parties</td></tr>
</table>

3.1.2 The relation between Safety and Risk

Generally speaking, safety consists both of subjective and objective elements. It does not automatically imply that, when a person experiences that he is safe from a psychological point of view, that he is automatically safe from a mathematical point of view and visa versa. The relation between subjective and objective components of safety with aspects of behaviour is presented in figure 3.2 (Bouma (1982)). Subjective safety is related to psychological aspects (see also (Stoessel (2001)) and thus can hardly be assessed objectively, while objective safety components can be assessed in objective terms if mathematical grounds are used. Note that sometimes the objective safety (measure) is based on subjective estimates. To define and to judge the objective elements of safety, it is vital to link safety with *risk* (*the combination of probability and consequences*), since safety cannot be quantified. The advantage hereof is that risk can be quantified and judged whether it is acceptable or not, while safety itself cannot.

Figure 3.2: Aspects of behaviour.

	Subjectively Safe	**Subjectively Unsafe**
Objectively Safe	*Healthy unconcern*	*Unhealthy anxiety*
Objectively Unsafe	*Unhealthy unconcern*	*Healthy anxiety*

3.1.3 *Definitions of Risk*

Both psychological and mathematical definitions of risk are discussed in a scale of literature. Examples of psychological (informal) definitions from Vlek (1990) and Schaalsma *et al*. (1990) are ”lack of perceived controllability”, ”set of possible negative consequences” and ”fear of loss”. More examples of (psychological) definitions of risk can be found in the survey of Vlek (1990; 1995; 1996; 2001; 2002); Bohnenblust & Slovic (1998); Slovic (1987; 1999); Adams (1995); the reports of Gezondheidsraad (1995; 1996); Coombs (1972); Libby & Fishburn (1977); Vlek & Stallen (1980) and Hypothese (2001). An integral approach of both mathematical and psychological definitions is treated by Suddle & Waarts (2003). The point is that psychological definitions of risk are, in principle, related to both risk perception and subjective elements of safety. Hence, these argumentations do not provide the answer to the question ”how safe or unsafe is an activity, or what is the effect of a safety measure in accordance with human risk and financial aspects.” Therefore, psychological definitions are beyond the scope of this thesis. In order to answer such questions in objective terms and to determine the risks, there is a need for a quantifiable (mathematical) approach and not an informal psychological one. Besides, a mathematical approach enables one to compare risk of different activities and use the risk analysis as a basis for rational decision-making. The common definition of risk (associated with a hazard) is a combination of the probability that a hazard will occur and the (usually negative) consequences of that hazard (Vrouwenvelder *et al*. (2001); Vrijling *et al*. (1998); Vrouwenvelder & Vrijling (1997)). In essence, it comes down to the following expression (the most frequently used definition in risk analysis):

$$R = P_f \cdot C_f \tag{3.1}$$

in which:

R	=	risk [fatalities per year or money per year];
P_f	=	probability of failure [year^{-1}];
C_f	=	consequence of the unwanted event [fatalities or money].

According to Kaplan & Garrick (1981), risk consists of three components; (1) scenario, (2) probability of that scenario and (3) consequence of that scenario. Kaplan & Garrick (1981) suggest also that one has to take all hazards into account, which can be accomplished by summing up all possible hazards (scenarios) with their consequences for an activity. Therefore, as an obvious extension, multiple scenarios (indexed *i*) may be taken into account. This can be presented with the following formula:

$$R = \sum_{i=1} P_{f_i} \cdot C_{f_i} \tag{3.2}$$

Consequences C_f to be taken into account include:

- Injury, or loss of life, due to structural collapse;
- Reconstruction costs;
- Loss of economic activity;
- Environmental losses.

It should be noted that it is possible to weigh the consequences C_f more heavily by taking them to a second power. Most of the time, there is an inverse relation between the probability that a hazard will occur and the consequences of that hazard.

3.2 Risk management process

3.2.1 Risk assessment

The risk assessment of a system consists of the use of all available information to estimate the risk to individuals or populations, property or the environment, from identified hazards, the comparison with targets, and the search for optimal solutions (Vrouwenvelder *et al*. (2001)). From a technical point of view, the extent of the risks and the effects of risk reducing measures can be quantified in a quantitative risk assessment (QRA). For this reason, the QRA can provide a basis for the rational decision-making about risks (Bedford & Cooke (2001)). A Risk analysis generally contains the steps: scope definition, hazard identification, modelling of hazard scenarios, estimation of consequences, estimation of probabilities and estimation of risks. The position of the risk analysis in the risk management process is illustrated in figure 3.3 (see e.g. Høj & Kröger (2002)). Note that different stakeholders are involved in the risk management process. Usually, QRA models reach the level of risk evaluation. In this thesis, it is desired to integrate the level of additional risk reducing measures in the QRA models.

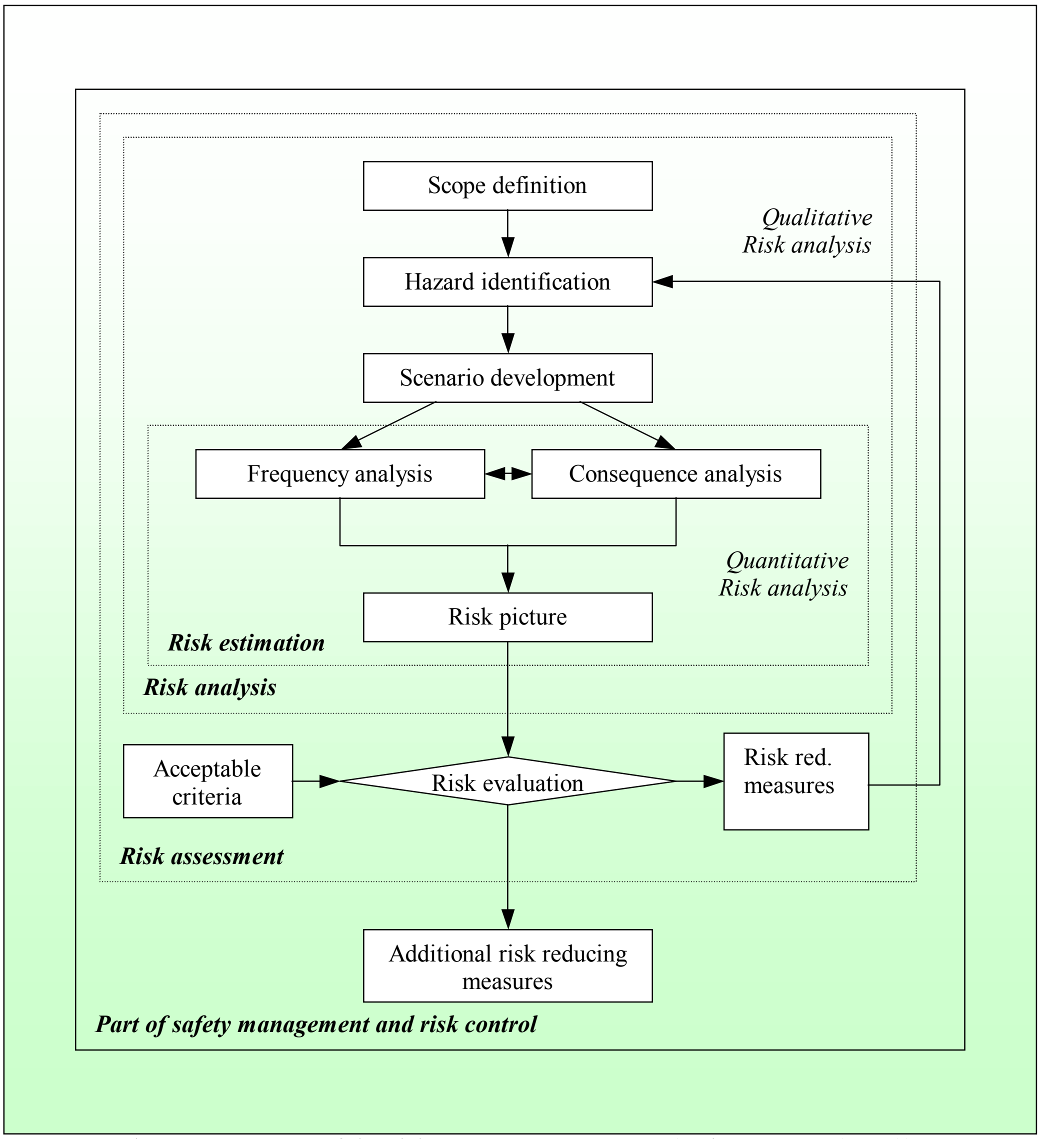

Figure 3.3: A part of the risk management process (Høj & Kröger (2002)).

The first three steps of the risk analysis are considered the qualitative part, the last three steps risk analysis form the quantitative part. In many cases only the qualitative part is carried out and measures are taken on an intuitive basis. Although not complete, such an analysis is certainly not without value. Better however, is to include the last three steps and perform a full quantitative risk analysis. In this complex decision making process, a clear identification of the risks, and the effects of risk reducing measures, are very useful (Vrouwenvelder *et al.* (2001)).

3.2.2 Risk evaluation

When a risk analysis is performed, it is important to realise that decision making about risks is very complex and that not only technical and mathematical aspects, but also political, psychological, societal, moral and emotional processes play an important role (Suddle (2002[A]); Roeser (2004); Jonkman *et al.* (2003[A])). If a risk analysis is carried out for only the qualitative part, the psychological and political aspects play a major role in risk acceptance and decision-making. Contrarily, when risk analysis is carried out until the quantitative part, limits for risk acceptance and economical criteria are considered for decision-making (see figure 3.4).

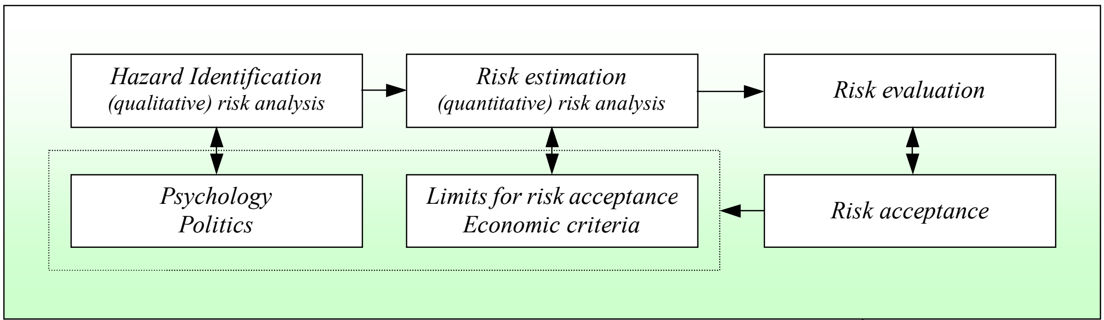

Figure 3.4: Risk analysis and risk acceptance (Suddle (2002[A])).

Furthermore, in some cases, especially scenarios with great consequences, *weighing factors* for all risk dimensions are used in order to make them comparable to each other and to relate them to the measures that must be taken for possible risk reduction (Coombs (1972); Libby & Fishburn (1977); Vlek & Stallen (1980); Vlek (1990); Vrouwenvelder *et al.* (2001). It is, therefore, recommendable to compare and to integrate different decision making elements, such as political, social, psychological, environmental, and quality risks or benefits, in a "one-dimensional" weighted risk R_w, e.g. in terms of money, as following (Suddle & Waarts (2003)):

$$R_w = \sum_{j=1} \alpha_j \sum_{i=1} P_{f_{ij}} \cdot C_{f_{ij}} \tag{3.3}$$

$$R_w = \sum_{j=1} \alpha_j \sum_{i=1} R_{ij} \tag{3.4}$$

in which:

R_w = weighted risk [year^{-1}];
α_j = (monetary) value per considered loss [cost unit].

It has to be noted that the weighted risk R_w may consist of cost unities, which can be financial, but not necessarily (see Seiler (2000)). Bohnenblust & Slovic (1998) introduced the so-called monetary collective risk, in which the marginal cost criterion is included.

The weighted risk R_w can easily be extended into multiple decision-making elements, depending on the origin of the decision-maker. The formulas (3.3) and (3.4) can be specified into particular risk components (Suddle & Waarts (2003)):

$$R_w = \alpha_1 \sum_{i=1} R_{human,i} + \alpha_2 \sum_{j=1} R_{enonomic,j} + \alpha_3 \sum_{k=1} R_{environment,k} + \alpha_4 \sum_{l=1} R_{quality,l} + ... \qquad (3.5)$$

in which:

α_1	=	(monetary) value per fatality or injury [cost unit];
α_2	=	(monetary) value per environmental risk [cost unit];
α_3	=	(monetary) value per economical risk [cost unit] (mostly $\alpha_3 = 1$);
α_4	=	(monetary) value per quality risk [cost unit], and so on…

Note that elements related to the human risks may even contain risk perception aspects of human beings. According to Lind (1996), safety criterions are not absolute. Cost-utility is only a part of the economic, social, cultural and political assessments that are required for responsible decision-making. Note that some α_j may also be negative (e.g. time). If these non-safety related aspects are quantified in the proposed weighted risk (analysis), and thus in one (monetary) dimension, safety measures can be balanced and optimised in respect of decision-making, shown as follows:

$$\text{Minimise:} \qquad C_{tot} = C_0(y) + \sum_{j=1} \frac{R_{wj}}{(1+r)^j} \qquad (3.6)$$

in which:

C_{tot}	=	total costs [money];
$C_0(y)$	=	the investment in a safety measure [money];
y	=	decision parameter;
j	=	the number of the year;
r	=	real rate of interest.

Equation (3.6) provides an overall mathematical-economic decision problem for balancing safety measures for all kinds of aspects by expressing both positive / negative risks and benefits of a project. Moreover, equation (3.6) is an extension of equation (3.11), in which only investments in safety measures are compared with both economic and human risks. The proposed equation (3.6) therefore becomes a justified supporting tool in decision-making.

3.2.3 Monetary values of elements of the weighted risk

The elements of the weighted risk, considered in the case studies of chapter 7, are the investments C_0, economical losses C_j, economic benefits $C_{benefits}$, human risks $E(N_d)$, quality risk $R_{quality}$ and environmental risk $R_{environmental}$. The components of the weighted risk can only be computed quantitatively, if the monetary value per considered risk α_j is determined. Some of these values can be found in literature. The monetary value per fatality or the valuation of human life depends on aspects such as Willingness To Pay (WTP), Willingness To Accept compensation (WTA), voluntariness and responsibility - all of which can be determined by e.g. a questionnaire - as discussed by Jones-Lee & Loomes (1995).

As shown, various methods can be used for determining that value. As a consequence, the monetary value per fatality has a wide range from € 300,000.= to € 20,000,000.= (see e.g. Blaeij (2003)). According to the Environmental Protection Agency, the value of a citizen in the US is approximately € 5,600,000. According to Vrouwenvelder *et al.* (2001), a reasonable value seems € 1,000,000, which will be the figure employed as the basis in this thesis. Blaeij (2003) analysed the value of a statistical life in road safety using stated preference methodologies and empirical estimates for the Netherlands, and concluded that the value of a statistical life in such circumstances varies between € 1,000,000 to € 11,400,000. An analysis of the valuation of a human life is also discussed by Vrijling & Gelder (2000). Another method to determine this value is using the so-called Life Quality Index (LQI) (see Lind (1994) or Rackwitz (2002)).

Rodenburg (2004) discusses that the WTP of employees working in a multifunctionally designed area is about € 7.= per person per month for a specific (individually chosen) bundle of facilities. This monetary value is derived from questionnaires based on Stated Preference techniques, and implies that per year a person working in such an environment is willing to pay € 84.= let say € 100.= per year for the use of a specific (individually chosen) bundle of facilities. It should be remarked that these facilities might anyhow not be similar to components of multiple use of space projects. In this research, however, this condition is eliminated.

Nyborg (1997) discusses a model of Schkade & Payne (1993), presenting that, based on CVM (contingent valuation) respondents, one would spend about \$ 1,000.= (≅ € 800) per year, per person to protect environmental quality. Dobbelsteen (2004) quotes an indicator for the green area preserved (GAP), which is about € 4.= / m^2, determined by Vogtländer (2001). The GAP is a measure of the avoided development of land outside the plan. The value discussed by Nyborg (1997) will not be used, since this value contains a general assumption, while the GAP provides the value for a certain preserved floor space. It should be noted that if we consider the monetary value of environmental space, large fluctuations prevail in that value. When this value is e.g. determined by the environmental space saved for the Green Hart Tunnel, this value will be much higher and more influential than the value of € 4.= per m^2, which will be used in this thesis ((€ 900 - 200) $\cdot 10^6$) / (8.5 $\cdot 10^3 \cdot$ 150) ≅ € 550.= per m^2.

Jones Lang La Salle (2002) provides prime rent prices for offices in multiple use of space projects. These prices vary from € 1,350.= to € 300.= per m^2 per year for Broadgate and Lehrter Bahnhof respectively. Since the projects of the case studies of chapter 7 are not located on such lucrative locations, a value of € 200 per m^2 per year is considered for both cases. The rent price per house is assumed to be € 9,000 per year.

3.3 Risk acceptance and decision-making

3.3.1 Introduction

When carrying out a quantitative risk analysis, the results have to be checked for risk acceptance criteria. When the results do not comply with these criteria, measures can be taken. Criteria for accepting or rejecting the assessed risks, include two related entities: the frequency, and the consequences (fatalities, monetary values, environmental values) of an undesired event. In general, one may state that the more severe the consequences, the lower the accepted probabilities are. In more detail, the acceptance limits for a given event may originate from three different angles (see e.g. Vrouwenvelder *et al.* (2001)): (1) a comparison with other risks related to *individual* safety; (2) *societal* aversion to big disasters, especially when many fatalities are involved; (3) *economic* considerations.

3.3.2 *Individually acceptable level of risk*

An overview of measures to express the individual risk is given by Bedford & Cooke (2001). The smallest component of the social acceptable risk is the personal cost-benefit assessment by the individual, proposed by Vrijling *et al*. (1998). Individual risk *IR* is defined as the probability that a person, who is permanently present at a certain location in the vicinity of an activity will be killed as a consequence of an accident of that activity. Usually, *IR* is expressed for a period of a year. It can be pictured both on a two and a three-dimensional (Suddle *et al*. (2004)) map by connecting points of equal *IR* around a facility, the risk contours (Ale (2002)) (see chapter 5). The *IR* can also be presented as a risk, which is depends on the presence time of a person. Logarithmic approaches for the individual risk can be found in e.g. Boudier *et al*. (1985) and Suddle (2002[A]; 2003[B])). Vrijling *et al*. (1998) proposed a criterion for the acceptable individual risk *IR* of a person, which takes into account the degree to which the activity is voluntary, and the benefit perceived (see also (Vrijling & Vrouwenvelder (1997)):

$$IR = P_{fi} \cdot P_{d|fi} \leq \beta_i \cdot 10^{-4} \tag{3.7}$$

in which:

P_{fi} = probability of failure *f* as a result of an event *i* [year^{-1}];
$P_{d|fi}$ = probability of being killed conditional upon the occurrence of event *i* and failure of the structure [-];
β_i = the policy factor that varies according to the degree to which participation in the activity is voluntary and with the perceived benefit.

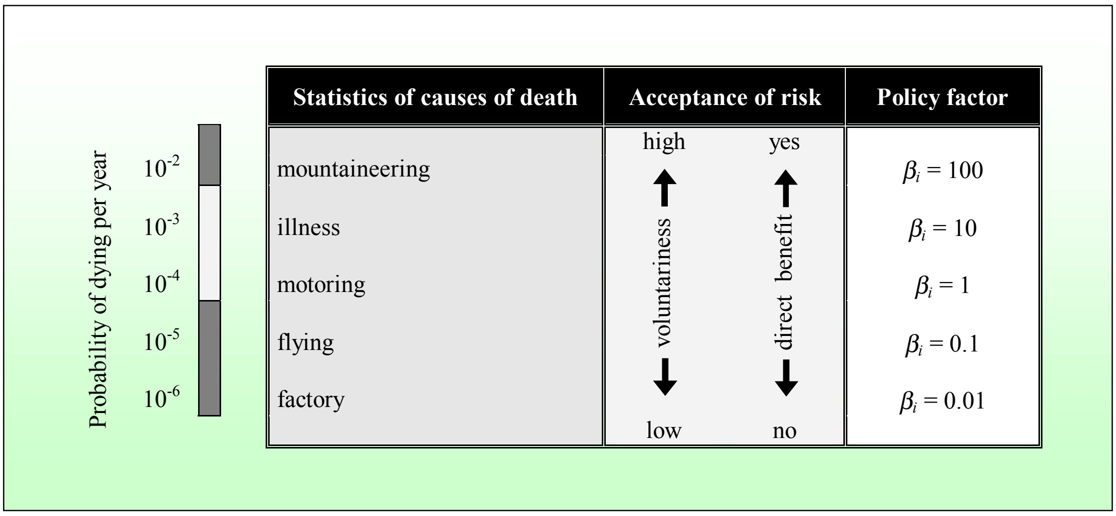

Figure 3.5: Personal risks in Western countries, deduced from the statistics of causes of death and the number of deaths and the number of participants per activity by Vrijling *et al*. (1998).

3.3.3 *Socially acceptable level of risk*

Societal risk *SR*, or group risk *GR*, is defined as; the probability per year that in an accident more than a certain number of people are killed. Societal risk is usually represented as a graph in which the cumulative frequency of more than *n* fatalities is given as a function of *N*, the number of people killed. This graph is called the *FN* curve.

A mathematical expression in the case of a straight *FN* curve (on log-log-scale) can be presented as a combination of Vrijling *et al.* (1998) and Vrouwenvelder *et al.* (2001):

$$1 - F_N(n) \leq \frac{C_i}{n^\gamma} \qquad \text{for all } n \geq 10 \tag{3.8}$$

$$1 - F_N(n) = P(N > n) \tag{3.9}$$

in which
$$C_i = \left[\frac{\beta_i \cdot 100}{k \cdot \sqrt{N_A}}\right]^2 \tag{3.10}$$

in which:

C_i	=	the (imaginary) acceptable probability for $n = 1$;
$1 - F_N(n)$	=	complementary cumulative distribution function in one year [-];
$P(N>n)$	=	probability of more than n fatalities in one year [-];
N	=	the number of people killed in one year in one accident;
n	=	number of fatalities in one year in one accident;
N_A	=	number of the independent locations;
γ	=	the slope of the *FN* curve, ranges from 1 to 2 (Vrijling & Gelder (1997);
k	=	the risk aversion factor; the value of k mostly is 3.

A standard with a steepness of $\gamma = 1$ is more or less risk neutral. If the steepness $\gamma \geq 1$ e.g. $\gamma = 2$, the standard is called risk averse. In this case, accidents in which a large number of people are killed, are less accepted with a relatively lower probability. Bohnenblust & Slovic (1998) indicate that the risk aversion factor is a function of the severity of the consequences. In general, the *FN* curve indicates the border between "acceptable" and "unacceptable" in a diagram with frequency on one axis and the number of fatalities on the other. It is quite customary to have two *FN* curves as indicated in figure 3.6 (left); one curve representing an upper limit above which activities or situations are not acceptable; another curve - this was abandoned in 1993 - representing a lower limit below which no further risk reductions are necessary. In figure 3.7 the societal risk criterion in The Netherlands, also called the VROM-rule for installations, is illustrated. The VROM-rule for roads is a factor 10 higher and is depicted per kilometre per year. In the area between the two limits, risk reducing measures should be considered and judged on an economical basis. Between these levels, it is required to reduce risks to levels as "as low as reasonably achievable" (ALARA) that is, until the costs of further measures would be grossly disproportionate to the benefit gained (see VROM / V &W (1998)). Bedford *et al.* (2004) discuss the merits of a cost benefit analysis and multi-attribute utility theory is considered as quantitative tool to support ALARA decision-making. In fact, the standards for group risk are used for urban planning near hazardous installations. Nowadays, this concept is adopted for urban planning near transport routes of hazardous materials. Some international *FN* standards are given in figure 3.6 (right) (Jonkman *et al.* (2001; 2003[A])). In contrast to other countries, the societal risk criterion in The Netherlands is much more stringent. Hence, it is not remarkable that some group risk results (of e.g. urban areas near transport routes) do not comply with the Dutch criteria of group risk (VROM-rule), while the same group risk results do comply with risk acceptance criteria of other countries. Nevertheless, the VROM-rule for roads will be used in this thesis as indication, because of the fact that some urban planning will develop adjacent and above the transport routes of hazardous materials and the level of risk acceptance criteria is a political issue.

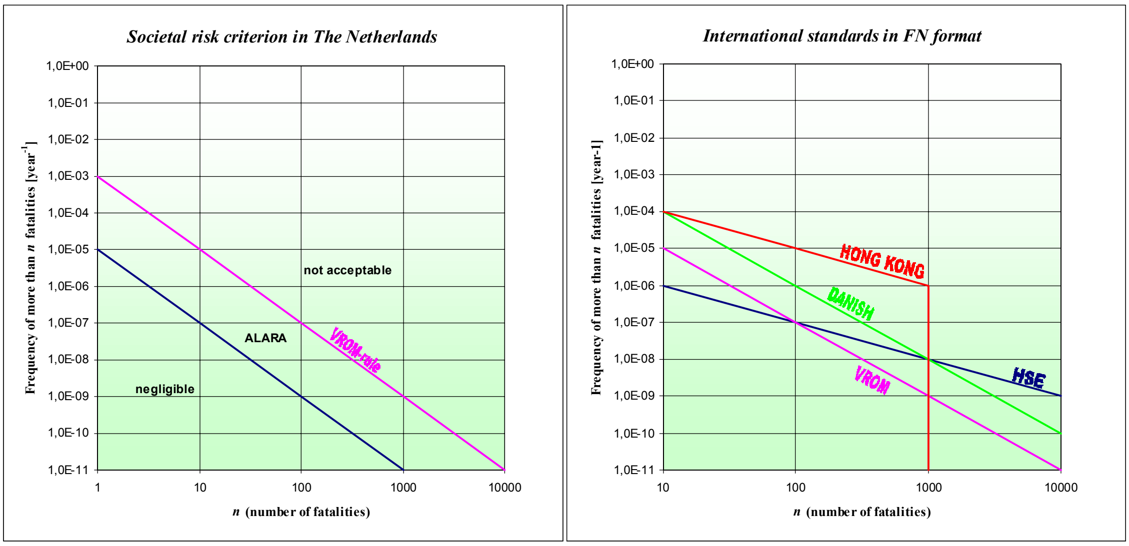

Figure 3.6: Group risk criterion in The Netherlands (left) and some international FN standards (right).

3.3.4 *Economic criteria*

According to Vrouwenvelder *et al.* (2001), the third acceptance criterion can be formulated as a mathematical-economic decision problem by expressing both investments and all consequences of the disaster in terms of money (assuming a given period of time). Besides, it may be suggested that a measure with less human risk is more expensive than one with large risk. To balance these measures, an economic criterion is required, for which it depends on the decision-maker whether the value of a human life is taken into account in the economic optimisation. Mathematically it comes down to the restricted form of equation (3.6) as presented by Vrouwenvelder *et al.* (2001):

Minimise:
$$C_{tot} = C_0(y) + \sum_{j=1} \frac{P_{Fj} \cdot \{C_j + \alpha \cdot E(N_d \mid F)\}}{(1+r)^j} \qquad (3.11)$$

Conditional upon:
$$P_{fi} \leq \frac{\beta_i \cdot 10^{-4}}{P_{d|fi}} \qquad (3.12)$$

$$1 - F_N(n) \leq \frac{C_i}{n^{\gamma}} \qquad (3.13)$$

in which:

C_j	=	damage cost in year *j* [money];
α	=	monetary value per fatality [money];
$E(N_d \mid \mathrm{F})$	=	expected number of fatalities given a failure in one year [-];
N_{pi}	=	number of participants in activity *i* [-];
$P_{Fj}(y)$	=	the failure in year *j*.

One should realise that $P_{Fj}(y)$ denotes the failure exactly in year j, that is not in any year before or after. The term C_j includes all costs after failure (also called the material losses): it includes direct damage, cost of repair, but also future failure costs of the repaired structure (if any).

3.3.5 Expected number of people killed

Other approaches to present risk results and to determine the effect of safety measures could be the expected number of people killed $E(N_d)$, also called the *PLL* (Potential Loss of Life) by e.g. Ale *et al*. (1996). The expected number of people killed, can be computed by using both individual risk *IR,* and group risk *GR*. When the expected number of people killed has to be computed by the individual risk *IR*, the following formulas can be used:

$$E(N_d) = P_{fi} \cdot P_{d|fi} \cdot N_{pi} \tag{3.14}$$

And $$E(N_d \mid F) = P_{d|fi} \cdot N_{pi} \tag{3.15}$$

When the expected number of people killed has to be computed by the group risk *GR*, the following formula can be used:

$$E(N_d) = \sum_{N=1}^{\infty} f_N N = \sum_{N=1}^{\infty} (F_N - F_{N+1}) N \tag{3.16}$$

in which:

$E(N_d)$ = the expected number of people killed in one year [-]; or the expected death rate [year^{-1}].

f_N = probability density function [-].

3.4 Use of Bayesian Networks

A Bayesian Network is a graphical tool that represents the relations between a set of variables, and a set of directed edges between variables (Hansen (1999); Jensen (1996; 2001)), which can then be divided into events and consequences. The major advantage of Bayesian Networks is that these networks can replace and compact both traditional fault trees, and event trees, in one model (Bobbio *et al*. (2001)), possibly using it as a probabilistic or a deterministic risk analysis. According to Friis-Hansen (2000) the potential of Bayesian Networks is that it is an intuitive modelling tool, partly based on artificial intelligence adding transparency and consistency to the models, therefore making it an interesting tool for this thesis. A Bayesian network consists of a set of nodes and a set of directed arrows, each node representing a probability distribution, which may in principle be continuous or discrete (Kurowicka & Cooke (2004)). Arrows indicate conditional probabilistic dependence such that the probability of a dependent variable being in a particular state is given for each combination of the states of the preceding variables. The dependence structure is thus represented by a set of conditional probability distributions. A variable that is dependent on other variables, is often referred to as a *child node*. Likewise, directly preceding variables are called *parents*. Nodes, which have no parents, are *called root* nodes and nodes without children are *leaf nodes*. Bayesian networks are sometimes referred to as directed a-cyclic graphs (DAGs), indicating that loops (or cycles) are not allowed.

A Bayesian network is a representation of the joint probability distribution of the entire variable domain $U = \{X_1,X_2,\ldots,X_n\}$. This is seen by applying the chain rule to the factorisation of the joint distribution into a chain of conditional probability distributions (Friis-Hansen (2000)):

$$P(U) = P(X_1, X_2,...,X_n) \tag{3.17}$$
$$= P(X_1 \mid X_2,...,X_n)P(X_2 \mid X_3,...,X_n)\cdots P(X_n) \tag{3.18}$$
$$= \prod_i P(X_i \mid pa(X_i)) \tag{3.19}$$

In which $P(X_1,\ldots,X_n)$ is the joint distribution of X_1 to X_n, and $P(X_1 \mid X_2,\ldots,X_n)$ is the conditional distribution of X_1 given $X_2,\cdots,X_n$. The notation $pa(X_i)$ stands for the set of parent variables of the variable X_i. From the updated joint table, the marginal distributions of each individual variable may be found by summation over all other variables. This is desired for calculating risk for all scenarios and is known as sum-marginalisation:

$$P(X_i) = \sum_{U \setminus \{X_i\}} P(U) = \sum_{U \setminus \{X_i\}} \prod_i P(X_i \mid pa(X_i)) \tag{3.20}$$

So, if the undesired events H_i, failure modes F, consequences C, (the effect of) safety measures M, and risk R, are elements of the entire variable domain $U = \{X_1,X_2,\ldots,X_n\}$, then every risk analysis with Bayesian Networks is possible (Suddle & Waarts (2003)).

$$H_i, F, M, C, R \in \{X_1, X_2,..., X_n\} \tag{3.21}$$

These safety measures may include the rescue availability or functional design, both of which are characteristic for deterministic risk analysis. These measures may also contain structural measures, which are characteristic for a probabilistic risk analysis. Besides, integration of these measures is a vital issue from the decision point of view, as mentioned in section 3.2.2. This provides the tool to quantify the effectiveness of safety measures regarding risk, which is wanted from a risk evaluation point of view. A standard Bayesian Network tool corresponding to a standard risk analysis for basic events may be expressed as:

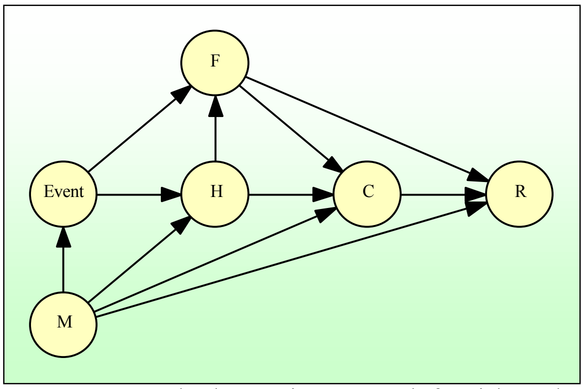

Figure 3.7: A standard Bayesian Network for risk analysis.

3.5 Set-up basic case studies

In order to quantify the risks in multiple use of space as described in chapter 2, it is essential to set-up virtual and schematic case studies.

The advantage of such cases is that risk analysis models can be developed and risk results can be presented for both the construction, and the exploitation stage. The height position of the infrastructure situated at the ground level, is an assumption made for the risk analysis models (see figure 2.8). If one prefers, one can work out the other four height levels of infrastructure regarding the risk assessment. These standard cases, which will be used as a central object in the following chapter, can be divided into three types: First of all, a case study is drawn up for realising buildings above roads. It is assumed that the building above the road consists of 10 storeys and is built above a 2x2 lane motorway. The span and the linear direction of the building are respectively 20 meters and 50 meters (see figure 3.8). Secondly, a case study is drawn up for realising buildings above railway tracks. An assumption has been made that the building above the railway track has the same dimensions. Logically, the traffic condition beneath the building is different from the previous variant; this is described in the model description (figure 3.9). Finally, almost the same case is developed for building above an existing building (figure 3.10). An assumption has been made that the building above the existing building can be built.

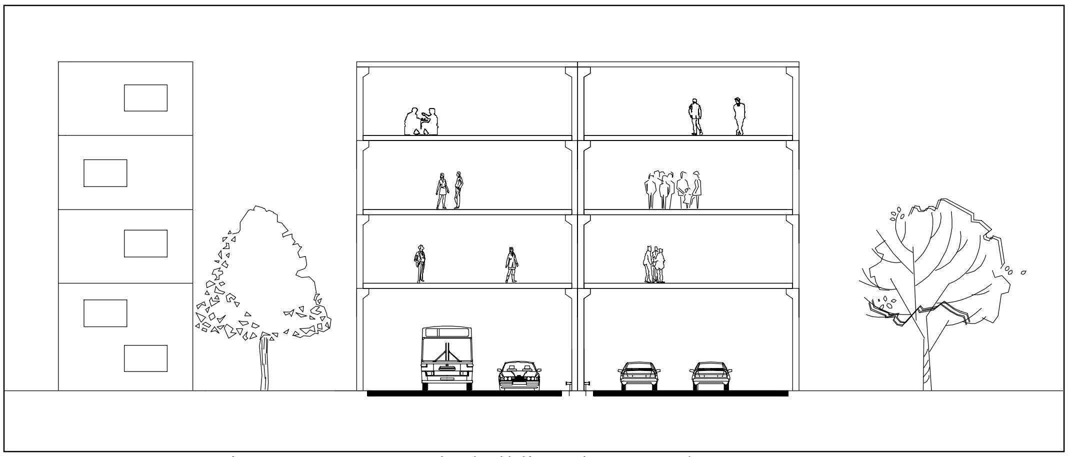

Figure 3.8: Case study; building above 2x2 lane motorway.

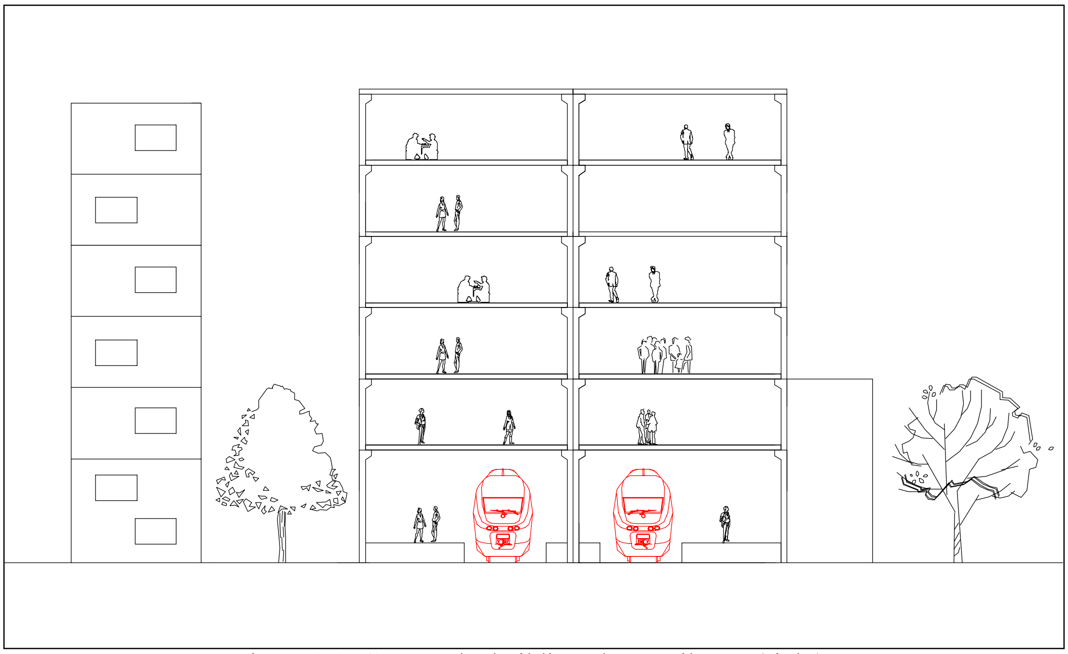

Figure 3.9: Case study; building above railways (right).

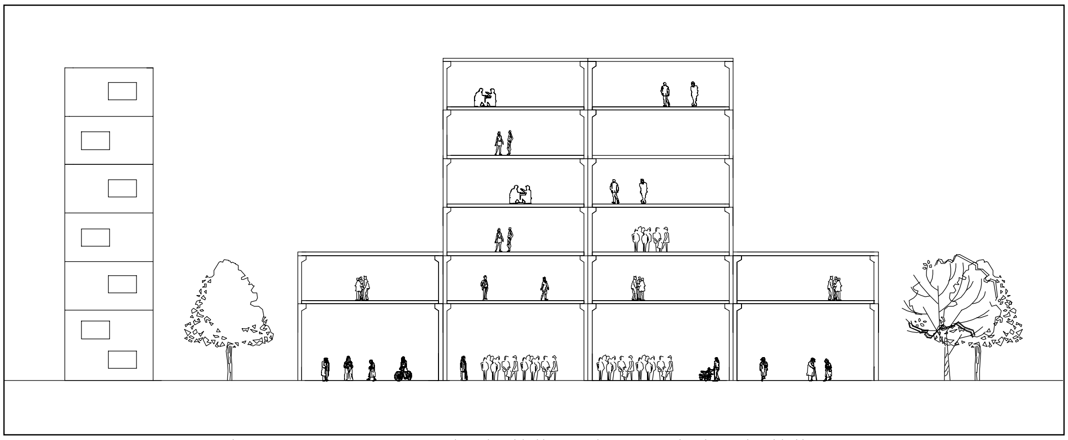

Figure 3.10: Case study; building above existing buildings.

3.6 Conclusions

This chapter presented that performing both safety, and risk assessment are characterised by many aspects, all of which should be considered carefully. First of all, it is recommendable to observe that safety consists of both objective and subjective elements. In order to objectify safety and to quantify risk, safety should be linked to risk (*the sum of probability x consequences*). However, one should also realise that when balancing safety measures with other non-technical aspects, such as political, social, and psychological aspects, should be considered in decision-making. In this respect, a methodological model has been presented, in which these aspects can be integrated. That model enables a general approach for optimising the effectiveness of safety measures with non-technical aspects in quantitative terms. This approach is based on presenting a weighted risk R_w in one dimension (e.g. money) in which all kind of benefits and losses can be taken into account, such as human, economical, environmental, and quality risks etc. For this, it is essential to quantify those risks and benefits in one dimension. Furthermore, the traditional risk acceptance criteria combined with the interrelation between three main criteria for risk acceptance, which can be divided into individual risk, risk on a social basis, and the economic criterion, is presented in this chapter. Despite ethical and moral questions, one (monetary) dimension of human risks, economical risk and non-safety related elements could be essential for deliberating safety measures. Finally, the use of a Bayesian Network is discussed.

4

Physical Safety in the Construction Stage

The case studies of projects situated over the motorway "Utrechtse Baan" in The Hague show that specifying requirements regarding safety at an as early as possible stage (the design stage) decreases risks for third parties during construction. It is essential to have clarity among those who are responsible for taking safety measures and it is necessary to have an adequate and effective organisation at the construction site. This can restrict potential danger during construction (Meijer & Visscher (2001)). Furthermore, an important lesson from these projects is that activities during the construction stage form a hazard for people present on the infrastructure beneath these so called third parties, such as drivers and passengers, are present, because the traffic on the infrastructure must continue (Suddle (2001^A)). In this regard, a methodology of safety assessment of third parties in the neighbourhood of these projects (such as users of infrastructure under building sites) is developed, in the M.Sc. project of Suddle (2001^A). This chapter gives an overview of this research work. Details of this chapter can be found in the mentioned thesis of Suddle (2001^A).

4.1 Classification of safety aspects the during construction stage

4.1.1 Introduction

Safety aspects for third parties during the construction stage in multiple use of space projects can be classified into four types: regulations, external conditions, design aspects and construction aspects. A full scope of these aspects is presented in (Suddle (2001^A)).

4.1.2 Regulations

In essence, regulations, like guidelines for contractors, control the safety during construction. However, on the basis of law, there are no explicit norms for the safety of third parties during construction, especially not for multiple use of space projects (Suddle (2001[B])). Other types of regulations are meant for structural calculations, materials, quality sets, organisation at the site etc. Both national and international standards are a part of this main aspect.

4.1.3 External conditions

External conditions, such as the traffic condition below, form a main parameter for the safety of third parties. These parameters determine both the intensity and the speed of traffic as discussed by Hansen (1999[B]). Furthermore, it is important to realise that safety of third parties during construction depends on where the building is constructed (e.g. above roads or above railway tracks), or when dealing with e.g. the different positions in height of the infrastructure (see figure 2.8). Typically, the surroundings impose these conditions. An example of this is the position of cables in the underground, which can also be considered an influencing parameter of external conditions. It is obvious that some of these conditions or parameters can hardly be influenced. Nevertheless, one may prevent risk for third parties by logistic measures (e.g. close off the road and reroute the traffic during construction).

4.1.4 Design aspects

Other parameters, which influence the safety of third parties, are largely related to design aspects. These aspects depend on e.g. the dimensions of the building, architectural design, structural elements, functional design of the building, and technological aspects. These parameters, which are characteristics of the considered project, can be varied, influenced, and controlled at an early moment in the design stage of the project. For more examples, see (Suddle (2001[A])).

4.1.5 Construction aspects

Finally, characteristical aspects related to construction work can be mentioned as a main part of the safety of third parties. Aspects fixed in the design stage can hardly be changed during the construction. Hence, mistakes made in the design stage will regularly come to light in the construction stage. Additionally, the construction stage is characterised by the fact that many parties are involved. Therefore, the organisation between these parties is crucial as well. During the construction stage, regulations, guidelines, boundaries, and preventive measures are relevant for the safety of third parties in multiple use of space projects.

4.2 Risk analysis

4.2.1 Qualitative risk analysis

A qualitative risk analysis for the safety of third parties has been performed by FMEA-techniques (Failure Mode and Effect Analysis), representing a complete overview of hazards and consequences for the construction of a building above a motorway.

Normally, a FMEA contains effects of failure like, cost increase, time loss, loss of quality, environmental damage, and loss of human life. Considering the aim of this study, both the risk regarding cost increase and the risk regarding loss of human life are taken into account. Vrouwenvelder *et al*. (1996) suggest that the FMEA should be performed for all activities during the construction stage, such as, ground escavations, fabrication of elements, transport of elements, removal of temporary structures etc. In this chapter, however, because of the risk assessment of these activities to third parties, particular activities on the construction site are considered in the FMEA. A section of the FMEA is presented in table 4.1 (adapted from (Suddle (2001[A])). It concludes from the FMEA that safety of third parties during construction largely depends on *falling elements*. The falling elements can be; bolts, screws, parts of concrete (structures), parts of a scaffold, building elements, hammers, beams, façade elements or even construction workers. In principle, there are more scenarios that may occur on the site, e.g. a strong increase of the ground water level, organisational failures, problems with soil stability and so forth. These scenarios can not be considered in this thesis, due to lack of recourses.

Table 4.1: An example of a section of the FMEA for safety of third parties during construction.

Failure mode	**Failure cause**	**Effect of failure**
logistic problems	planning fault	time loss
collapse of concrete element	design fault	costs, time loss, fatalities
fixing concrete elements	element falls	costs, time loss, loss of quality, fatalities
huge deformations of elements	element collapses and falls	costs, time loss, loss of quality, fatalities
no right composition of concrete	production fault	costs, time loss, loss of quality
fire in building	gas leak	costs, time loss, loss of quality, fatalities
Activity: Installing temporary structures / scaffolds; remove temporary structures		
fixing / removing temporary structures	construction fault collapse of temporary structures construction falls construction element falls	costs, time loss, fatalities

4.2.2 Quantitative risk analysis

Hence, these falling elements may cause fatalities among people present at the infrastructure and in some cases economical risks as well as. This observation is analysed in more detail by a quantitative risk analysis using Bayesian Networks. In this regard, possible quantifiable parameters are transformed into conditional probabilities, which are determined from both the classification aspects for safety of third parties during construction (section 4.1) and the FMEA (table 4.1). These quantifiable aspects, considered in Bayesian Networks, are the following:

- (Design) errors;
- The situation below the building and the probability of hitting a car;
- The position where the element falls (inside or outside the building);
- The weight of the falling element;
- The actions of elements in relation with the installation of elements;
- The probability of elements falling;
- The collapse of the main structure of the building caused by falling elements;
- The height from which the element falls;
- Fatalities and economical risk.

Each of those aspects represents a node in these networks (see figure 4.1). Each node is divided into categories corresponding with events of that node. The relations between the nodes are connected with arrows, which specify the probable influence between these nodes (as presented in section 3.5). Figure 4.1 shows the relation between the falling of elements and other (quantified) aspects. The loss of human lives depends on e.g. where the element falls, the height from which the element falls, and the weight of the element. Another relation might be that elements of different classes are positioned on different areas of the building. Such elements may not be easily presented in a standard event tree. The probabilities of each node are determined by historical data, expert opinion, or by engineering judgement. In some cases, especially cases for which historical data is unavailable - such as the probability of elements falling -, an expert opinion, or an (in house) engineering judgement is used. The failure probability is determined using the likelihood of the occurrence of hazardous events along with different probabilities (see table 4.2). The determination of consequences of hazardous events is based upon either calculations or the same order of magnitude severities of events. The next section will give an overview of how the conditional probabilities are determined. Furthermore, it is assumed for the case studies that the duration of the project is exactly one year.

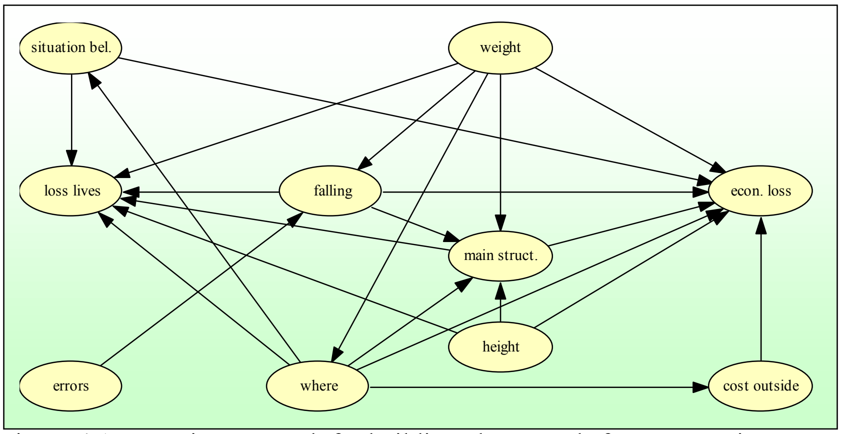

Figure 4.1: Bayesian Network for building above roads for construction stage.

Table 4.2: Frequency of occurrence of hazardous events combined with different probabilities.

Category of likelihood	Description	Probability of failure
I. Frequent	Likely to occur frequently. The hazard will be continually experienced	10^{-1}
II. Probable	Will occur several times. The hazard can be expected to occur often	10^{-2}
III. Occasional	Likely to occur several times. The hazard can be expected to occur several times	10^{-3}
IV. Remote	Likely to occur sometimes in the life cycle. The hazard can reasonably be expected to occur	10^{-4}
V. Improbable	Unlikely to occur but possible. It can be assumed that the hazard will exceptionally occur	10^{-5}
VI. Incredible	Extremely unlikely to occur. It can be assumed that the hazard shall not occur	10^{-6}

4.2.3 *Quantification of probabilities and relations of aspects for building above roads*

- *(Design) errors*

For the probability of partial collapse due to fatal (design) errors in the project, the assumption is made that the *P*(*(design) errors*) is approximately 10^{-4}, which corresponds to the category "remote" of the likelihood table 4.2.

- *The situation below the building and the probability of hitting a car*

When computing the probability that a person of the third party is hit by a falling element, it is relevant to know the situation below the building. The situation below the building corresponds with the *P*(*element falls on a car or the road | element falls outside the building*) and *P*(*element falls on cars | element falls inside the building | building collapses*). These two parameters can be determined respectively by the ratio of total cars in the risk zones A_{cars} / $A_{outside2}$ and total cars beneath the building A_{cars} / $A_{building}$. In the considered case, an assumption has been made that there are 15 cars present on average below the building (≈ 15 · 13 = 195 m^2). $A_{building}$ is equal to 20 · 50 = 1000 m^2. So, the *P*(*element hits a car | element falls*) and the *P*(*element hits the road | element falls*) are 0.195 and 0.805 respectively.

- *The position where the element falls (inside or outside the building)*

The position where the element falls depends on the footprint areas of the risk zones of the considered case. The ratio of the building footprint area and the footprint area of the risk zones outside the building $A_{building}$ / $A_{outside1,2}$ determines the *P*(*element falls outside or inside the building | element falls*). In the considered case of paragraph 3.6, the analysis comes to the following: the value of risk zones outside the building is estimated to be 2 meters out of the façade of the building (see figure 4.2). By this, the value of $A_{outside1,2}$ can be calculated: this is 2 · ((2 · 50 + 2 · 20)) = 280 m^2. The area of the footprint of the building $A_{building}$ is equal to 20 · 50 = 1000 m^2. Hence, the probability *P*(*element falls outside or inside the building | element falls*) is equal to 280 / 1000 = 0,28. If the risk of people present on infrastructure has to be taken into account only, than $A_{outside1}$ is equal to 2 · (20 · 2) = 80 m^2. The probability *P*(*element falls outside or inside the building | element falls*) is in this case equal to 80 / 1000 = 0,08.

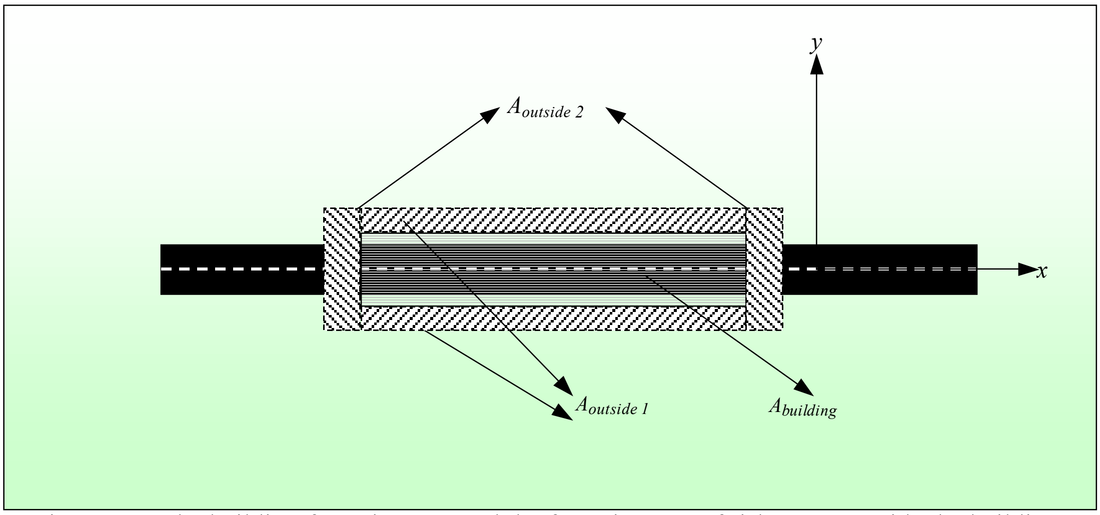

Figure 4.2: The building footprint area and the footprint area of risk zones outside the building.

❑ *The weight of the falling element*

In order to investigate the effect of a falling element, five different weight-classes (of falling elements, which are used in the building) are formulated (table 4.3). For the considered case, the elements of the building are classified into these weight classes.

Table 4.3: Examples of elements in different weight classes.

Weight-class	Example of elements
I. < 5 kg	Very light material, bolts, screws, concrete remains, etc.
II. 5 - 100 kg	Light material, interior material, light dividing walls, construction workers, etc.
III. 100 - 1000 kg	Structural elements for the façade construction, equipment, etc.
IV. 1000 - 10000 kg	Structural elements, beams, hollow core beams, heavy equipment, etc.
V. > 10000 kg	Heavy structural elements, main structure of the building, etc.

❑ *The actions with elements in relation with the assembly of elements*

It is not only the weight class that determines the risk to third parties, but also the actions per element of the weight class, e.g. for assembly, are the main causes whether the element falls or not, this thus determines the probability of an element falling. Therefore, the distribution of total elements in the building is determined for the case study of figure 3.8. Subsequently, this distribution is transformed into the distribution of the actions per element of each weight class (see table 4.4 and figure 4.3). This means that the output probabilities of the Bayesian Network, which represents the probability per action with an element, should be multiplied with the total actions per project per year. For the considered case, it is assumed that the construction elements consist of hollow core beams and concrete beams, which are lifted to each storey of the building. It is assumed that elements of the façade structure are prefabricated elements of $1 \cdot 1\ m^2$.

Table 4.4: Distribution of elements and distribution of actions per element (Suddle (2001[A])).

Weight-class	The number of risky elements per storey	Total number of elements	Distribution of elements	Actions per element	Total actions	Distribution of actions per element
I. < 5 kg	500	5000	0,1753	1	5000	0.055
II. 5 - 100 kg	1520	15200	0,5330	3	45600	0.498
III. 100 - 1000 kg	700	7000	0,2454	3	21000	0.229
IV. 1000 - 10000 kg	129	1290	0,0452	15	19350	0.211
V. > 10000 kg	3	30	0,0011	20	600	0.007

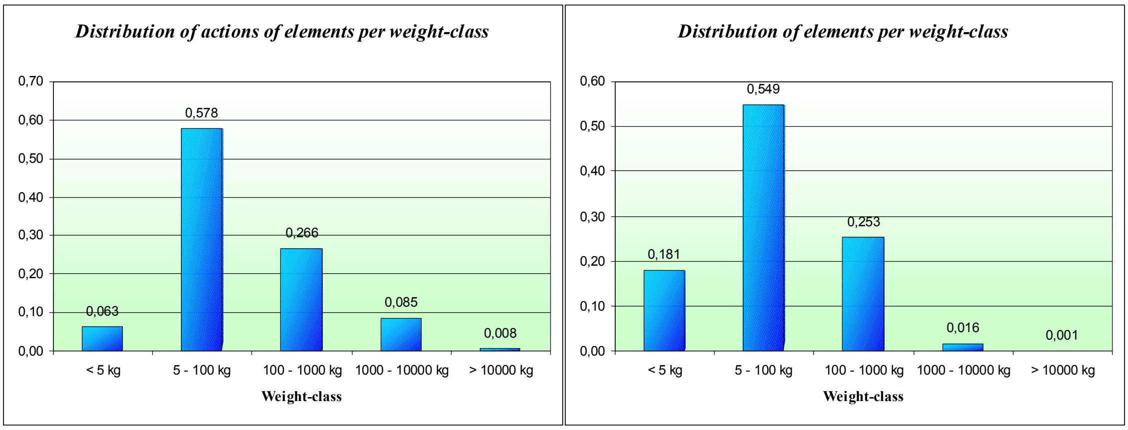

Figure 4.3: Distribution of elements and distribution of actions per element (Suddle (2001[A])).

- *The probability of elements falling*

Because no data could be found about the probability of elements falling per weight class, expert opinions have been consulted (see also Suddle (2001[A])). Ten experienced disciplines were asked to give their opinion about the likelihood of elements falling per weight-class. The failure probability is determined using the likelihood of the occurrence of falling per weight class, along with different probabilities (see table 4.2). The experts varied from scientists specialised in construction technology in multiple use of space projects, to construction workers. It seemed that their opinion regarding the probability of failure mainly correlated with each other; the smaller the element, the higher the probability that an element falls (an exponential increase). The average probability of elements falling per weight class per project is given in figure 4.4.

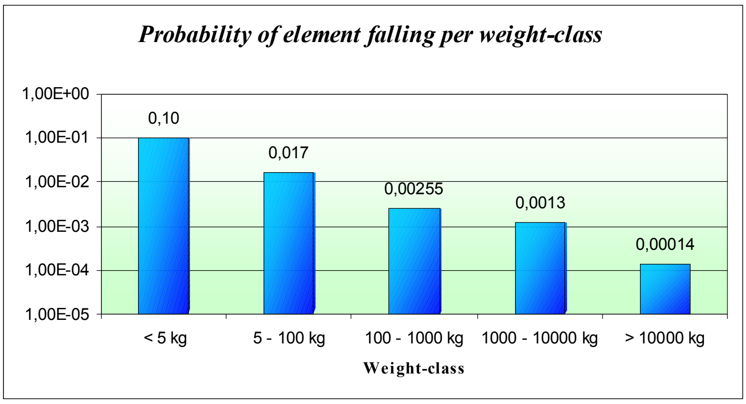

Figure 4.4: The average probability of element falling [action^{-1}], according to case study chapter 3.

- *The collapse of the main structure of the building caused by falling elements*

The bearing structure of the building will only collapse, when the element falls inside the building during construction. In this respect, the *P*(*collapse of the building* | *weight class* | *element falls inside building* | *element falls*) is determined by a combination of engineering judgement, laws of mass, and impulse. A logical assumption has been made that the heavier the element (class), and the higher the falling length, the higher the probability that the building collapses due to the falling of an element inside the building (see figure 4.5).

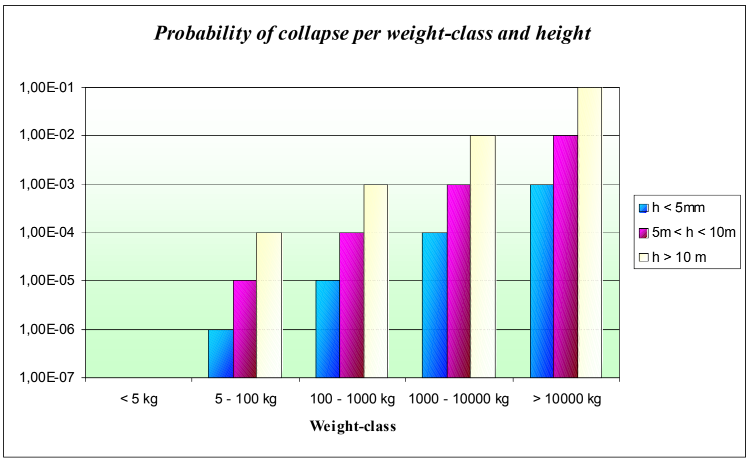

Figure 4.5: The assumed probability of collapse of the building, due to elements falling inside the building.

❑ *The height from which the element falls*

The height from which the element falls, is integrated in the Bayesian Network as a variable in the risk analysis. This variable corresponds with the ratio of the height of the falling element in comparison with the height of the building. Three different height levels are proportionally considered; $h < 5$ meter; 5 meter $< h <$ 10 meter and $h > 10$ meter. For the considered case, in which the height of the building is 50 meters, the proportions are set to be 0.1, 0.1 and 0.8 respectively.

❑ *Fatalities and economical risk*

The probabilities of the node "fatalities" and "economical risk" are determined by engineering judgement (for a full overview see (Suddle (2001[A])). The node "fatalities" is divided into injury and loss of life. It has to be noted that *P*(*person being killed* | *an element falls on a person*) is almost 1, even if an element is even less than 5 kg falling (see figure 4.6). Nevertheless, different probabilities are assumed for being killed due to elements falling and hitting people; the laws of impulse are taken into account, as described earlier in the determination of the collapse of the main structure of the building caused by falling elements. For the probability of being killed by small falling elements, however, a correction factor has been taken into account, because passengers in the car on the road are protected in some way.

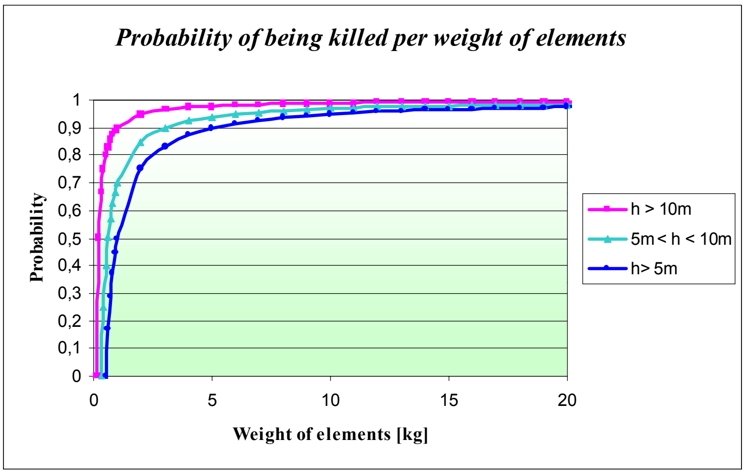

Figure 4.6: The probability of being killed due to a falling element.

Economical damage mainly depends on, e.g. closing of the road for a long period of a few weeks, due to the collapse of the building above. In this regard five different cost-classes (of economical risk) were considered, and the effect of elements falling in the risk zone is determined (table 4.5). It is assumed that the economical damage increases logarithmically when the weight class is increased. The falling of small elements, such as screws, could hardly cause high damage costs, while the falling of large concrete beams may cause high costs, because of the possible large recovery time of the infrastructure (figure 4.7).

Table 4.5: Examples of different weight classes.

Cost-class	Example of costs
I. No costs	In case of no element falls
II. < € 10,000	Very light damage to vehicles, etc.
III. € 10,000 - € 100,000	Light damage to infrastructure and total loss of (expensive) vehicles, etc.
IV. € 100,000 - € 1,000,000	Damage to infrastructure, etc.
V. > € 1,000,000	Heavy damage, close off the road and reroute the traffic for a long period, etc.

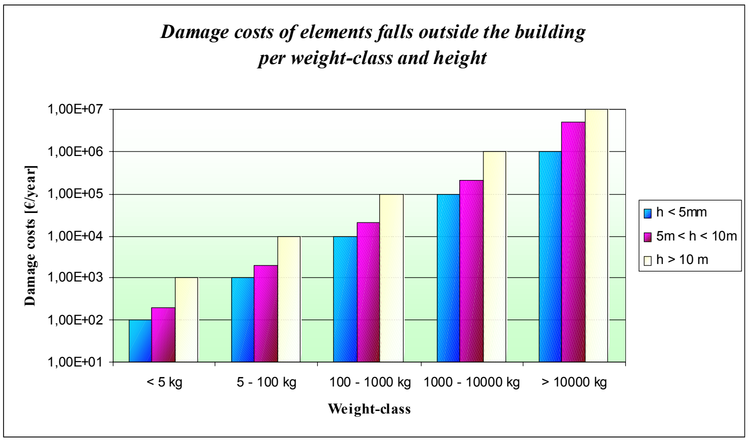

Figure 4.7: Damage costs of element falls in the risk-zones of the building.

4.2.4 *Quantification of probabilities above railways and existing buildings*

- *Quantification of probabilities above railways*

In order to determine the risks to third parties in the construction stage, because of construction above railways and existing buildings, risk analysis models are composed for both cases (figure 3.9 and 3.10). Although the strategy of quantifying the probabilities is almost the same as presented in the previous section, some differences between the previous sections will be discussed in this section. One of the main differences is *the situation below the building*, and thus the presence of people at the platform and in the train. In this regard, an extra node is added in the Bayesian Network of building above a railway track, which represents the situation at a platform (see figure 4.8). In the considered case, it is assumed that on an average level the quantity of people present in the train and on the platform is respectively 50 and 200. This means that the proportion of people present in the train and on the platform is respectively 0.2 and 0.8, which will be used as input for the Bayesian Network of figure 4.8. In addition, the probability *P*(*person on the platform hit by a falling element* | *element falls on platform* | *element falls*) is known. The average footprint of a person A_{person} is given by Hansen (1999[B]), which is 0,21 m^2. The surface of the platform $A_{platform}$ is 500 m^2.

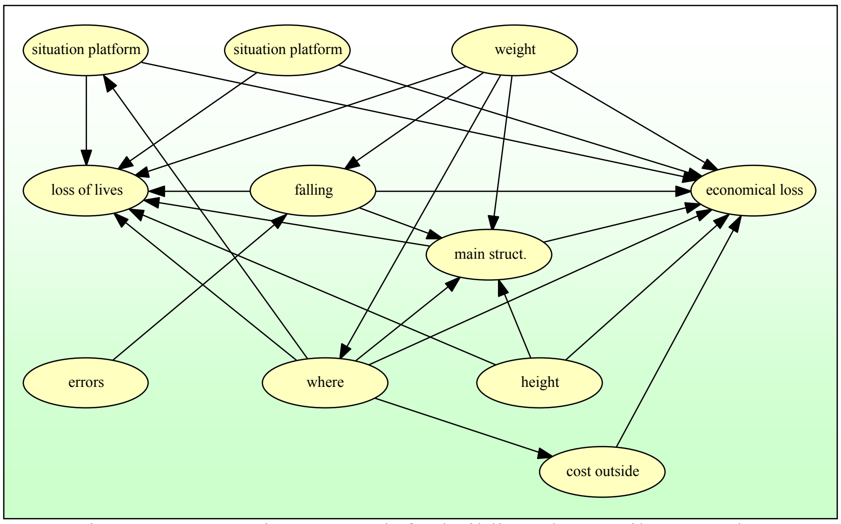

Figure 4.8: Bayesian Network for building above railway tracks.

Thus the probability in question is equal to $50 \cdot 0.21 / 500 = 0.021$. This probability is proportionally smaller in the risk zones ($0,021 \cdot 0.02 = 4.2 \cdot 10^{-4}$). For this case, the probability of being killed due to a falling element on the platform is almost the same as the probability distribution function of the previous section. The financial damage due to falling elements (similarly determined as in the previous section), is much bigger for railways than for roads, because rerouting the train traffic is not an option (Suddle (2001[A])). An extensive description of economical losses for both roads and railways is presented in section 5.2.3.

- *Quantification of probabilities above buildings*

Likewise, the risks analysis models for third parties (people present in the existing building) are also drawn up for realising a building on top of an existing building. One of the main differences between the model of building above a building and the previous ones is that e.g. the node situation on the platform does not exist. Moreover, the situation beneath the building is less dynamic than the previous ones, which means that the probabilities can be determined easily. Other probabilities are set to be the same as used in the previous models. The result of the risk analysis is presented in the next paragraph.

4.3 Results of risk analysis

4.3.1 Individual Risk

The (individual) risk calculated from the Bayesian Network (figure 4.1) presents the risk per action of a considered element per year. In order to calculate the risk per year, the output probabilities are multiplied by the number of actions per year. Subsequently, the individual risk *IR,* can be determined by multiplying the computed risk with the total presence time of a considered person per year. The expected loss of human lives $E(N_d)$ can be computed by multiplying the individual risk *IR* with the number of participants per year conform formula 3.18. Table 4.6 shows that the individual risk in building above roadways is lower than for building above railway tracks, and the $E(N_d)$ for building above roads is almost in the same order of magnitude (1.0) as building above railway tracks. Constructing a building above existing buildings is done with less risk. Furthermore, the schematic individual risk contours at the construction site can be depicted on a two-dimensional map (figure 4.9). It becomes clear that the individual risk for third parties in the neighbourhood of the constructed building is the highest, especially in the so-called risk zones.

Table 4.6: The individual risk of third parties and loss of human life of building above roads, railways and existing buildings (results adapted from thesis; Suddle (2001[A])).

Building above:	Roadway	Railway	Building
Individual risk *IR*	$3.0 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$	$3.0 \cdot 10^{-7}$
Expected loss of human life $E(N_d)$	1.65	1.33	$8.01 \cdot 10^{-4}$
Expected injuries	5.46	1.72	$8.10 \cdot 10^{-6}$

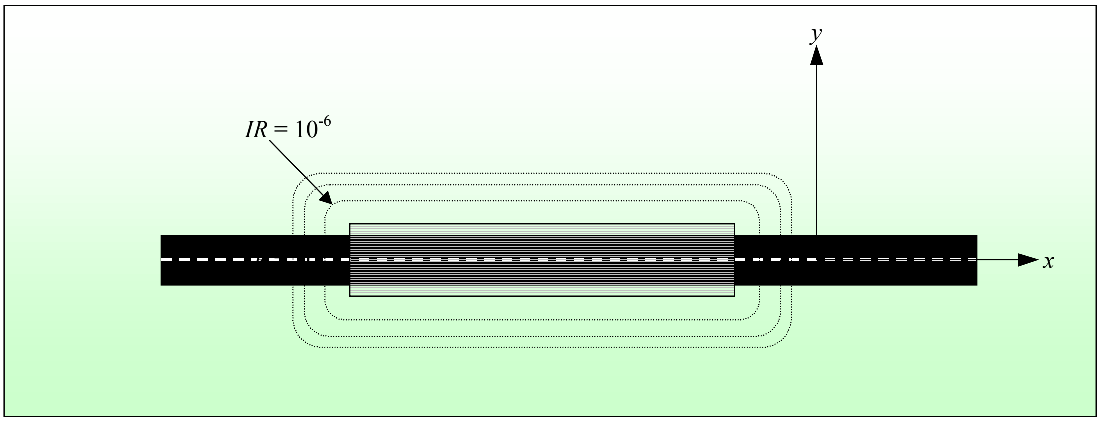

Figure 4.9: Schematic risk contours during construction stage for building above road.

4.3.2 *Group Risk*

In the same way, group risk can be computed for constructing buildings above roads, railways, and existing buildings for the considered cases. The results of the group risk are presented in figure 4.10 (Suddle (2003[A])). This figure shows that the group risk for construction above roads, railway tracks, and existing buildings is almost negligible. Note that constructing a building on top of an existing building complies with the acceptable level of group risk.

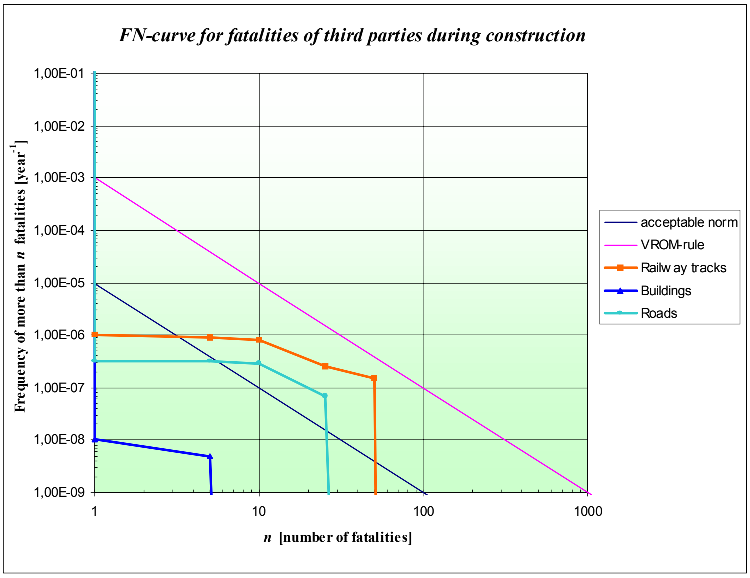

Figure 4.10: Group risks of building above transport routes.

4.3.3 *Checking for compliance with limits of risk acceptance*

Up until now, explicit norms of risk acceptance for the safety of third parties during construction have not yet been made. It should be noted that the determination of the exact risk acceptance level is a political issue. The method discussed by Vrijling *et al*. (1996), which is based on voluntariness (see section 3.3.2 and 3.3.3), is used as indication for the criteria of both individual risk *IR,* and group risk *GR*. The policy factor for third parties is set to be $\beta_i = 0.01$. The risk acceptance criterion for individual risk *IR* is thus 10^{-6} per year.

In order to determine the acceptable group risk criterion, it is assumed that independent locations N_A are 10 and the factor C_i is 0.01. The risk acceptance criterion for group risk *GR* is presented in figure 4.10. When considering these acceptance limits for risk acceptance, the results of the individual risk *IR* for building above railways and roads infrastructure are slightly exceeded. Therefore, safety measures are analysed and optimised for building above road infrastructure in paragraph 4.5.

4.3.4 Economical losses and comparison with human risk

The economical losses can also be computed by multiplying the risk per action, obtained from the Bayesian Network of figure 4.1, with the total number of actions. The results show that, as presented in table 4.7 from a financial point of view, building above railways does not significantly differ from building over roads. Again, the risk of third parties due to constructing a building on top of existing buildings is relatively low. In the same table, the human risks are compared with the economical losses, for which the monetary value per fatality α is assumed to be € 1,000,000,= (see table 4.7). It becomes clear that the expected economical costs are less of a concern than the expected loss of life. So, one may assume that when optimising safety measures, the investments of measures will be primarily compared with the expected loss of lives. Besides, a higher monetary value per fatality α will almost eliminate the effect of the economical aspects during optimisation.

Table 4.7: Comparison of human risks and economical losses including a monetary value per fatality.

Building above:	Roadway	Railway	Building
$E(N_d)$ [fatalities year^{-1}]	1.65	1.33	$8.01 \cdot 10^{-4}$
$E(N_d) \cdot \alpha$[€ year^{-1}]	1,650,000	1,330,000	801
$E(C_j)$ [€ year^{-1}]	945,000	1,035,750	17,700

4.4 Sensitivity analysis

In order to formulate safety measures and to determine their effects, a sensitivity analysis is performed. The sensitivity analysis provides both transparency of relevant scenarios and uncertainties of the results of a risk analysis. The dominant aspects are: (1) the number of actions per project; (2) the position where the element falls; (3) the situation below the building; (4) the weight of the falling element.

Furthermore, the risk zones of the building, the façades spanning the road, form an important nexus for the safety of third parties present on the infrastructure (see also figure 4.9). Surprisingly, factors, such as (design) errors, and collapsing of the main structure of the building caused by falling elements turn out to be hardly of any influence on the overall risk. The uncertainty in the calculated probabilities is approximated to be between 40 and 45 %, depending on the distribution of weight-classes. This is determined by evaluation of the conditional probabilities that were determined by engineering judgement. So, the result of expected loss of human lives $E(N_d)$ varies between 1,20 and 2,31. Another main influence parameter for the individual risk is the height of the building. The relation between the height of the building and the individual risk *IR* is presented in figure 4.11. This figure presents that the higher the building, the higher the individual risk of third parties. It also means that the higher the building, the more safety measures have to be taken. In contrast, the covering length of the building hardly influences the individual risk of the third parties during construction stage.

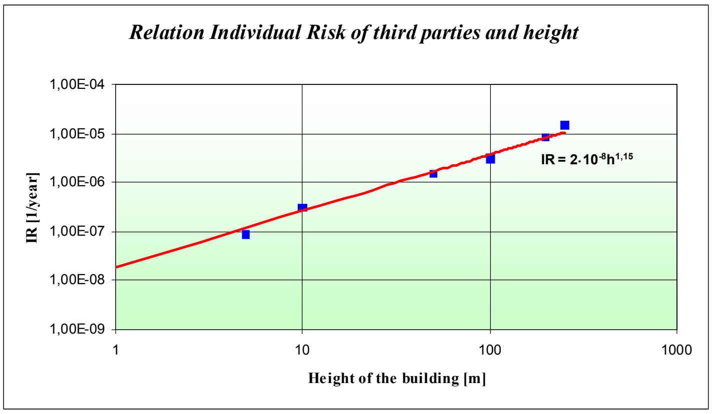

Figure 4.11: The relation between height of the building the individual risk of third parties.

4.5 Optimisation of safety measures for constructing buildings over roads

4.5.1 Formulation of safety measures

Before optimising safety measures, one should notice that the optimisation of safety measures for the construction stage differs from the optimisation for the exploitation stage, because e.g. the period of construction is shorter than the period of exploitation and therefore the optimisation of measures for the construction stage is carried out separately. However, the measures implemented for the construction stage may influence the risks and even the optimisation during exploitation. Still, approaching both optimisations separately results in a clearer presentation of the methodology of comparing economical aspects with human risks.

In this regard, safety measures are formulated and optimised for the construction stage in the case of realising buildings above roads. These measures can be divided into two main groups; *structural / functional* measures (such as applying different types of a protection canopy to prevent falling elements ever reaching the third parties), and *logistic measures* (such as closing off the road and rerouting the traffic). Total costs $C_{tot,}$, consisting of investments C_0 ,and their economical risk C_i (direct and indirect), combined with the expected loss of human lives $E(N_d)$, are determined per measure. The formulated measures, as named in table 4.8, are implemented in and verified by the Bayesian Network of figure 4.1 by adding a node (e.g. protection canopy / shelter) or changing conditional probabilities between these nodes in the original Bayesian Networks of figure 4.1. Logically, changes exert influence on the economical risk as well as the risk for loss of human lives. The result and the effect of the formulated safety measures are represented in table 4.8. An example of implementing such a measure (a shelter / protection canopy) in a Bayesian Network is presented in figure 4.12.

Table 4.8: Safety measures; their investments and their risks ($\alpha = 0$).

Safety Measures	Investments C_0	Economical risk C_i	Total Costs C_{tot}	$E(N_d)$
0: Initial situation	-	€ 970,000	€ 970,000	1.65
1: Heavy concrete floor under building	€ 330,000	€ 770,000	€ 1,100,000	0.69
2: Heavy concrete floor in risk zone	€ 110,000	€ 770,000	€ 880,000	0.72
3: Light plate in risk zone	€ 79,000	€ 850,000	€ 923,000	0.77
4: Construction during the night	€ 1,800,000	€ 950,000	€ 2,750,000	0.01
5: Close off the road and reroute traffic	€ 4,100,000	€ 950,000	€ 5,050,000	0
6: Pump concrete	€ 100,000	€ 890,000	€ 990,000	1.63
7: COMBI 2&6	€ 210,000	€ 700,000	€ 910,000	0.67

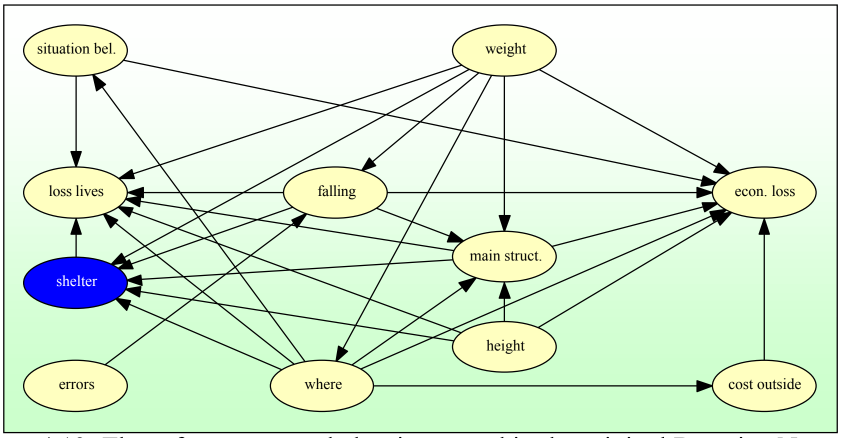

Figure 4.12: The safety measure shelter integrated in the original Bayesian Network.

4.5.2 Decision making on safety measures

Considering the safety measures of table 4.8, the decision maker, mostly the municipality, finds itself in a dilemma: "which measure has to be given preference?", the one of minimum investments, C_0, the one that minimises the economical risk, C_i, or the one that decreases the loss of human lives $E(N_d)$. This results in the situation that the decision for a measure is not always based on minimising economical grounds, but that human risk should be taken into account as well. So, several options to implement measures are considered.

If we focus for instance on safety measure 5 of table 4.8 - closing off the road and rerouting the traffic - or measure 4 - construction during the night - the expected number of loss of human lives $E(N_d)$, can be reduced to almost zero, this because a very small number of people are exposed to the effects of falling elements (small numbers of participants N_{pi}). Controversially, the total costs C_{tot} of such measures are relative high, because the investments in this measure are high as well.

However, these costs can be reduced in case of pumping concrete to floors of the building (measure 6 of table 4.8), through which the number of actions of lifting, moving and elevating (structural) elements can be minimised. Applying measure 6 means that the human risk in terms of number of loss of human lives $E(N_d)$ can also be reduced in comparison to the initial situation (case study, measure 0). In the initial situation, it is assumed that no support floor or a protection canopy is applied for interrupting falling elements and a hollow core slab floor is implemented as floor system for the building. Unfortunately, in comparison with the initial situation, the change in the human risk is not a substantial progression, the value for $E(N_d)$ was 1.65 and becomes 1.63. The main advantage of applying a protection canopy or a support floor under the building is that the risk predominantly caused by small (non-structural) elements, is eliminated. Besides, a protection canopy may also prevent a psychological (shock) effect of motorists.

If one would like to achieve a stronger reduction in the $E(N_d)$ value, one may implement a combination of measure 2, and 6 (heavy concrete floor under the building and pumping concrete to the floors). In table 4.9, the (sub)total costs, $C_{tot,}$ per measure and the expected loss of lives $E(N_d)$ are compared with a monetary value of a human being α of € 500,000.= and € 5,000,000.= respectively. This table emphasises that decision-making on a minimum base is not only complex, but also depends on which type of risks are considered, and the value of a human life, if it is taken into account at all.

Table 4.9: Solutions for safety measures; their investments and their risks.

Safety Measures	(Sub)total Costs C_{tot} if$_t$ α = € 0	$E(N_d)$	Total Costs if$_t$ α = € 500,000	Total Costs if$_t$ α = € 5,000,000
0: Initial situation	€ 970,000	1.65	€ 1,800,000	€ 9,200,000
1: Heavy concrete floor under building	€ 1,100,000	0.69	€ 1,450,000	€ 4,550,000
2: Heavy concrete floor in risk zone	€ 880,000	0.72	€ 1,240,000	€ 4,480,000
3: Light plate in risk zone	€ 923,000	0.77	€ 1,310,000	€ 4,770,000
4: Construction during the night	€ 2,750,000	0.01	€ 2,700,000	€ 2,800,000
5: Close off the road and reroute traffic	€ 5,050,000	0	€ 5,000,000	€ 5,050,000
6: Pump concrete	€ 990,000	1.63	€ 1,810,000	€ 9,140,000
7: COMBI 2&6	€ 910,000	0.67	€ 1,250,000	€ 4,260,000

In this section, the optimisation for the construction stage of constructing buildings above roads has been shown. Because both the methodology and the risk of building over roads is almost of the same magnitude as for building over rail tracks, it can be assumed that the optimisation is also estimated for building over rail tracks.

4.6 Integration of measures in construction stage

The combination of both the formulated safety measures of section 4.5 and the hesitation of decision makers can contribute to an instrument - existing recommendations - that can generally be applied in multiple use of space projects. In this regard, two types of recommendations can be formulated, namely: (1) recommendations for municipalities and (2) recommendations for design engineers.

Case studies of projects built above the motorway Utrechtse Baan in The Hague showed that municipalities have formulated such extreme contradicting demands at the construction site, that these were difficult to realise for the contractor (Suddle (2001[B]; 2002[B])). However, one should strive to balance these extremes, and almost not realisable demands or measures, with the demands of the contractor. Therefore, municipalities are advised to cope with the concept of risk acceptance instead of risk exclusion.

The recommendation to designers - the architect or the structural engineer - is to permanently integrate the formulated safety measures (see section 4.5) in the architectural, functional, and structural design of the building above the infrastructure. The disadvantage of temporary safety measures is that these are a cost-raising factor in projects. In contrast, if permanent safety measures are implemented, synergetic effects can be achieved; the safety for third parties can be guaranteed and the designer can bring out a multifunctional design, by which extra costs for removing the safety measure can be saved (Suddle (2002[D])). Some examples should be mentioned allowing the designer to achieve the goal of integration of measures in the design of the building. For instance, it is assumed in the risk analysis that the façade elements of the building are prefabricated.

One may also implement façade elements of the building with a strong deformation capacity or one may realise a strong and elastic protection canopy. The outcome of such a measure is that the falling element will not fall through the protection canopy and therefore hit a motorist. One may also design the periphery of the building or design the shape of the building in such a way that the safety for third parties in the construction stage is minimised. The construction type may also influence the overall safety.

For instance, when the façade and other structural elements are transported to a floor, the erection of these elements should be done from inside the building rather than from the outside of the building. The transport and erection of these elements from outside the building may cause a considerable risk for third parties due to falling elements. Using and applying ”set backs” in the shape of the building can also contribute to the safety of third parties (see figure 4.13). In this way, the height of the risk zones can be decreased, i.e. the falling of objects will only take place once in the risk zone while the first construction floor is realised.

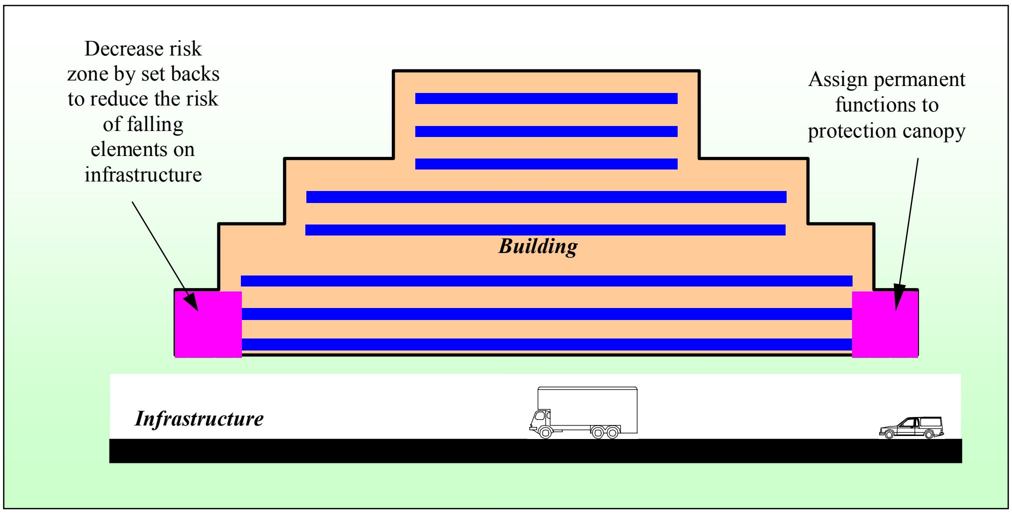

Figure 4.13: Improvement of the safety for third parties can be realised by set backs in the shape of the building.(Suddle (2002[B])).

Another practical measure is to implement several permanent support floors in the risk zones or the lower storeys and assigning functions to them such as a parking garage. These can intercept falling elements from higher floors. By this, the elements are not only intercepted at an early stage, but also the impulse of the falling element can strongly be reduced. Configuration with the shape of the building should therefore be used in architectural impression of buildings above roads and railways. The formulated safety measures (see section 4.5.1) can also be integrated in the functional design of the building. If we consider the safety measure ”applying a protection canopy”, a function like a restaurant or a parking garage can be integrated in the lower floors of the building. This can save the costs for removing the protection floor after the construction.

4.7 Conclusions

This chapter presents the approach for the safety of third parties during the construction stage. Risk analysis by means of Bayesian Networks is an outstanding approach to determine the risks of third parties during construction. Although the construction stage of multiple use of space projects is quite short in comparison with the life time of a project. This chapter shows that, the lack of safety during the construction of multiple use of space projects can have serious consequences for third parties. The implementation of safety measures is therefore inevitable. However, decision-making on safety measures is complex and involves different points of views. Minimising the total costs or the investments in safety measures does not always provide maximum safety for third parties. It is, therefore, strongly recommended that safety measures should be integrated in the design of such projects. By this, the costs for removing the measures, can be reduced if not completely eliminated. Finally, it should be stated that if it is possible to combine such measures with measures during exploitation, an extra synergetic effect could be achieved.

5

Physical Safety in the Exploitation Stage

The focus of this chapter is on safety during the exploitation stage. It has already been stated in chapter 1 that safety is one of the prime considerations in both the covered infrastructure, and the buildings above it. More activities take place on the same surface area, causing more people to be possible victims of a single catastrophe. In this regard, this chapter proposes a methodology for assessing physical safety in the exploitation stage for the combination of buildings above roads, with or without transport of hazardous materials. The overview of this chapter contains approaches for both individual and societal risk combined with economical risk in multiple use of space projects. An M.Sc. research has been carried out by Heilig (2002), related to this Ph.D. research, in which societal risk was quantified for buildings above roads and railways in the exploitation stage. Some results of Heilig (2002) are used in this chapter and some of the missing links are scrutinised in more detail.

5.1 Classification of aspects during the exploitation stage

5.1.1 Introduction

In order to perform a quantitative risk analysis for the exploitation stage, three basic areas can be distinguished (see (Suddle (2002^A)):

1. The building (above the infrastructure);
2. The infrastructure (beneath the building);
3. The vicinity (surrounding the infrastructure).

It may be assumed that the interrelations of the different areas may influence the overall safety level. In general, a risk analysis, which will be performed on cases, should focus on four different situations (figure 5.1) (Suddle (2002[G])):

- 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);
- 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).

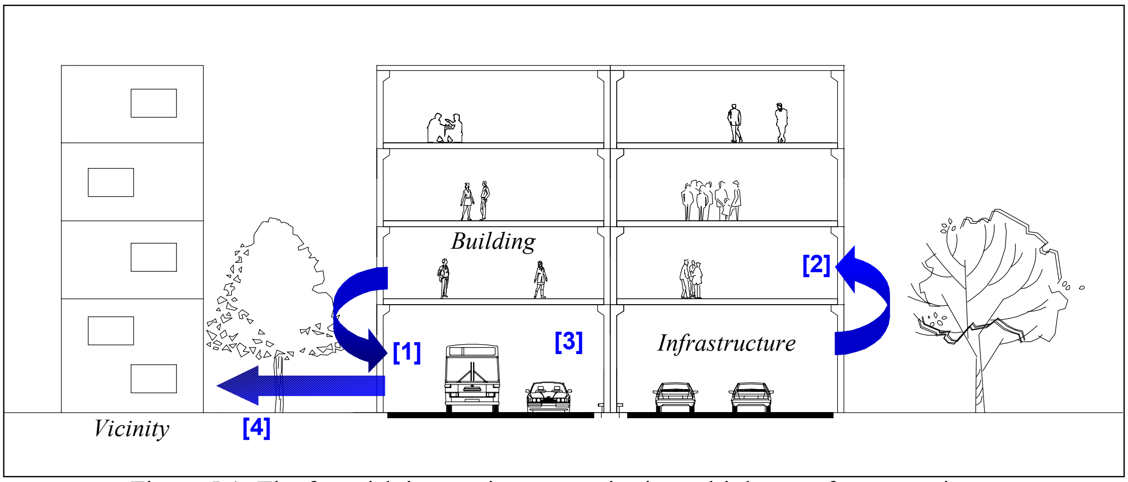

Figure 5.1: The four risk interaction categories in multiple use of space projects.

One may also consider the external risks from the vicinity towards the infrastructure or the internal risks inside the building above the infrastructure, such as fire and explosion. However, these risks are negligible and do not differ from buildings built adjacent to the infrastructure or elsewhere (see e.g. CIB (2001)). Therefore, these risks are beyond the scope of this research. The characteristics of these three basic areas, which will be integrated as basic parameters of the risk analysis models, will be described in the following sections.

5.1.2 The building above the infrastructure

The fundamental characteristics of a building above infrastructure are its dimensions, such as height h, span l, and covering length of the building L. These dimensions are generally imposed by the urban conditions and the architectural and structural design, related to the function of the building, which in its turn determines the number of people present in the building and the duration of their presence. These two elements are significant for quantitative risk analysis. Examples of functions of buildings, in which both intensity and the time of the presence of people will vary, are residential buildings, office buildings, a park, or a parking garage (see figure 5.2).

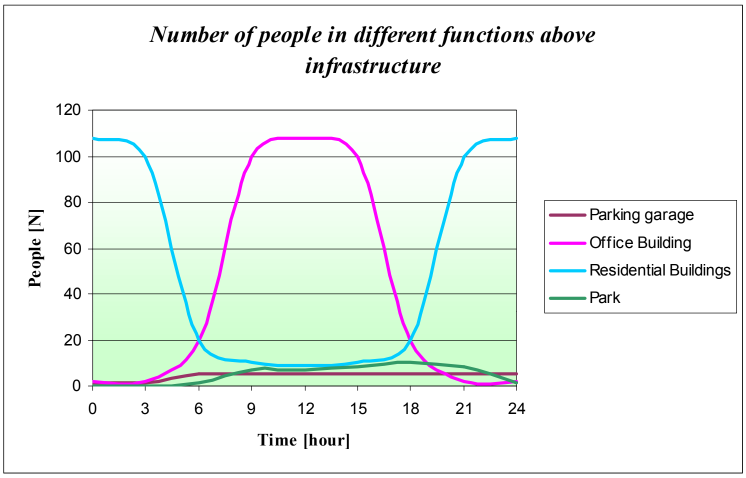

Figure 5.2: Examples of number of people in different functions above infrastructure during the day.

5.1.3 The infrastructure

The characteristics of the infrastructure during exploitation stage depend on the type of infrastructure on which the building is built, e.g. above roads or above railway tracks, which determine the (traffic) condition, the probability, the consequence and thus the risk of an accident on infrastructure. According to Mulders (2003) the probability of an accident on road infrastructure is 100 times higher than on rail infrastructure, because the railway traffic is a system that is more centrally controlled. In contrast, the consequences of an accident on rail infrastructure are in most cases greater, because a great number of people are involved in trains and mostly large quantities of hazardous materials are transported per ship (Kleef *et al.* (2001)). Besides, railway traffic consists of planning, traffic control systems, signal systems, ATB[1)], trains, and the infrastructure (rails, switches and crossings). Roadway traffic can be considered as a system existing of road, vehicles and drivers. Furthermore, the ratio of passing vehicles and heavy traffic, in particular both quantities and type of the transport of hazardous goods, are basic parameters for the activities that take place on the infrastructure (see also section 5.2.3).

5.1.4 The vicinity

The density of the buildings, and thus the number of people present, are considered when modelling the vicinity. The population density in the vicinity depends on the location under consideration and thus the function of that location (see section 5.2.3). The location may consist of a rural or an urban place. The density of people varies between 1,000 persons per km^2 up to 10,000 persons per km^2 for respectively low and high-densely populated areas (Heilig (2002)).

5.2 Risk analysis

5.2.1 Qualitative risk analysis

A qualitative risk analysis is performed for people in the neighbourhood of multiple use of space projects using FMEA-techniques for the four risk interrelations between those three areas.

1) ATB is the Dutch abbreviation for Automatic Train Control system, which controls reading high speed and stops for red signals.

These techniques are here applied for the exploitation of a building over a motorway (a full scope of the FMEA is presented in the M.Sc. thesis of Heilig (2002)). As mentioned in the previous chapter, considering the aim of this research, risk regarding cost increase and loss of human life are taken into account. A section of the FMEA with its major hazards is presented in table 5.1, which is subsequently transformed into the main Bayesian Network of figure 5.6. 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 5.1 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. Both have different consequences and probabilities on different areas. Furthermore, the hazards taking place on the infrastructure can be grouped into four dominant classes: *traffic accidents* (mechanical load on the structure of the building), *fires*, *leaks of toxic substances*, and *explosions* (see also Suddle *et al*. (2004) and Taylor (1994)). In contrast, the hazards in the building are mainly *fire*, *explosions,* and in some cases (with a very low probability of occurrence) *falling objects*.

Table 5.1: An example of a section of the FMEA for safety of people during the exploitation (see Heilig (2002)).

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

Both the characteristics and the effect distances / effect areas of the mentioned scenarios are significant for the QRA. An overview of the critical scenarios of table 5.2 will be discussed in the following section. In table 5.2, both the characteristics and the effect distances / effect areas are given (adapted from various literature (CPR 14 (1997), CPR 18 (2000), Kleef *et al*. (2000), BZK (1997)). BZK (1997) and Persson (2002)) describe both consequences and effect distances of calamities in both urban areas and tunnels respectively.

Table 5.2: Characteristics of hazards with their effect distances / effect areas.

Hazard	Characteristics of hazards	Effect Distances	Reference
Fires	Time, temperature and intensity	10 - 50m	Person (2002)
Leak of toxic substances	Exposure time and concentration	10 - 50 m (liquids) 5 km (gasses)	BZK (1997) CPR 18 (2000)
Explosions	Peak overpressure and impulse	200 - 400m	CPR 18 (2000)
Traffic accidents	Resistance of structure and intensity of load	20 m	-

5.2.2 *Quantitative risk analysis and critical scenarios in the exploitation stage*

- *Fires*

Fires on infrastructure may be the result of leaks from tanks transporting hazardous materials. Fires may also be the result of an accident on the infrastructure. In buildings, fires can occur as a result of an accidental ignition (see FMEA section 5.2.1). Toxic releases from fires could be a problem (Taylor (1994)). In most situations, toxic smoke will be generated above the level at which it can cause acute toxic effects, especially inside the building or in the (covered) infrastructure (Drysdale (1994)). Fires are hazardous both because of their direct heating effect, by convection within the fire itself, and because of the radiation from the fire (CIB (2001)). For humans, in case of fire engulfment the effects are on skin and on the lungs. Indoors (in buildings and tunnels / covered infrastructure), smoke rather than the fire itself, is the most frequent cause of death. Fire can constitute a hazard for the infrastructure and the building above by damaging the structural elements of that building and by adversely affected installations. The rate of burning, the shape of the flame, the heat radiation pattern, smoke, toxic gas production, and heat losses to the surroundings are the basic elements defining the range of hazards and possible spread of fire. Detailed event trees of fires are presented in Appendix A. The main cases of fire, which must be treated for risk analysis of buildings above roads and railway tracks, are (CPR 18 (2000); CUR (1998); Taylor (1994)):

- *Pool fires*, in which a liquid is collected on the ground (infrastructure), and burns as a roughly conical flame (i.e. without substantial influence of ventilation);
- *Running front fires*, similar to pool fires, but in which the flame front spreads due to the flow of the liquid fuel;
- Confined, or *compartment fires*, in buildings or heavy goods vehicles on the infrastructure;
- *Flash fires*, in gas clouds;
- *Jet fires*, from escaping gas or liquid;
- *Fires* from *boiling liquid expanding vapour explosions* (BLEVES).

These fires can be grouped into four main fire intensities with their characteristics, which are considered in this research (CUR (1998) or Both (2001)) as presented in table 5.3. Fire on the infrastructure varies between 5 MW light fire (passenger cars), 100 MW heavy fire (busses / trains) and 300 MW extreme fire (trucks / trains). Fire in the building varies between roughly 1 MW and 100 MW. It is a very rare case that a fire of 300 MW occurs in a building. The type of the fire indicates the temperature of the fire at a certain location in the covered infrastructure.

Table 5.3: Fire characteristics in the covered infrastructure (see e.g. Person (2002)).

Type of fire	Maximum Temperature [°C]	Effect distance [m]	Smoke [m]
5 MW (compartment fires; small)	500	10 - 15	50
20 - 100 MW (compartment fires; heavy)	700	50	100
300 MW (pool fire)	1200	150 - 750 m^2	250
300 MW (flash fire)	1200	20 - 60	500
300 MW (jet fire)	1200 - 1250	250 - 300	1000

Persson (2002) presents models for temperature, heat release, and smoke concentrations as functions of the distance and the time in tunnels. These models indicate that the temperature will exponentially descend with the distance from the fire and time passed since ignition. The models of Persson (2002), partly based on assumptions, are used for presenting the relation between the temperature and the distance from the fire in the covered infrastructure (figure 5.3).

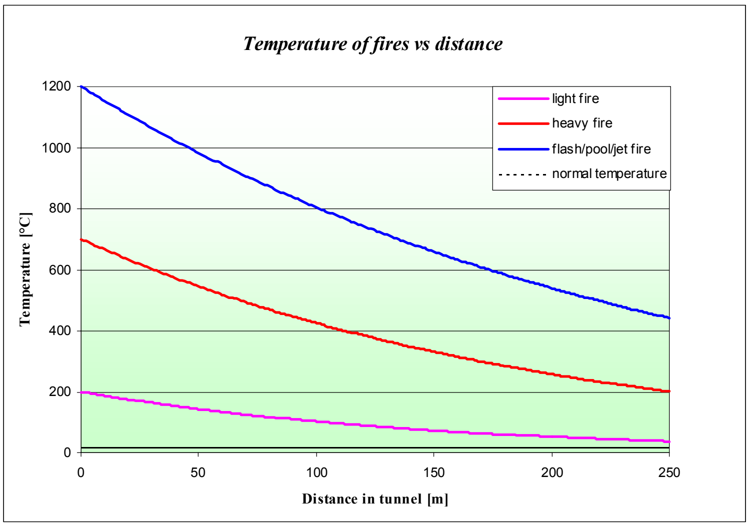

Figure 5.3: Temperature of fire at the infrastructure vs distance in a tunnel / covered infrastructure (according to models discussed by Persson (2002)).

Considering the previous, it becomes clear that when a fire occurs on infrastructure, the factors of time and the intensity of the fire are significant parameters affecting the damage or the collapse of the building above the infrastructure (risk category [2]).

- *Explosions*

In this research three kind of explosions are considered, following from several surveys e.g. by Baker *et al.* (1983) or Berg *et al.* (2001): (1) *BLEVE* (on the infrastructure); (2) *deflagration* (in buildings and the infrastructure) and (3) *detonation* (on the infrastructure).

- BLEVE (according to Weerheijm et al. (2002))
BLEVE is an acronym for “Boiling Liquid Expanding Vapour Explosion”. A BLEVE is the consequence of the failure of a pressure vessel containing a liquefied gas. Under ambient conditions, the temperature of such a liquid is beyond the boiling point. According to the incident record, a BLEVE is usually the consequence of a fire that heats the vessel, and thereby increasing its internal pressure. At the same time, the fire reduces the vessels’ material strength (Berg & Weerheijm (2004)). If by a sudden failure of the vessel, the internal pressure suddenly drops, a fraction of the liquid will immediately evaporate.

The quick change of the liquid phase to the vapour phase goes hand in hand with a big volume increase. The vapour pushes the surrounding air away, which results in a blast wave in the vicinity. The blast wave of a BLEVE could cause damage a substantial distance from the explosion (Weerheijm *et al*. (2002)). If the vapour is ignited in open air, it will burn as a fireball, in which the blast effects are negligible, causing an intense heat radiation (Cooke & Meeuwissen (1989)). If the accident happens at ground level (in open air), a rapidly growing hemisphere is formed. It becomes a full sphere and will rise in the air as the sphere attains its maximum diameter. A cloud of dust will whirl up behind the fireball because of the rapid flow of heated air. Rising up, the ball cools and begins to shrink. The effect distance of a BLEVE in open air ranges between 200 - 400 meters, particularly caused by the intense heat radiation (CPR 18 (2000)). In the covered infrastructure, however, it is questionable whether such a fireball with intense heat radiation will form, because the availability of the oxygen supply in the tunnel / covered infrastructure is limited. In the covered infrastructure, the blast effects (air shock / large peak overpressure) will be the main contributor to the total damage of the tunnel and buildings above it along with the death of people inside the tunnel and the building.

- Deflagration (according to Berg & Weerheijm (2004))
If, as a consequence of an incident, a flammable gas tanker in a tunnel is damaged and develops a leak, a vapour-air cloud may rise, filling the entire tunnel / covered infrastructure downstream. A vapour-air premixture is capable of propagating a flame only if the vapour concentration is between certain limits, namely the flammability limits. On ignition by a spark a flame front develops, which initially propagates away from the point of ignition in the form of a sphere. After having filled the full covered infrastructure cross-section, the flame front will grow through the flammable mixture towards the tunnel / covered infrastructure exits. Initially, the propagation velocity of the flame is no higher than just a few meters per second. The flame has a thickness of less than 1 mm and constitutes an interface between the flammable mixture and the combustion products. In this thin interface the combustion reaction takes place. A further speed up of the process develops under the influence of the geometric boundary conditions. Rigid boundaries of the flow such as the tunnel walls and a possible traffic jam of standing vehicles determine the structure of the expansion flow. This structure consists of velocity gradients in the boundary layers along rigid walls and in the wake behind rigid obstacles. Velocity gradients are unstable as they break up into vortex motion (turbulence). Meeting these flow structures, the flame front deforms and enlarges its surface area and thereby increasing its propagation velocity. Growing expansion flow velocities are the consequence. Increasing flow velocities go hand in hand with growing turbulence intensities. During this development, the flame front increasingly assumes the shape of a thick turbulent mixing zone between flammable mixture on one side and combustion products on the other. Inside this mixing zone, the internal flame surface area (where the combustion reaction occurs) could perhaps become very large. The acceleration of the process goes on as long as flammable mixture is available or until the flame meets a tunnel exit. A flame propagation that develops through such a process is called a deflagration. The positive phase of the gas explosion in case of deflagration is relatively long and the peak overpressure varies between 10 - 800 kPa ($\cong$ 0.1 to 8.0 bar) and the propagation velocities of the order of 2 - 800 ms^{-1}. If this development is allowed to go on long enough, and it gains a sufficient level of velocity (many hundreds of m/s) and pressure (many bars), it is possible that the physical process of flame propagation abruptly and fundamentally changes to detonation (Berg & Weerheijm (2004)).

- Detonation (according to Berg & Weerheijm (2004))
By coincidence favourable conditions for deflagration-detonation transition may rise in the vicinity of the flame front. Such conditions may, for instance, exist in an intense turbulent mixing of hot reaction products with cold unburned mixture at such a rate that partial and local quenching occurs.

A sudden temperature rise through a chance local compression may trigger such a hot spot to react more or less instantaneously (a local sub explosion). This local sub explosion produces a blast wave superposed on top of the pressure level of the deflagration process. If the blast wave of the sub explosion is strong enough to compress the flammable mixture far beyond auto-ignition, the flame front couples to the blast wave and may engulf the entire flame propagation process. A flame propagation process of such a mechanism, in which the flame has coupled to a strong compression shockwave, is called a detonation (Berg & Weerheijm (2004)). Depending on the reactivity and concentration of gas, the shock wave may continue to accelerate, or may drop to deflagration. Detonation wave properties, characteristic of stoichiometric mixtures of air with the most common hydrocarbons, are roughly: a wave overpressure of $1.5 - 2.0 \cdot 10^3$ kPa ($\cong$ 15 - 20 bar) and a wave propagation velocity of 1500 - 2000 m/s (Berg & Weerheijm (2004)). Consequently, both deflagration and detonation are mostly fatal for the structure of the covered infrastructure as well as for all people present inside. In general, according to Baker *et al.* (1983), an explosion of such magnitude consists of four components: a blast wave, atmospheric and ground effects, fragmentation and missile effects, and thermal radiation effects. Schematised blast waves of both deflagration and detonation and general shape of P-I damage limit curves are shown in figure 5.4.

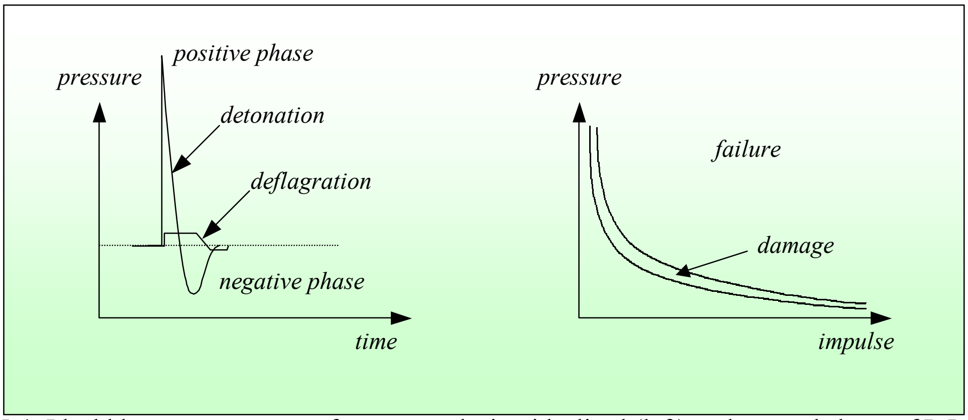

Figure 5.4: Ideal blast wave structure from an explosion idealised (left) and general shape of P-I damage limit curves for structures (right).

Moreover, it is discussed by Baker *et al.* (1983) and Berg *et al.* (2001; 2002) that if the ratio L/D - which is the length of the tunnel (in this thesis the covering length of the infrastructure) L divided by the average diameter of the covered infrastructure D - is more than 10, the probability of a detonation in the pipe / tunnel be increase rapidly. In this research, it is therefore assumed that if L/D of the covered infrastructure is more than 10, the possibility of a detonation is valid (see also section 5.2.3 and Appendix A). More research and methods to calculate these components has been done on detonations and explosions (see e.g. Cooper & Kurowski (1996)).

❑ *Release of toxic gasses*

Toxicology is an extremely complex subject on which little direct experience exists[2)] (e.g. Taylor (1994) and Akker (1998)). In this part of the thesis, major elements of a release of toxic substances are discussed. In essence, the effect of a toxic chemical depends to a very large extent on the amount or dose of the substance, which is imposed on an organism. Therefore, both the *concentration* of the gas and the *exposure time* are significant parameters for the QRA.

2) The available information is obtained from animal experiments, and with very poor control of accidents in which large releases of gases have occurred.

Mostly, the effect of a release of a toxic gas is characterised by a response, for example the fraction of the population that dies. The fatality probability for individuals is generally assumed to follow a gaussian distribution. Figure 5.5 presents a schematic cumulative distribution curve, in which the fraction of a given population is shown, giving a specific level of response (for data see CPR 18 (2000)). The concentration of a toxic gas in the air depends on e.g. wind speed, the wind direction or the façade permeability in buildings. Releases of toxic gasses generally fall into one of two categories. *Light gasses* such as ammonia initially spread upward (unless they are mixed with air and are cold, for example as a result of evaporation of the liquid), later diffusing neutrally. These rarely present a serious threat to life, unless they occur in a narrow valley, between buildings, or indoors. *Heavy gasses* and mixtures tend to spread horizontally, forming a dense low-lying cloud of gas (e.g. chlorine). This may travel with the wind across a populated area or collect in narrow valleys, making this scenario much more hazardous. Most of the time the cloud will tend to disperse, but in some cases a cloud will remain in valleys for a longer period, given that the weather conditions are stable.

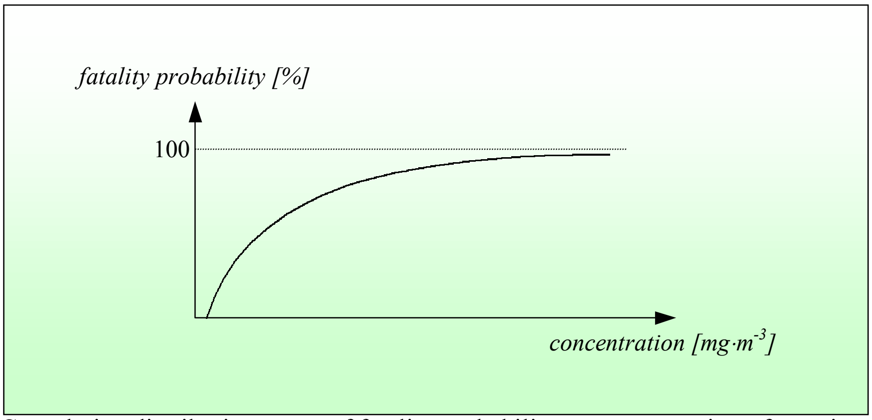

Figure 5.5: Cumulative distribution curve of fatality probability vs concentration of a toxic gas (see CPR 18 (2000)).

- *Collisions affecting the structure of the building above the infrastructure*

Traffic accidents (e.g. derailment of trains or collisions) can cause a large mechanical load on the structure that on its part can lead to the collapse of the building above the infrastructure. This building collapse may occur if the applied load is bigger than the strength of the structure of the building. The total load of the traffic accident towards the main structure of the building, of course, depends on both the speed and the mass (and thus the impulse) of the considered vehicle. The properties of the scenarios, discussed in this section, are basic elements for the over all schematic Bayesian Network of figure 5.6 and will be used for drawing up measures. Additionally, it is important to note that when considering any scenario that may occur on the infrastructure, in order to determine the risks for people present in the building above the infrastructure (risk category [2]), the (probability of) *collapse* of that building is a significant parameter. The collapse of the building above the infrastructure can be caused by fire, an explosion, or a mechanical accident inflicted upon the building. In contrast, release of toxic gasses may cause victims in the covered infrastructure or the buildings above the infrastructure rather than a collapse of a structure of the building above the infrastructure (Suddle (2004[B])). Regarding the risk upon the vicinity (risk category [2]), it is particularly the covering length of the infrastructure that may influence the risk on people in the vicinity.

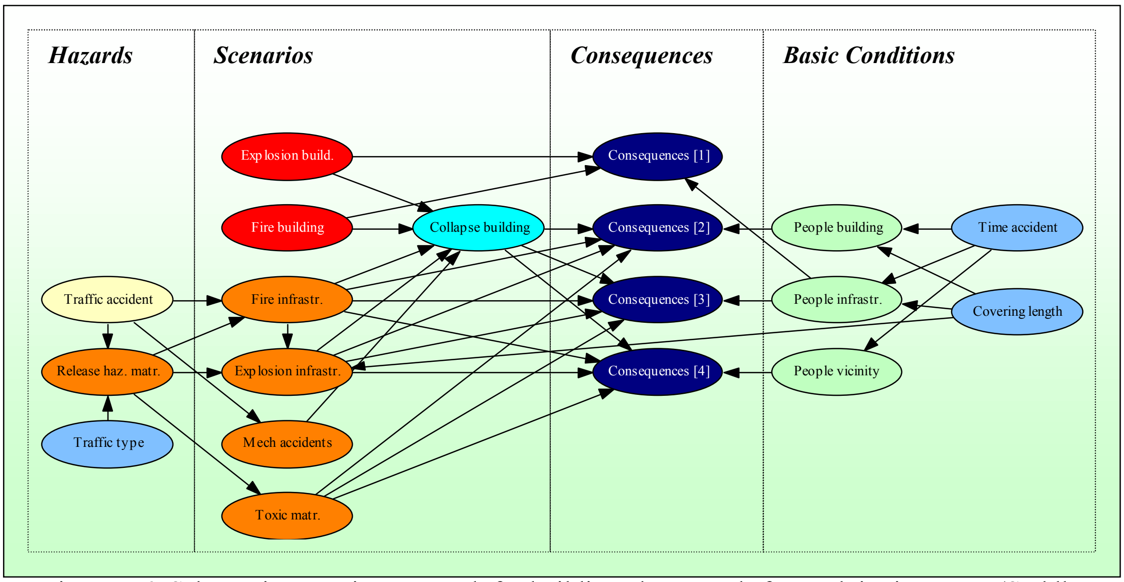

Figure 5.6: Schematic Bayesian Network for building above roads for exploitation stage (Suddle (2004^B)).

Note that the Bayesian Network of figure 5.6 is an overall network to conduct a quantitative risk analysis, this means that this Network consists of various nodes between the main nodes. The full Bayesian Network with sub nodes is presented in Appendix A. Moreover, scenarios taking place on the infrastructure remain the same when the infrastructure is covered. The consequences, however, are the great difference between impact on structures above and beside the infrastructure when it is covered or uncovered. As mentioned, it is the collapse of the building above, which may cause fatalities in the building above the infrastructure. So, if the probabilities of collapse due to scenarios can be determined, the risk can be presented in the 3rd spatial dimension (see next section).

5.2.3 Quantification of probabilities and relations of aspects

In order to quantify the probabilities and relations of aspects, a literature review has been performed. A national risk assessment for selected hazardous material in transportation in the USA is presented by Brown *et al.* (2000). Methods for determining and processing probabilities are discussed in CPR 12 (1997) (yellow book). Methods for the calculation of physical effects can be found in CPR 14 (1997) (red book). The green book CPR 16 (1997) contains damage models for exposure to heat radiation, explosion effects on structures and humans, toxic products released during a fire, acute intoxication, and indoor protection against toxic substances. Guidelines for quantitative risk assessment, mostly used for QRA, are described in CPR 18 (2000) (purple book). Persson (2002) describes a methodology for performing a QRA considering an unidirectional road tunnel. Heilig (2002) presented an overview of probabilities for scenarios taking place on the covered infrastructure. These methods, guidelines, and probabilities are investigated in this study. However, not all probabilities of hazards can be found in literature. In this regard, it is quite customary to estimate such probabilities on the basis of (in house) engineering judgement. Sometimes, there is a need for field-research (demanding a lot of time and money), which is, as stated in chapter 1, beyond the scope of this study. The main parameters for the QRA and thus the basic input for Bayesian Networks will be discussed in this section. A full overview of probabilities used in the network, obtained from the mentioned literature and used in the Bayesian Network, is presented in *Appendix A*. The quantifiable aspects, considered in the Bayesian Network of figure 5.6, are treated as follows:

1. *Basic conditions:*
   a. Covering length of infrastructure (see Appendix A1a);
   b. People present in building, covered infrastructure, and vicinity (see Appendix A1b).
2. *Hazards:*
   a. Traffic accident (see Appendix A2a);
   b. Transport of hazardous materials (see Appendix A2b);
   c. Following up scenarios of LF, GF, LT and GT (see Appendix A2c).
3. *Collapse of building above infrastructure due to scenarios:*
   a. Explosion on covered infrastructure (see Appendix A3a);
   b. Fire in building and covered infrastructure and fire spread (see Appendix A3b);
   c. Mechanical accidents towards main structure building above (see Appendix A3c).
4. *Consequences on infrastructure, building and vicinity:*
   a. Fatalities (see Appendix A4a);
   b. Economical losses (main text chapter 5).

- Ad 1

In the QRA, three covering lengths of infrastructure are considered: 30 m, 30 - 100 m, 100 - 1000 m. Subsequently, the number of people present in different areas (building above the infrastructure, on the infrastructure and the vicinity) are determined for those covering lengths.

- Ad 2

Basic hazards, such as the probability of a traffic accident, fraction of transport of hazardous materials, and following up scenarios of the hazardous materials LF (Liquid Flammables), GF (Gaseous Flammables), LT (Liquid Toxics) and GT (Gaseous Toxics) could easily be found in several studies (e.g. Kruiskamp (2002); Weger *et al*. (2001); AVIV (1997); Persson (2002); CUR (1998); CPR 18 (2000), Rosmuller (2001)).

- Ad 3

No probabilities were found in literature concerning the collapse of the building above the infrastructure due to explosion on covered infrastructure, fire spread, or collisions with the main structure of the building above. To determine these probabilities, assumptions were made based upon (in house) engineering judgement. For the explosion scenario, it is assumed that the probability of collapse of the building above the infrastructure due to a BLEVE, deflagration and detonation scenario is respectively 0.9, 0.5 and 0.99. Likewise, the probabilities of building collapse due to fire and collisions against the building structure, are estimated. The probability of explosion, BLEVE and a detonation is varied with the covering length of the infrastructure. It is assumed that a large covering length will result in a relatively high probability of a detonation scenario (also discussed by Berg *et al*. (2001)). Probabilities for fires occurring in buildings and covered infrastructures can be found in the surveys of CUR (1998); Holborn *et al*. (2002) and Frantzich (1998). The probability of a collision affecting the main structure of the building has been determined mathematically (see Appendix A).

- Ad 4

Ale *et al*. (1996) introduced the basic calculations for both group risk and individual risk. Primarily, the occurrence of scenarios depends on both the quantity and the type of the transported hazardous material (on the road). Ale *et al*. (1996), makes a logical inference stating that the data used to calculate the group risk depends on the specified location and the people present on that location. Subsequently, the total area affected by a (relevant) scenario can be determined (see also table 5.2). After that, the number of people present in the specified area can be computed from population data. The fraction of number of people present in the affected area provides the number of people killed in that area, given a scenario.

However, in multiple use of space projects, the physical separation of the infrastructure (enclosing or covering), has an influence on the effected area and thus on the consequences of the scenarios. Because of this, the number of fatalities due to a scenario in the vicinity differ from the situation when the infrastructure is not covered (see also section 5.3). Obviously, it depends on the scenario which fraction of the number of people present in that area will be killed.

According to Weger *et al.* (2001) and Berrogi (1999), the number of fatalities in a relative small area grid of e.g. 50 · 50 m^2 are fixed numbers, to which the calculations of fatalities seems to be quite predictable. If the number of fatalities regarding group risk is modelled in such small grids in Bayesian Networks, a large number of consequence (grid) nodes would be needed, through which the transparency of such a network would become very unclear. Consequently, the fatalities regarding the group risk are modelled for a relative high area grid of 1 · 1 km^2. Such an approach has some disadvantages, because a large area grid introduces uncertainties for predicting fatalities. Nevertheless, these uncertainties can be somewhat minimised by means of mathematical approaches. Besides, this thesis stresses the methodology for risk assessment in particular, rather than an exact calculation of the risk. Before focussing on the mathematical functions, one has to note that there is a variation in the expected number of fatalities due to an accident scenario. In general, the larger the consequences, the larger the variation. Accidents may also result in injuries rather than deaths. An attribute of this type of accident is that the standard deviation is high. If this point is considered together with the relative high area grid, the number of people killed due to a scenario can be considered as an average number of people killed in that specific area (in this example area grid of 1 · 1 km^2) along with the standard deviation. Using this, the fixed number of fatalities can be transformed into probabilistic data. Hence, this fraction of fatalities in that area should be considered as a probabilistic distribution function. These conditional probability density functions for different scenarios, especially scenarios with large numbers of fatalities, can be determined by a gamma density function (equation 5.1 to 5.3).

$$f_x(X) = \frac{1}{\Gamma(\alpha)\beta^k} X^{\alpha-1} e^{\frac{-X}{\beta}} \quad \text{in which:} \quad X \geq 0,\ \alpha \geq 0,\ \beta \geq 0 \tag{5.1}$$

In which:

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} e^{-t} dt \tag{5.2}$$

The mean value and the deviation can be determined by the following relation:

$$V_X = \frac{\sigma_X}{\mu_X} = \frac{\beta\sqrt{\alpha}}{\alpha\beta} = \frac{1}{\sqrt{\alpha}} \tag{5.3}$$

In this thesis, the modelling of the fatalities for the four main scenarios of each area (the building above the infrastructure, the infrastructure and the vicinity) for each risk category [1], [2], [3], and [4] is determined by the mentioned gamma distribution function. First of all, the number of people present in the affected area was determined. Then the average number of people killed due to a scenario per risk category was determined. A full overview of these distribution functions per scenario per risk category is presented in Appendix A.

Furthermore, the reader should keep in mind that, the more people present in a specific area, the greater the uncertainty to predict the fatalities among the number of people present in that area. This does not only mean that the mean value increases, but the deviation increases as well, and so the uncertainty in the predictions of the model increases (see also the sensitivity analysis, section 5.5).

When considering *economical losses*, one can say that economical damage mainly depends on both the direct and the indirect economical loss on the considered location. In this study, the economical loss is considered on the basis of a logarithmic scale. In case of closing off the infrastructure for a period longer than a few years, due to e.g. the collapse of the building above, the indirect economical consequences could be enormous. In this regard, five different cost-classes (of economical risk) were considered and particularly the effect is determined for the basic scenarios. Refinement of economical losses will be highly appreciated.

Table 5.4: Examples of several economical loss classes for building above roads (on a logarithmic scale).

Cost-class	Example of costs
I. No costs	In case of no hazard occurrence
II. < € 100,000	Light damage to vehicles and to infrastructure, etc.
III. € 100,000 - € 1,000,000	Damage to infrastructure and building, etc.
IV. € 1,000,000 - € 10,000,000	Damage to infrastructure and building above combined with and closure of infrastructure for weeks, etc.
V. > € 10,000,000	Heavy damage to infrastructure and building above and buildings in the vicinity combined with close off the road and reroute the traffic for a long period, etc.

5.2.4 *Quantification of probabilities of aspects above railways and existing buildings*

Probabilities and consequences of rail transport can be found in the relevant literature. The European Standard for railways, RAMS, (CENELEK (1999[A & B])) provides in qualitative terms, typical categories of probability or frequency of occurrence of a hazardous event and a description of each category for a railway system. The basic frequency of occurrence of a hazardous event on railways, such as derailments, can be found in the SAVE (1995[A & B]) reports. The survey of Kleef *et al*. (2001) - also the so-called MAVIT tunnel incidents - presents a deterministic analysis, carrying out the development of scenarios. Particularly the fire scenario on infrastructure and at railway- and roadway tunnels has been analysed. Note that the transport of hazardous materials over railway contains different subdivisions than the divisions of road transport. In essence, when assessing risks above railways, some parameters and consequences differ from the assessment of risks above roads. Mostly, the load on railways per wagon in quantitative terms is much higher (and thus the consequences are bigger too) than the quantity transported by road. In contrast, because it is a much more automated traffic system (see section 5.2.3), the probability of a hazard occurrence on railways is much lower than on roads (see e.g. the study of Mulders (2003). This results in different consequences for scenarios. In fact, the method of determination and quantification of probabilities and relations of aspects above railways or existing buildings, is almost the same as the quantification of probabilities and relations of aspects above roads. Some of the main quantifications are summed up in Appendix A. These are derived from the mentioned surveys, in which some additional parameters, such as probabilities and consequences are introduced, when risks are assessed above railways (e.g. derailment and electrocution). The hazards, probabilities and basic conditions, integrated in the risk analysis, that differ from building above roads are:

5. *Basic conditions:*
   a. People present in building, covered infrastructure (see Appendix A5a).
6. *Hazards:*
   a. Probability of a traffic accident (see Appendix A6a);
   b. Fraction of transport of hazardous materials (see Appendix A6b);
   c. Electrocution (see Appendix A6c).
7. *Collapse of building above infrastructure due to critical scenarios:*
   a. Collisions affecting the main structure of building above (see Appendix A7a).
8. *Consequences on infrastructure, building and vicinity:*
   a. Economical losses (see Appendix A8a).

Furthermore, the same classification is used for the fire scenario in railways, as for the risk analysis on road infrastructure. Fatalities on the covered railways and vicinity are normally higher, because a great number of people are present in the tunnel and larger amount of hazardous materials is transported. Details on modelling of fatalities near and above railways can be found in the thesis of Heilig (2002). The rest of the conditional probability functions for fatalities are similarly determined as presented in previous sections. The Bayesian Network for risk analysis for railways is presented in *Appendix A*. When considering *building above existing buildings*, a lot of scenarios disappear from the scene, particularly scenarios regarding transport of hazardous materials. The remaining scenarios, with the same probabilities and consequences that are taken into account in the risk analysis are fire and explosion (see also risk analysis of Holický & Vorlícek (1999) and Magnusson *et al*. (1996)). Besides, the expected costs will be much lower than if building over railways and roads.

5.3 Three-dimensional approach of Individual Risk Contours

5.3.1 Two-dimensional and Three-dimensional individual risk contours

Both societal risk and individual risk of hazardous installations form boundaries for urban planning. Subsequently, these risks are adopted in urban planning around line infrastructure for the transport of hazardous materials, which can also be considered as ”moving” hazardous installations. Traditionally, the city is planned far away from hazardous installations and hazardous installations are planned far from the city. Line infrastructure for the transport of hazardous materials is, however, mostly in use for transport of people as well 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 geographical position and is displayed in the form of iso-risk contours on a geographical map. The individual risk is thus not characteristic for any person, but only 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. Bottelberghs (2000); Ale (2002)). The schematic risk contours for a hazardous installation and a transport route are shown in figure 5.7. Nowadays, due to a lack of space in combination with awareness of spatial quality, one is forced to look for new concepts for urban planning 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, an approach and a creation for the third dimension are inevitable. When considering the three-dimensional individual risk contours for installations, one may assume that the shape of such contours, in open-air, may be a half ellipsoid, as presented in figure 5.7 (Suddle *et al*. (2004)). These risk contours are related to the intensity of combustion caused by a flame (Drysdale (1999). A similar but transposed figure for line infrastructure is also drawn.

Although the contours are depicted as closed in all dimensions, 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:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1 \tag{5.4}$$

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 $a \to \infty$):

$$\frac{y^2}{b^2}+\frac{z^2}{c^2}=1 \tag{5.5}$$

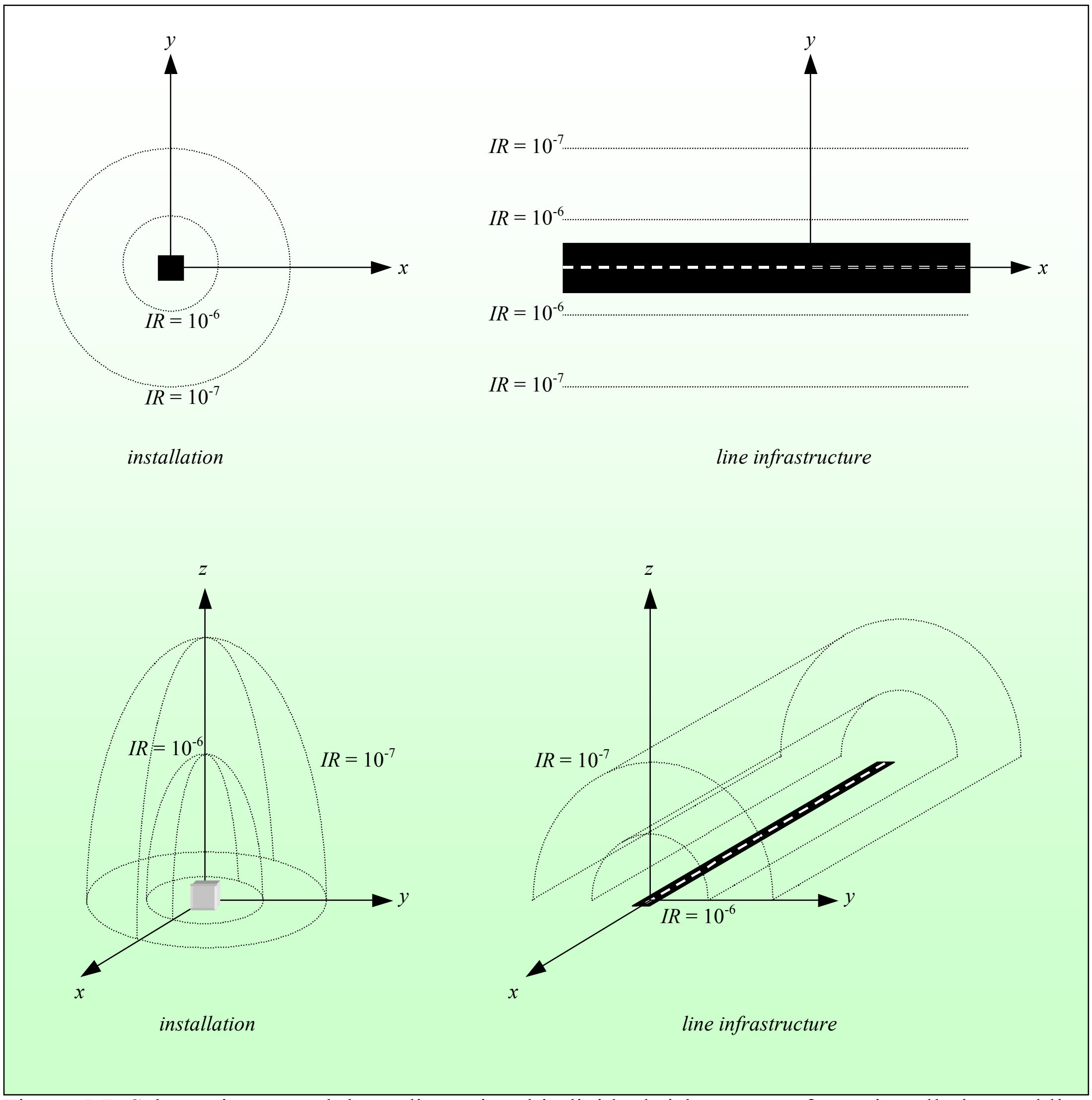

Figure 5.7: Schematic two and three-dimensional individual risk contours for an installation and line infrastructure (Suddle *et al*. (2004)).

For both examples, the height of the risk contour depends on the (quantity of) hazardous materials produced in the installation, or the (quantity of) hazardous materials transported at the infrastructure. In most cases the height (z) of the individual risk 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 CFD (Computational Fluid Dynamics) [3)]. 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.

5.3.2 Basic conditions

The realisation of buildings above infrastructure can influence the shape and the surface 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 using Bayesian Networks. The individual risk has to be analysed per storey of the building above infrastructure (h_0, h_1, … , h_n), as presented in figure 5.8.

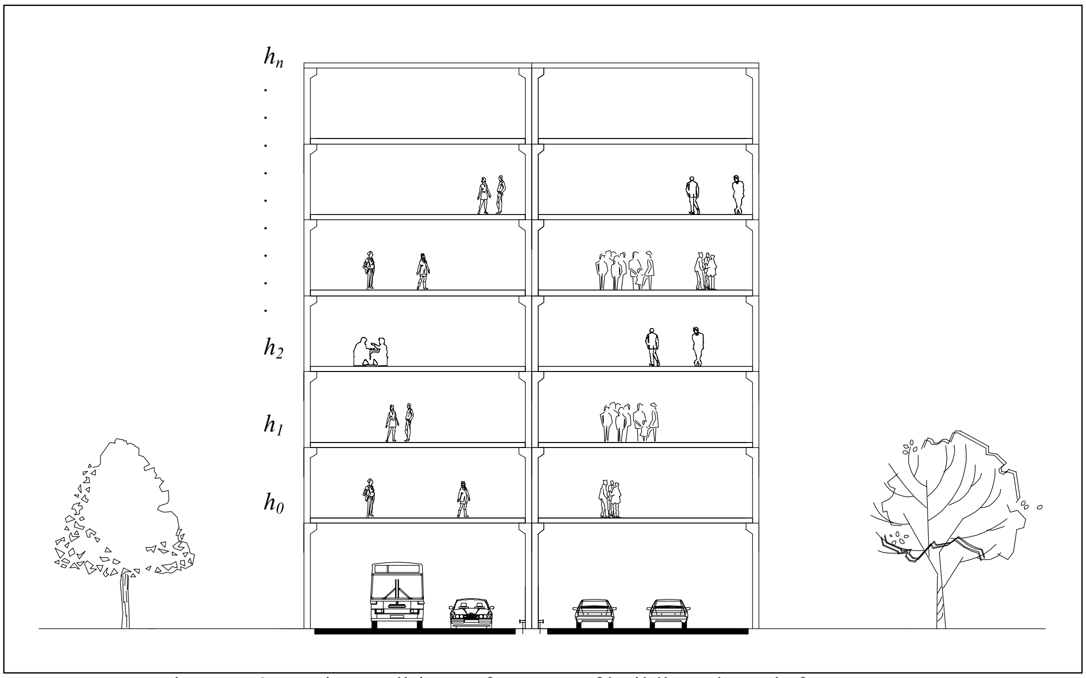

Figure 5.8: Basic conditions of storeys of building above infrastructure.

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 (Taylor (1994)). These accidents can also be the starting points of others. A fire for instance can cause an explosion and vise 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.

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3) CDF calculations are often used to calculate the effects of fires and explosions in and around complex structures such as oilrigs and tunnels. In essence, the calculations involve the numerical solution of the coupled differential equation describing the laws of conservation of mass, impulse and energy.

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 or not, as stated in the section 5.2.2.

5.3.3 Programming in Bayesian Networks

A quantitative risk analysis is done for the main scenarios. The Bayesian Networks are used for the quantitative risk analysis as presented in figure 5.9 and 5.10. These networks represent the relations between the events on the infrastructure and the building. These relations are quantified in (conditional) probabilities. The (change of) individual risk per increasing storey of the building is considered in these networks. An accident on the infrastructure may cause an explosion, which in its turn can cause a fire followed by the collapse of the building. This results in a variation of the individual risk per storey. The node explosion is divided into three classes: a BLEVE, a deflagration, and a detonation. An accident influencing the infrastructure may also cause the release of toxic gasses, which affects the individual risk in the building as well. Figure 5.10 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. A high fire intensity can lead to the collapse of the building.

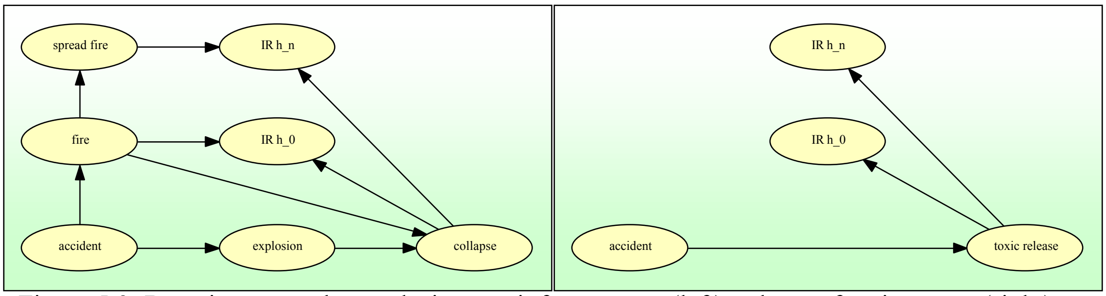

Figure 5.9: Bayesian networks; explosions on infrastructure (left), release of toxic gasses (right) on infrastructure.

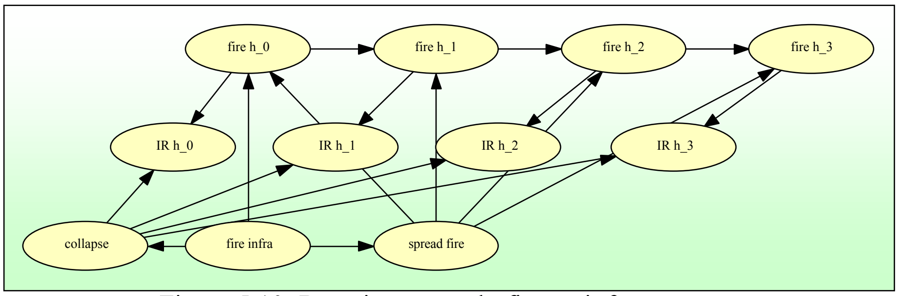

Figure 5.10: Bayesian network: fire on infrastructure.

5.3.4 Results of the Risk Analysis per storey

The results of the risk analysis are presented in table 5.5. Table 5.5 consists of 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 *IRh_i / 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}*).

Table 5.5: Results of the risk analysis.

Risk Level	Explosion		Release of toxic gasses		Collisions affecting the building structure		Fires	
	IRh_i	*IRh_i/IRh_{-1}*	*IRh_i*	*IRh_i/IRh_{-1}*	*IRh_i*	*IRh_i/IRh_{-1}*	*IRh_i*	*IRh_i/IRh_{-1}*
Infrastructure	10^{-9}	-	10^{-8}	-	10^{-6}	-	$1\cdot10^{-6}$	-
h_o	10^{-9}	1	10^{-10}	0.01	$7\cdot10^{-7}$	0,7	$7.1\cdot10^{-7}$	0,71
h_1	10^{-9}	1	10^{-10}	0.01	$7\cdot10^{-7}$	0,7	$6.7\cdot10^{-7}$	0,67
h_2	10^{-9}	1	10^{-10}	0.01	$7\cdot10^{-7}$	0,7	$6.2\cdot10^{-7}$	0,62
h_3	10^{-9}	1	10^{-10}	0.01	$7\cdot10^{-7}$	0,7	$5.7\cdot10^{-7}$	0,57
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
h_n	$1\cdot10^{-9}$	1	10^{-10}	0.01	$7\cdot10^{-7}$	0.7	10^{-7}	0.1

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 decrease” 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 economical terms, non-proportionaly expensive (see section 6.4.3).

The results of table 5.5 are graphically presented in figure 5.11 and 5.12. In these figures, the increase or decrease of relative risk contours is depicted. 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 figure 5.11). The toxic gasses can only reach the open-air and the building at the both 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 ten 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 figure 5.12).

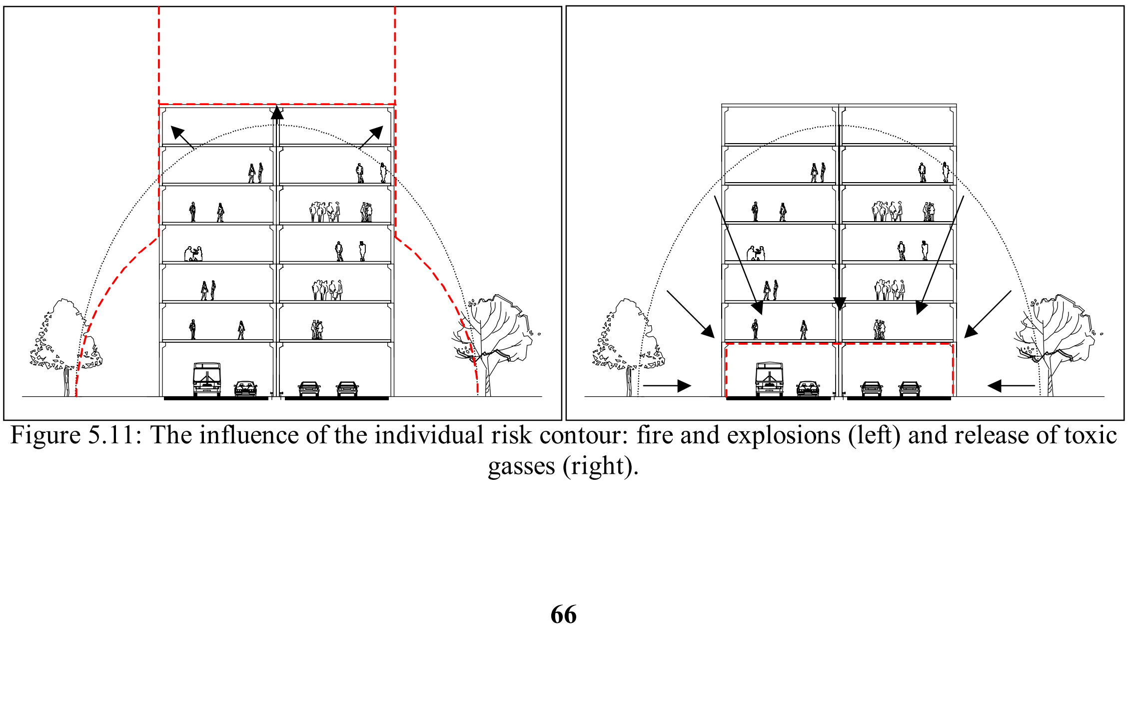

Figure 5.11: The influence of the individual risk contour: fire and explosions (left) and release of toxic gasses (right).

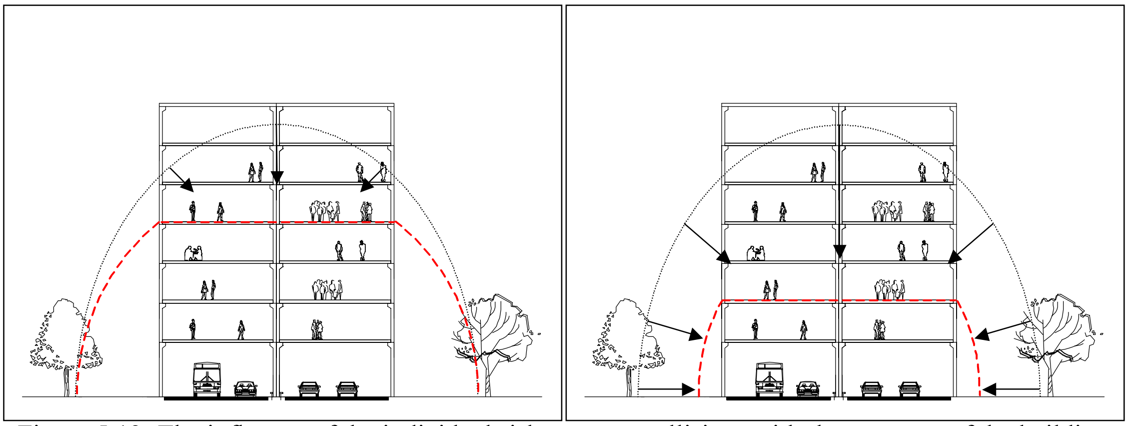

Figure 5.12: The influence of the individual risk contour: collisions with the structure of the building (left) and fire on the infrastructure (right).

5.3.5 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 chapter 6):

- The amount of explosive and toxic materials transported on the infrastructure:
  If the transport of explosive and toxic materials is prohibited, the individual risk contour will almost be restricted 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). These measures can be divided into functional and structural measures.

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

5.4 Results of risk analysis

5.4.1 Individual Risk

- *Individual risk for building above roads / railways / buildings*

The risk calculated from the Bayesian Network of Appendix A is the risk per vehicle. In order to calculate the risk per kilometre per year, the computed risk is multiplied by the number of vehicles that pass per year. The individual risk is computed for three different covering lengths of the infrastructure for building above roads, railways, and existing buildings respectively. The probabilities that are taken into account, dominate the determination of the individual risk regarding the four critical scenarios (table 5.6). It appears that an increase in the covering length of the infrastructure, results in an increase of the individual risk in the building above infrastructure. The individual risk for building above existing buildings is approximately 10^{-7}. This risk is much lower than the risk of buildings above roads and is therefore not elaborated on any further in this thesis.

Table 5.6: The individual risk at the building above roads, railways and existing buildings.

Covering Length	30 m			100 m			1000 m		
Building above roads									
Scenario i	P_{fi}	$P_{d\|fi}$	IR_i	P_{fi}	$P_{d\|fi}$	IR_i	P_{fi}	$P_{d\|fi}$	IR_i
1. Collisions against structure building	$5\cdot10^{-5}$	0.1	$5\cdot10^{-6}$	$5\cdot10^{-5}$	0.1	$5\cdot10^{-6}$	$5\cdot10^{-5}$	0.1	$5\cdot10^{-6}$
2. Fires	$2\cdot10^{-5}$	0.05	$1\cdot10^{-6}$	$2\cdot10^{-5}$	0.07	$1\cdot10^{-6}$	$2\cdot10^{-5}$	0.1	$5\cdot10^{-6}$
3. Leak of toxic substances	$6\cdot10^{-7}$	0.5	$3\cdot10^{-7}$	$6\cdot10^{-7}$	0.5	$3\cdot10^{-7}$	$6\cdot10^{-7}$	0.5	$3\cdot10^{-7}$
4. Explosions	$1\cdot10^{-8}$	1	$1\cdot10^{-8}$	$3\cdot10^{-7}$	1	$3\cdot10^{-7}$	$5\cdot10^{-6}$	1	$5\cdot10^{-6}$
Total ΣIR	$6\cdot10^{-6}$			$7\cdot10^{-6}$			$1.5\cdot10^{-5}$		
Building above railways									
Scenario i	P_{fi}	$P_{d\|fi}$	IR_i	P_{fi}	$P_{d\|fi}$	IR_i	P_{fi}	$P_{d\|fi}$	IR_i
1. Collisions against structure the building	$7\cdot10^{-7}$	0.1	$7\cdot10^{-8}$	$5\cdot10^{-6}$	0.1	$5\cdot10^{-7}$	$9\cdot10^{-6}$	0.1	$9\cdot10^{-7}$
2. Fires	$2\cdot10^{-6}$	0.05	$1\cdot10^{-7}$	$2\cdot10^{-6}$	0.07	$1\cdot10^{-7}$	$2\cdot10^{-6}$	0.1	$2\cdot10^{-7}$
3. Leak of toxic substances	$2\cdot10^{-6}$	0.5	$8\cdot10^{-7}$	$2\cdot10^{-6}$	0.5	$8\cdot10^{-7}$	$2\cdot10^{-6}$	0.5	$8\cdot10^{-7}$
4. Explosions	$4\cdot10^{-8}$	1	$4\cdot10^{-8}$	$8\cdot10^{-8}$	1	$8\cdot10^{-8}$	$1\cdot10^{-6}$	1	$1\cdot10^{-6}$
Total ΣIR	$1\cdot10^{-6}$			$2\cdot10^{-6}$			$3\cdot10^{-6}$		
Building above existing buildings									
Scenario i	P_{fi}	$P_{d\|fi}$	IR_i	P_{fi}	$P_{d\|fi}$	IR_i	P_{fi}	$P_{d\|fi}$	IR_i
1. Fires	$1\cdot10^{-4}$	0.001	$1\cdot10^{-7}$	$3\cdot10^{-4}$	0.001	$3\cdot10^{-7}$	$8\cdot10^{-4}$	0.001	$8\cdot10^{-7}$
2. Explosions	$1\cdot10^{-9}$	1	$1\cdot10^{-9}$	$1\cdot10^{-9}$	1	$1\cdot10^{-9}$	$1\cdot10^{-9}$	1	$1\cdot10^{-9}$
Total ΣIR	$1\cdot10^{-7}$			$3\cdot10^{-7}$			$8\cdot10^{-7}$		

5.4.2 Group Risk

- *Group risk for building above roads*

Likewise, the societal / group risk is directly calculated from the Bayesian Network for three different covering lengths and depicted in the FN-diagrams per risk category. The FN-diagrams of figure 5.13 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 infrastructure towards the building above the infrastructure (risk category [2]) are relatively high. The building above the infrastructure is the main source 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 vicinity due to transport of hazardous materials can be decreased by covering the infrastructure for a larger distance (see figure 5.13 right and bottom), while the risk increases in the tunnel (risk category [3]).

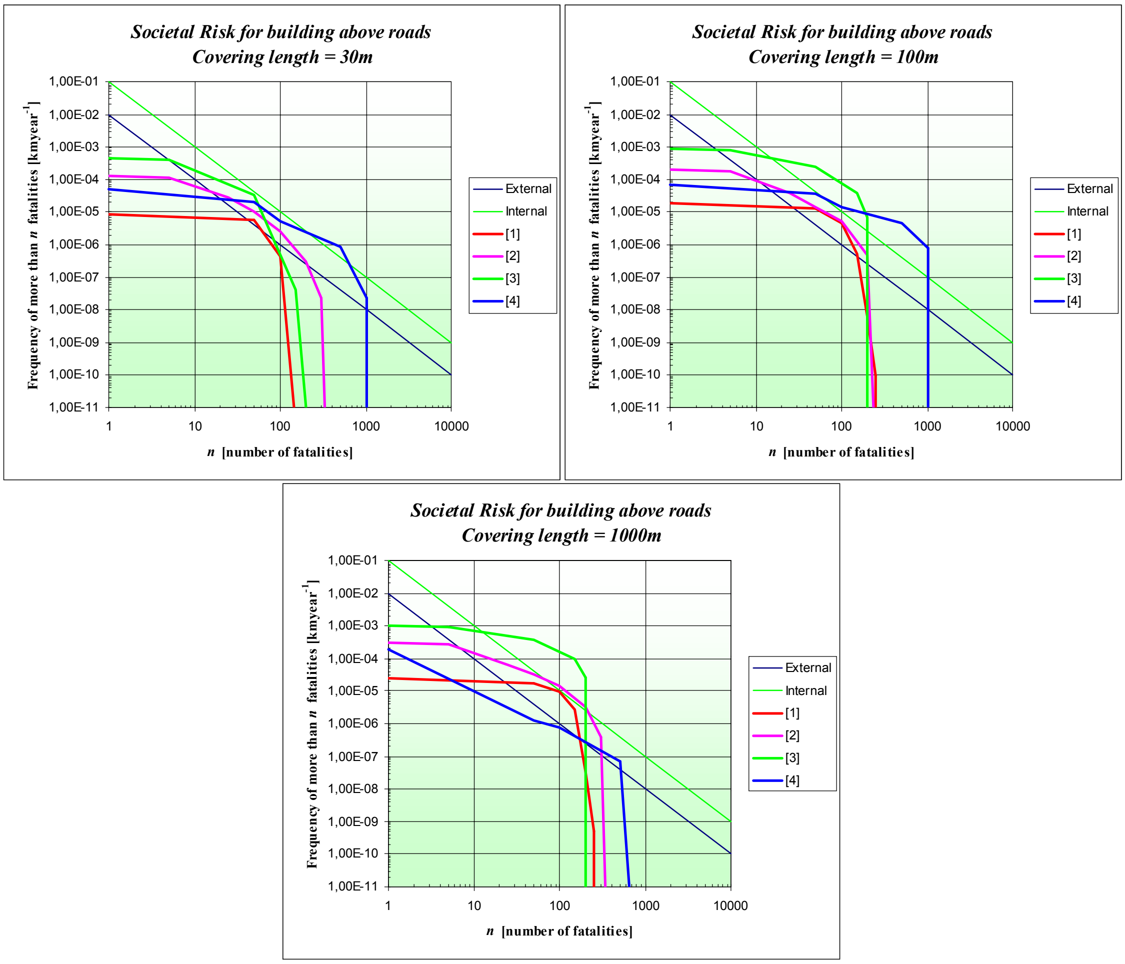

Figure 5.13: Societal risk for building above roads with a covering length of 30m (left), 100m (right) and 1000m (bottom).

- *Group risk for building above railways and above existing buildings*

The risk analysis for building above railways is performed in the same way as it is done for building above roads. The group risk is presented here for a covering length of 30 meter (figure 5.14 left). The covering lengths of 100 and 1000 meters have the same principles as building above roads and are therefore not presented.

Likewise, the group risk for building above existing buildings is calculated. Figure 5.14 right shows that the group risk for building above existing buildings is negligible, since there is no transport of hazardous materials. In fact, fire and in some cases explosions may occur. So, it may be concluded that building above existing buildings does not introduce an additional risk. Therefore, building above existing buildings will not be worked out in this thesis. However, some measures (see chapter 6) proposed for buildings above the infrastructure can be applied for building above existing buildings as well.

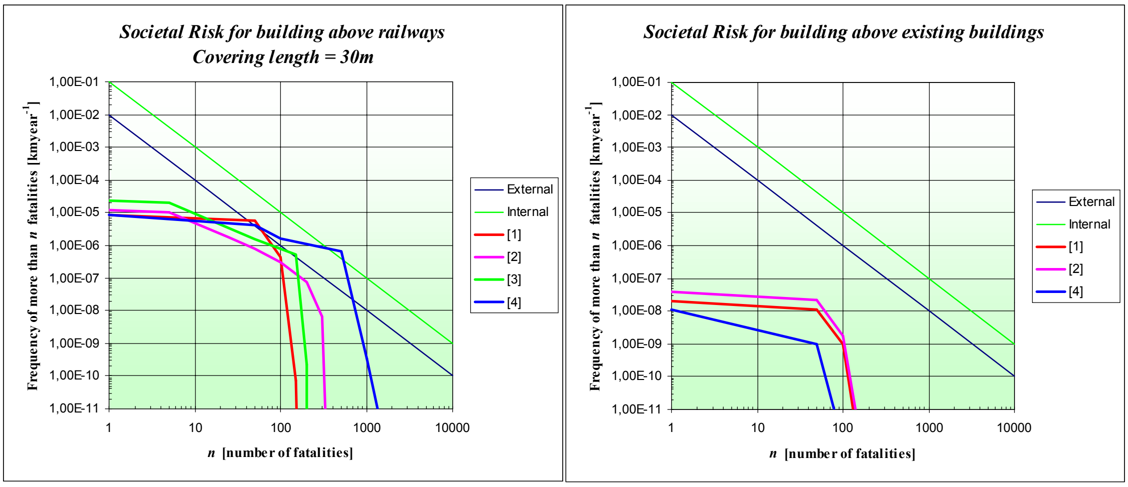

Figure 5.14: Societal risk for building above railways with a covering length of 30m (left) and societal risk for realising buildings above existing buildings (right).

- *Expected number of people killed*

If we correlate the $E(N_d)$, the expected loss of human lives per kilometre per year, with the covering length, remarkable results are obtained (figure 5.15). Although the relation is not of a linear type, it can be observed that the $E(N_d)$ for the vicinity (risk category [4]) decreases, if the covering length of the infrastructure increases. In contrast, the $E(N_d)$ 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 $E(N_d)$ of risk category [2] and risk category [1] enlarges slowly in case of an increase of the covering length of the infrastructure (Suddle (2004[B])).

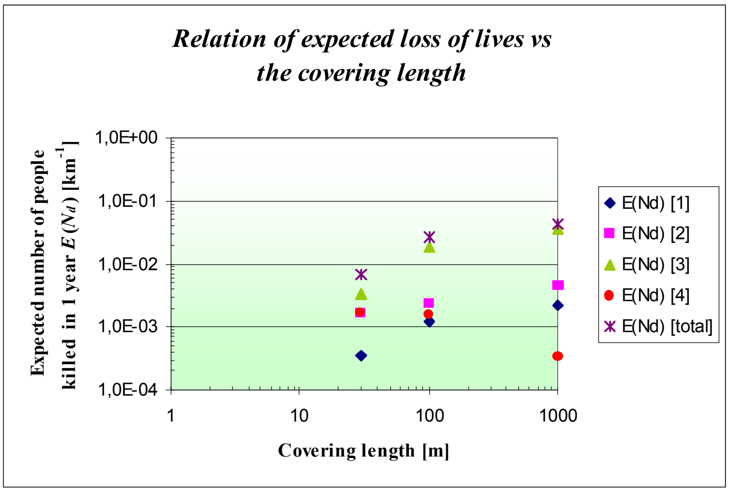

Figure 5.15: Relation of expected loss of lives vs the covering length of the infrastructure.

This phenomenon is schematically presented in figure 5.16, 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 and [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 (2002), in which the $\Delta E(N_d)$ increases with 30% if the infrastructure is covered compared to a road which is not covered.

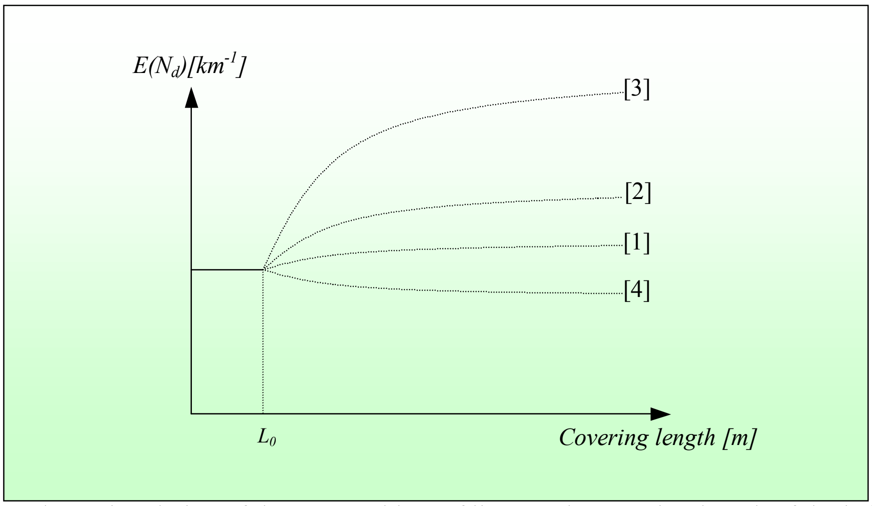

Figure 5.16: Schematic relation of the expected loss of lives vs the covering length of the infrastructure.

5.4.3 Checking for compliance with limits of risk acceptance

It should be noted that the determination of the exact risk acceptance level is a political issue. In this research, the method discussed by Vrijling *et al.* (1996) will be used as indication for the risk acceptance level for both individual risk *IR* and group risk *GR*, which is based on voluntariness (see section 3.3.2 and 3.3.3). The policy factor for external safety is set to be β_i = 0.01, so the limits for risk acceptance can be determined (see table 5.7). Note that β_i = 0.1 for internal safety. The risk acceptance criterion for individual risk is thus 10^{-6} per year.

In order to determine the acceptable group risk criterion, it is assumed that independent locations N_A are 10 and the factor C_i varies between 0.1 and 0.01. The risk acceptance criterion for group risk *GR* is integrated and presented in figure 5.13 and 5.14 for both internal and external safety. Note that the risk acceptance level used for internal safety varies in studies of e.g. TCE (2003) and Wiersma & Molag (2001). When considering these acceptance limits for risk acceptance, the results for building over rail and road infrastructure are slightly exceeded. Therefore in the next chapter, safety measures are analysed and optimised for building above road infrastructure.

Table 5.7: Several betas for several risk categories.

Risk category s	Betas (β_i)	Independent locations N_A	C_i
[1] External safety and risks from the building in relation to the infrastructure beneath	0.01	10	0.01
[2] External safety and risks from the infrastructure towards the building	0.01	10	0.01
[3] Internal safety and risks from the structures enclosing the infrastructure	0.1	100	0.1
[4] External safety and risks from the infrastructure towards the vicinity	0.01	10	0.01

5.4.4 Economical losses

The calculated economical losses are as follows:

Table 5.8: The economical losses for several scenarios versus the covering length.

Covering Length	**30 m**			**100 m**			**1000 m**		
Building above roads									
Scenario i	P_{fi}	C_{fi}	R_i	P_{fi}	C_{fi}	R_i	P_{fi}	C_{fi}	R_i
1. Collisions against structure building	$5 \cdot 10^{-5}$	$5 \cdot 10^{5}$	$3 \cdot 10^{1}$	$5 \cdot 10^{-5}$	$5 \cdot 10^{5}$	$3 \cdot 10^{1}$	$5 \cdot 10^{-5}$	$5 \cdot 10^{5}$	$3 \cdot 10^{1}$
2. Fires	$2 \cdot 10^{-5}$	$2 \cdot 10^{6}$	$4 \cdot 10^{1}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{6}$	$4 \cdot 10^{1}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{7}$	$4 \cdot 10^{2}$
3. Leak of toxic substances	$6 \cdot 10^{-7}$	$2 \cdot 10^{4}$	$1 \cdot 10^{-2}$	$6 \cdot 10^{-7}$	$2 \cdot 10^{4}$	$1 \cdot 10^{-2}$	$6 \cdot 10^{-7}$	$2 \cdot 10^{4}$	$1 \cdot 10^{-2}$
4. Explosions	$1 \cdot 10^{-8}$	$1 \cdot 10^{8}$	1	$3 \cdot 10^{-6}$	$5 \cdot 10^{7}$	$2 \cdot 10^{2}$	$5 \cdot 10^{-6}$	$3 \cdot 10^{8}$	$2 \cdot 10^{3}$
$E(C_i)$ [€·year^{-1}]			$7 \cdot 10^{1}$			$2 \cdot 10^{2}$			$2 \cdot 10^{3}$
Building above railways									
Scenario i	P_{fi}	C_{fi}	R_i	P_{fi}	C_{fi}	R_i	P_{fi}	C_{fi}	R_i
1. Collisions against structure building	$7 \cdot 10^{-7}$	$1 \cdot 10^{6}$	$7 \cdot 10^{-1}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{6}$	3	$9 \cdot 10^{-6}$	$1 \cdot 10^{6}$	9
2. Fires	$2 \cdot 10^{-6}$	$2 \cdot 10^{6}$	4	$2 \cdot 10^{-6}$	$2 \cdot 10^{6}$	4	$2 \cdot 10^{-6}$	$2 \cdot 10^{7}$	$4 \cdot 10^{1}$
3. Leak of toxic substances	$2 \cdot 10^{-8}$	$2 \cdot 10^{4}$	$4 \cdot 10^{-4}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{4}$	$4 \cdot 10^{-4}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{4}$	$4 \cdot 10^{-4}$
4. Explosions	$4 \cdot 10^{-8}$	$1 \cdot 10^{8}$	4	$8 \cdot 10^{-8}$	$5 \cdot 10^{8}$	$4 \cdot 10^{2}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{9}$	$5 \cdot 10^{3}$
$E(C_i)$ [€·year^{-1}]			10			$4 \cdot 10^{2}$			$5 \cdot 10^{3}$
Building above existing buildings									
Scenario i	P_{fi}	C_{fi}	R_i	P_{fi}	C_{fi}	R_i	P_{fi}	C_{fi}	R_i
1. Fires	$1 \cdot 10^{-4}$	$1 \cdot 10^{5}$	10	$3 \cdot 10^{-4}$	$3 \cdot 10^{5}$	$9 \cdot 10^{1}$	$8 \cdot 10^{-4}$	$5 \cdot 10^{5}$	$4 \cdot 10^{2}$
2. Explosions	$1 \cdot 10^{-9}$	$1 \cdot 10^{6}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-9}$	$3 \cdot 10^{6}$	$3 \cdot 10^{-3}$	$1 \cdot 10^{-9}$	$1 \cdot 10^{7}$	$1 \cdot 10^{-2}$
$E(C_i)$ [€·year^{-1}]			10			$9 \cdot 10^{1}$			$8 \cdot 10^{2}$

It appears that the scenario ”explosions” (including BLEVE & detonation) is the main scenario when determining the expected economical loss in multiple use of space. Within the entire spectrum of risk of hazardous materials transportation in multiple use of space, the probability of a gas explosion in a tunnel may be relatively low but, on the other hand, the geometry of the covered infrastructure constitutes optimal conditions for a gas explosion to develop devastating economical consequences.

More details on the calculations of the expected economical losses are presented by Heilig (2002). Arends (2003) classified economical losses into more specific classes than are used in this thesis. The risk analysis also shows that the longer the covering length of the infrastructure, the higher the economical losses will be (figure 5.17).

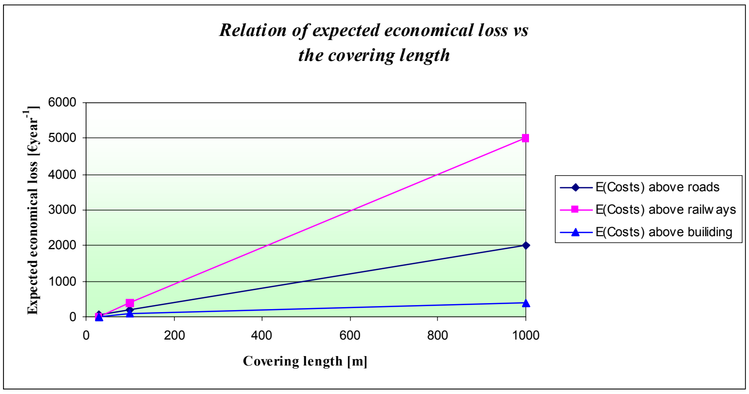

Figure 5.17: The economical losses for several scenarios vs the covering length of the infrastructure.

5.4.5 Comparison of human risks with economical losses

If we compare the human risks with the economical losses assuming a monetary value per fatality α of € 1,000,000,=, then the following comparison can be made:

Table 5.9: Comparison of human risks and economical losses including a monetary value per fatality.

Covering Length	30 m	100 m	1000 m
$E(N_d)_{total}$ [fatalities km^{-1}year^{-1}]	$7.0 \cdot 10^{-3}$	$2.7 \cdot 10^{-2}$	$4.2 \cdot 10^{-2}$
$E(N_d)_{total} \cdot \alpha$[€ km^{-1}year^{-1}]	$7.0 \cdot 10^{3}$	$2.7 \cdot 10^{4}$	$4.2 \cdot 10^{4}$
$E(C_j)_{total}$ [€ km^{-1}year^{-1}]	$1.7 \cdot 10^{2}$	$6.7 \cdot 10^{2}$	$2.0 \cdot 10^{3}$

It is quite surprising that in this case, the expected economical losses are relatively low, and are of less value in comparison with the expected loss of life per year. So, one may assume that when the optimisation of safety measures is considered, the investments will be primarily compared to the expected loss of lives.

5.5 Sensitivity analysis

First of all, it should be noted by risk analysts that, according to several experts (e.g. Bedford & Cooke (2001)), the calculation of an FN-curve is just an estimation, rather than an exact presentation of risk results. In addition to that, the presented models and results are simplified depictions of reality and will be in fact used to measure the effect on both human and economical risks regarding safety measures. Cooke & Meeuwisen (1989) show that the lack of appropriate data causes large uncertainties in parameters, for instance with the BLEVE scenario.

Second, some critical notes on several software programs for computing FN-curves should be made. Laheij *et al.* (2003) presented a benchmark exercise for a hypothetical establishment wherein a comparison is made between five software tools available in The Netherlands for conducting a quantified risk analysis. The main conclusion of the survey of Laheij *et al.* (2003) was that large differences exist among the used software for that hypothetical plant. The results in FN-curves for all participants were found largely within one order of magnitude, a factor 100. So, one may assume that the presentation of the FN-diagrams in this thesis will not be that accurate, which is in fact not disturbing. In fact, FN-diagrams should be used to determine the effects of measures, rather than solely presenting risk results of an urban area adjacent to a transport route of hazardous materials, which is done too often on behalf of municipalities.

Moreover, a FN-diagram does not ensure that scenarios, with a low probability of occurrence, will not occur in the future. If the same error / uncertainty in these FN-diagrams is considered for determining the risk reducing effect of measures, the comparison of measures can still be done. The uncertainties in the parameters of the considered risk analysis will be discussed in this section. According to Pasman & Vrijling (2003), an order of magnitude ranking of events is desired before any detailed work is to be carried out. In this regard, Pasman & Vrijling (2003) present a risk matrix of consequence class (magnitude of effect, or severity) versus probability of occurrence (frequency per year) enabling prioritisation of actions during reduce risk. Figure 5.18 presents the four critical areas in the FN-diagram. In essence, the sensitivity of the four main areas in the FN-diagram can be summed up as in table 5.10.

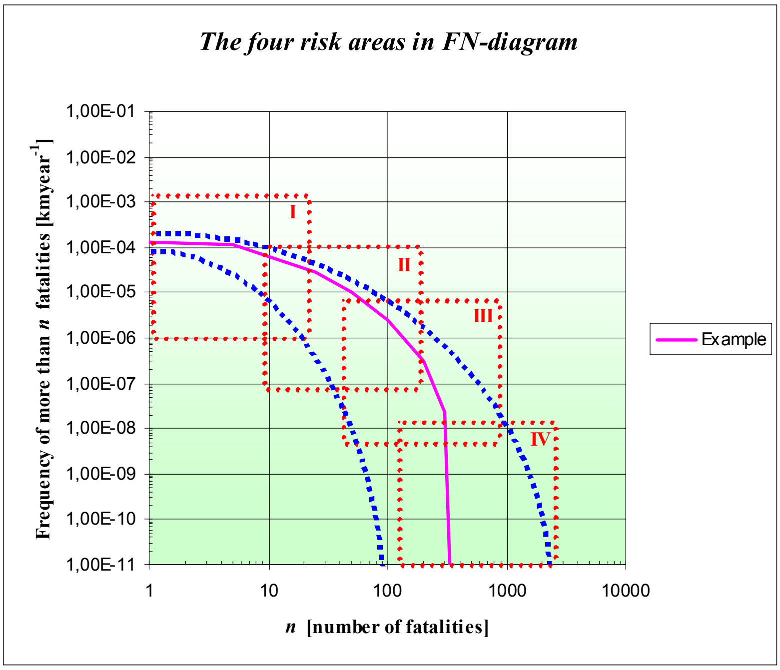

Figure 5.18: The four risk areas in the FN-diagram.

Table 5.10: The probability and frequency of the four main areas in the FN-diagram.

Four main areas in the FN-diagram	P_f	C_f
I. Local traffic accidents and small fires in buildings or on the infrastructure	High	Low
II. Fires on the infrastructure	Medium	Medium
III. Explosions on the infrastructure	Low	High
IV. Release of toxic gasses	Very low	Very high

In order to determine the sensitivity of initial risks, it is important to consider both the consequences and the probabilities of a hazardous event in these four areas. Furthermore, it should be noted that the curves of a FN-diagram are relevant from the point at which the number of fatalities is more than 10, because the relevance of the group risk becomes high. Both the variation and sensitivity of the FN-curve will be described per area.

In general, when dealing with small accidents and consequences, the probability is relatively high and the consequences can easily be modelled. In contrast, when dealing with scenarios with major consequences, the variance of the probability is quite wide and additionally the number of fatalities is difficult to determine. This effect is presented in FN-diagram of figure 5.18 by dotted lines, in which variance determines the sensitivity of the FN-curve.

- *Area I: Local traffic accidents and small fires in buildings or on the infrastructure*

The effect of local traffic accidents, causing small numbers of fatalities, depends mainly on the frequency of a traffic accident, which could be more than once per year. As described in section 5.2.4, the probability of a traffic accident is related to the driving attitude of the drivers. Hansen (1999) presented various aspects on which the result of the risk analysis may depend. These aspects mainly consists of visual observation aspects of drivers, such as traffic signs, visualisation distances, type of road, psychological condition of drivers, etc. From the survey of Poort (2002) it can be concluded that the probability of occurrence of a hazardous event will increase rapidly if the use of railways is intensified. Heilig (2002) also showed that the variance of the probability of a traffic accident, based upon perception of a motorist, lies approximately between 10 - 30%. So, the results in this area may be presented too pessimistically or optimistically.

- *Area II: Fires on infrastructure*

The magnitude of the risks of fires on infrastructure and buildings contains variance as well. These are introduced by the intensity of fire, and the possible scenario that may result. Table 5.10 shows that the conditional probabilities of fire spreading to other functions are significant in this area. Both Holborn *et al*. (2002) and Frantzich (1998) show, that the risk calculations of fires in buildings are usually done with a great number of variables. Magnusson *et al*. (1996) described a fire safety design based on calculations, in which uncertainty is analysed and safety is verified. Therefore, the probabilities of fire, depending on the time of exposure, vary easily between 10 - 100%.

- *Area III: Explosions on infrastructure*

As mentioned earlier, an explosion causes a blast wave, atmospheric and ground effects, fragmentation and missile effects, and thermal radiation effects. Fatalities due to falling or flying objects are considered and are to be calculated in the risk analysis. However, due to several reasons, a separate analysis of these flying objects is not done in this research. So, one may expect that a significant error / uncertainty has been introduced. Besides, both the impact and the large effect distances of such a scenario and the number of fatalities due to that scenario, result in a wide range of risk results.

- *Area IV: Release of toxic gasses*

Release of toxic gasses is the main characteristic of this area. In this area, the variance of the result lies particularly in the consequences of the accident, thus in the number of fatalities. Because the modelling of the vicinity and the people in the vicinity is extremely complex, it is difficult to calculate the exact amount of fatalities. Moreover, different materials have different effects on the considered people in those areas. It is also important to realise that if a toxic gas is released, the people indoors are in some way protected in comparison to people outdoors.

Safety measures are not taken into account in the sensitivity analysis. Nonetheless, the mentioned uncertainties in the probability of a hazard and the consequences of that hazard have effects on the uncertainties in the calculated economical risk as well.

5.6 Conclusions

This chapter showed that the safety during exploitation is a crucial issue, requiring special attention. The assessment of safety can be done with risk analysis using Bayesian Networks. One of the main conclusions of this chapter is that in principle, the scenarios occurring on the infrastructure remain almost the same when the infrastructure is not covered, while the effects of these scenarios largely differ. The changes in the effects are caused by the fact that the infrastructure is enclosed and covered with buildings. By this, four risk interaction categories are introduced; [1] risks of the buildings above the infrastructure to the enclosed infrastructure, [2] risks of the infrastructure to the building above, [3] internal risks in the covered infrastructure and [4] the risks of the infrastructure to the vicinity.

In order to perform a quantitative risk analysis, it is important to separate both the probabilities and the consequences of the critical scenarios that may occur on the infrastructure, such as fires, explosions, release of toxic gasses and collisions against the structure of the building above the infrastructure. Surprisingly, intensifying the space or using the space multiple does not a priori mean that the overall risk is increased. This argument is emphasised by the individual risk in the 3^{rd} dimension for each scenario separately. This approach illustrates the fact that, for instance, release of toxic gasses on the covered infrastructure can be enclosed into the infrastructure, saving large number of fatalities in the vicinity, despite the unavoidable fatalities occurring in the covered infrastructure due to that scenario. The most important aspect for modelling the risk in the third dimension was the collapse of the building above the infrastructure.

The results of the risk analysis show that realising buildings above existing buildings is a form of multiple use of space with less risk in comparison to realising buildings above infrastructure, because there is no transport of hazardous materials when realising buildings on top of existing buildings.

Finally, it can be stated that some critical notes of the use of FN-curves should be made. FN-diagrams should be particularly used to determine the effects of measures, rather than solely presenting risk results of an urban area adjacent to a transport route of hazardous materials. Because, a FN-diagram does not ensure that scenarios, with a low probability of occurrence, will not happen in the future.

6

The Optimisation of Safety Measures in the Exploitation Stage

This chapter focuses on the effect, comparison, and optimisation of safety measures on both human and economical risks for the four critical scenarios in multiple use of space projects, i.e. fires, explosions, release of toxic gasses, and collisions. In general, these measures are taken to reach a certain level of safety. There are several measures that can be implemented against critical scenarios in multiple use of space projects. These measures will reduce the probability and / or the consequences of an incident in the building above the infrastructure, in the vicinity, or in the covered infrastructure itself. From a risk management point of view, it is desired for the implemented measures to be cost effective. The risk reducing effects of safety measures are determined quantitatively, if possible. These effects, applicable to multiple use of space projects, are presented in this chapter.

6.1 Approaches for safety measures

6.1.1 Safety chain and time period

One of the most used classifications of safety measures is the so-called *safety chain*. The safety chain is particularly drawn up in order to classify the moment of action of the safety measures (BZK (2000)). Sometimes the safety chain is combined with a Bow-tie model (c.f. Suddle (2002[A])). This makes it possible to present the moment of implementing measures on particular events before, during, or after an accident. Generally, a safety chain consists of five levels. These are presented in table 6.1.

Table 6.1: The five levels of the safety chain and their objectives.

Level of safety chain	Objective of safety measure
Pro-action	Safety measures in planning phase (pre-construction)
Prevention	Measures and provisions to prevent accidents
Preparation	Preparation of actions during accidents
Repression	Actions during accident (also called mitigation measures)
Follow-up	Dealing with post-accident situations

Some examples of safety measures are shown in table 6.2, which also presents that the time period of implementing safety measure varies largely, depending on the feasibility. The moment at which a safety measure can be implemented, depends mainly on the policy of the (local) government, and the actors of the considered project. For instance: banning the transport of dangerous goods from infrastructure could be a very effective measure for people living adjacent to that transport route. It is, however, a measure that can be implemented after a long period, say 5 to 10 years on a national scale. Locally, this measure can be implemented in a much shorter time. A measure such as derailment control could be less effective but could be realised in a relatively short period (e.g. 3 to 5 years). Table 6.2 also illustrates the fact that the safety measures of different levels of the safety chain result in a different time period for realisation of that safety measure. It may be assumed that the time period for realisation of the safety measurers from a higher level of the safety chain (e.g. pro-action) is longer than of a measure from a lower level of the safety chain (e.g. repression). Sometimes, the time period for realisation may vary largely (e.g. follow-up). Note that local circumstances in the future, such as plans and procedures by the (local) government, may differ completely in comparison to the current situation.

Table 6.2: Examples of safety measures.

Level of Safety Chain	Safety measure	Effect of the safety measure	Time period for realisation of safety measures
Pro-action	nationally banning transport of hazardous materials	no accident with hazardous materials	long period
	rerouting transport of hazardous materials	no accident with hazardous materials in densely populated areas	middle period
	explosion resistant walls tunnel	consequences will be minimised for building above	middle period
Prevention	reducing the speed limit	decrease accident frequency	short period
	fire resistant walls covered infrastructure	consequences will be minimised for building above	middle period
		collapse of the tunnel structure is not possible	middle period
	functional measures in the building	population at risk is small	during design stage of a project
Preparation	evacuation plan of people in the building	population at risk is small	during design stage of a project
Repression	sprinklers in covered infrastructure or building	prevents escalation of fire	short - middle period
	ventilation in covered infrastructure	prevents escalation of fire	short - middle period
	medical care / emergency response	minimises wounded people to be killed	short - middle period
Follow-up	replacement of equipment after damage more easy	return to the normal situation as soon as possible	-

The time scale for feasibility of implementing measures is used in the project / case study of the railway track in Dordrecht of Wiersma *et al.* (2004[B]). In this study, three significant time periods were distinguished:

1. t_{short} : Safety measures can be applied in a very short period (1 - 3 years);
2. t_{middle} : Safety measures can be applied after a middle term period (3 - 10 years);
3. t_{long} : Safety measures can be applied after a long period (more than 10 years).

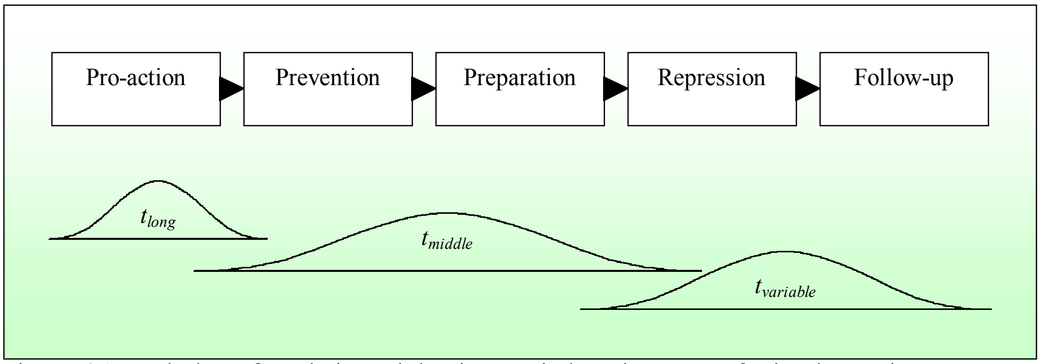

Figure 6.1: Both the safety chain and the time period are important for implementing measures.

6.2.2 *The Risk Reducing Effect*

There are several measures that can be implemented in multiple land use projects, which will reduce either the probability or the consequences of an incident in the building or infrastructure. In general, the effect of a measure is expressed in terms of: (1) avoided number of deaths per year $\Delta E(N_d)$; (2) avoided number of injuries per year and (3) avoided material damage per year. Additionally, it should be stated that the risk reducing effect of measures depends both upon probabilities and consequences used in the original risk analysis, in which safety measures are not considered. The risk reducing effect regarding safety measures for human risks is usually depicted in FN-diagrams, as in figure 6.2. Considering the mathematical definitions of risk (as presented in chapter 3), the risk reducing effect can be mathematically determined as follows:

$$R = \sum_{i=1} P_{f_i} \cdot C_{f_i} \tag{6.1}$$

$$\Delta R_i = \frac{\partial R_i}{\partial P_{f_i}} \Delta P_{f_i} + \frac{\partial R_i}{\partial C_{f_i}} \Delta C_{f_i} \tag{6.2}$$

$$\Delta R_i = C_{f_i} \cdot \Delta P_{f_i} + P_{f_i} \cdot \Delta C_{f_i} \tag{6.3}$$

in which:

ΔR_i = risk reducing effect of a measure [fatalities or money year^{-1}];
ΔC_{fi} = consequence reducing action [fatalities or money];
ΔP_{fi} = probability reducing action [year^{-1}].

Sometimes it is completely (un) clear whether the risk reducing effect of a safety measure is the result of either the ΔC_{fi} (consequence reducing action) or the ΔP_{fi} (probability reducing action), or a combination of these two. In other words the movement of the FN-curve to origin can be caused by a decrease of either ΔC_{fi} , or ΔP_{fi} , or even a combination of these two.

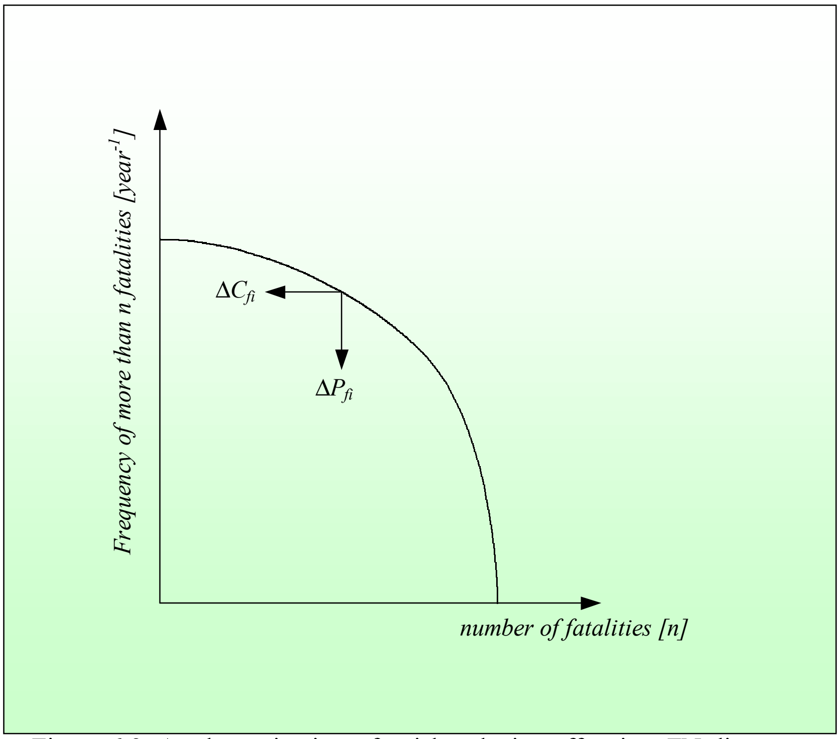

Figure 6.2: A schematic view of a risk reducing effect in a FN-diagram.

6.2 Structural, Functional and Human related measures

6.2.1 Introduction

Stoop (1990) urged in his thesis to implement safety measures in the design stage of every project. In this respect, safety measures should be implemented in multiple use of space projects from different viewpoints. The Ministry of Transport, Public Works, and Water Management for instance divided measures for tunnels into three types (see e.g. BOMVIT (2002)): (1) design of the structure (structural measures); (2) design and maintenance of the electrical installations (installation related measures) and (3) exploitation of the tunnel and its traffic rules (traffic management). When considering multiple use of space projects, safety measures can be implemented to (the boundaries of) the building above the infrastructure, the infrastructure itself and the vicinity (as mentioned in section 5.1). Observing the safety system of such projects (as presented in chapter 1), we distinguish safety measures into three main categories (Suddle (2002[D; E]; 2004[A])), which will be utilised and combined crosswise, if possible, with the safety chain in the next paragraph:

- ❑ Functional safety measures;
- ❑ Structural safety measures;
- ❑ Human related safety measures.

The scale level of functional measures is mostly related to the urban development or the configuration of space along the infrastructure. The scale level of structural and human related measures interacts with the building or infrastructure level. The measures are treated from a probabilistic point of view in the next paragraph.

6.2.2 Functional safety measures

- *Logistic and proactive measures*

A very traditional safety measure for multiple use of space projects is to implement a functional measure from a logistical point of view, in which one separates the transport of hazardous materials from the normal traffic (also discussed by e.g. Arends (2003)). In addition, one may decide to preclude the realisation of buildings above infrastructure on which the transport of such materials takes place. Other functional measures could be the implementation of uni-directional tubes on infrastructure below the building to prevent frontal collisions. One may also set up a new chemical installation next to the place where the hazardous material is processed, if possible.

According to the accident frequencies discussed in the report of SAVE (1995[A & B]), logistical measures such as reducing the speed limit, regulation of traffic, can be effective as well (see also Appendix A). By this, the probability of traffic accidents and collisions on the infrastructure decreases if the speed limit is reduced. On railway tracks over which buildings are realised, switches and crossings should not be placed, by which the probability of a derailment scenario decreases strongly.

In some areas in The Netherlands, a part of the transport of dangerous goods takes place through urban areas. In fact, these routes were especially planned and designed for the transport of hazardous goods. However, due to e.g. a lack of space, urban developments concentrate more and more on these locations (Ale (2003)). Therefore, prohibiting transport of hazardous materials or prohibiting urban development are both controversial and almost impossible solutions. From this point of view, there is a strong need for measures that stimulate the continuity of both the transport of hazardous material and the urban development above those transport routes, if possible. In this regard, a proactive / functional measure could be the realisation of functions implying a low density of population above and along the infrastructure (see figure 5.2), such as a park or parking garages, through which the number of people exposed to the risk of the transported goods can be minimised. In essence, due to safety considerations and an acceptable level for group risk, there is an inverse relation between the population density and the number of transported dangerous goods in a specific area. The higher the number of transported hazardous materials, the lower the population density that can be allowed. This phenomenon is worked out superficially and presented in CPR 18 (2000)).

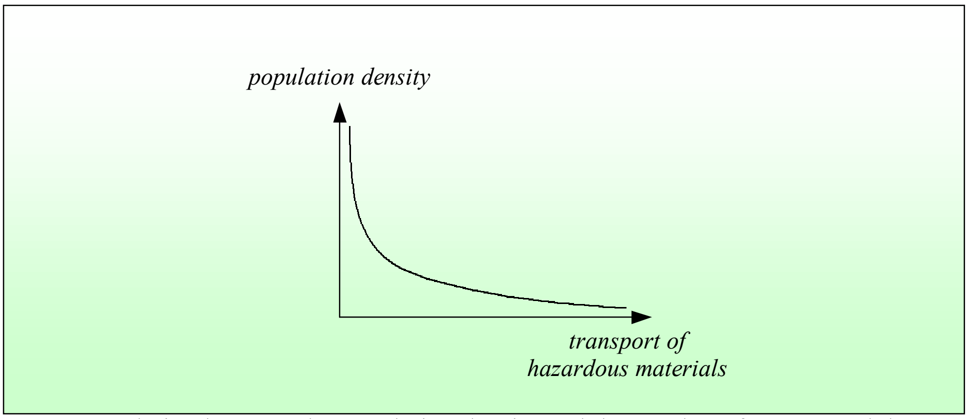

Figure 6.3: Inverse relation between the population density and the number of transported dangerous goods (see CPR 18 (2000)).

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, as discussed in section 5.2.2, and fire.

- *The effect of the width and height of the tunnel*

In situations like figure 6.4, the height of the covered infrastructure depends on the height of the lowest storey of the building h_o. The width of the covered infrastructure depends on the span l of the building.

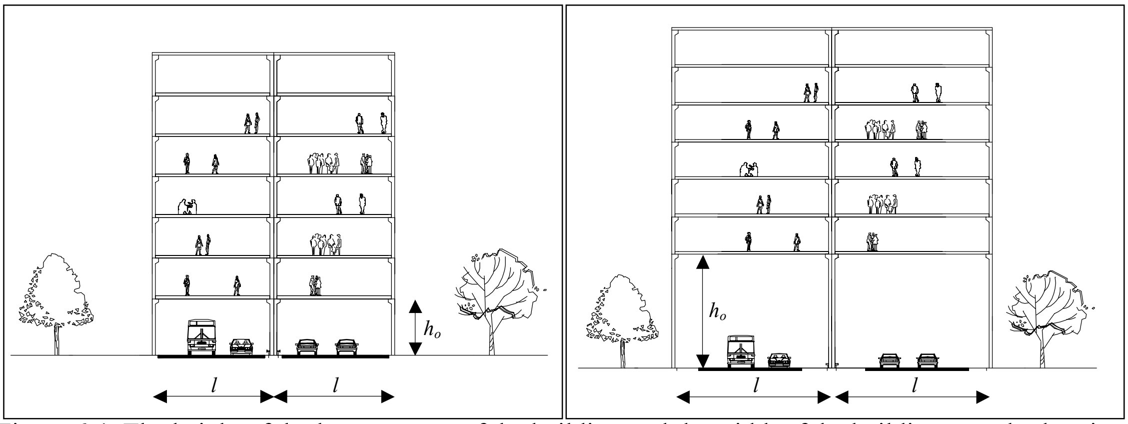

Figure 6.4: The height of the lowest storey of the building and the width of the building: standard variant (left) and the variant with a higher lowest storey and a larger width (right).

These two parameters form the basis for the possible scenarios at the infrastructure. Suppose h_o is designed at a minimum of 4 meters 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 $L/D > 10$.

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_o 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 (figure 6.4). An example, in which the lowest storey h_o is high and has a big span l, is the conceptual Gateway project of Schiphol Airport, Amsterdam. This concept, however, is based on architectural design rather than safety considerations (figure 6.5).

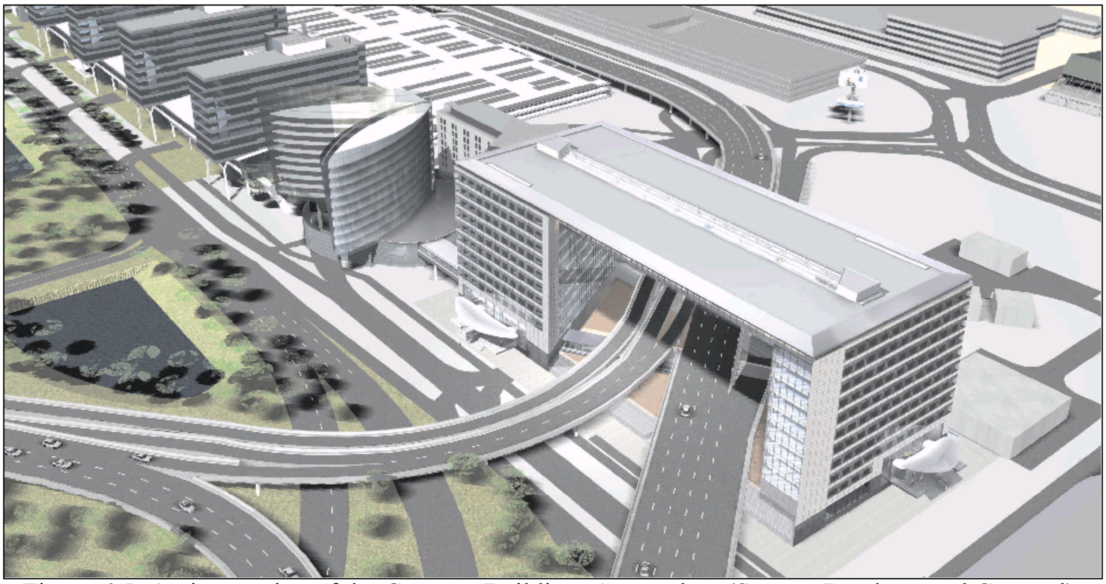

Figure 6.5: An impression of the Gateway Building, Amsterdam (Source: Benthem and Crouwel).

- *The effect of the length of covered infrastructure*

Multiple use of space becomes interesting when the infrastructure is covered for long distances (Suddle *et al*. (2004)). 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. 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*. (2001). The effect of the covering length of infrastructure for the main scenarios is presented in table 6.3. One can read that a small covering length of infrastructure is positive regarding the explosion scenario. Any advantages regarding toxic gasses are, however, not seen by a small covering length of the infrastructure.

Table 6.3: The effect of the covering length of infrastructure on the damage to the building above the infrastructure and the vicinity.

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

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, as discussed in section 5.3.4. 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 figure 6.6. This is, however, not valid for small coverings.

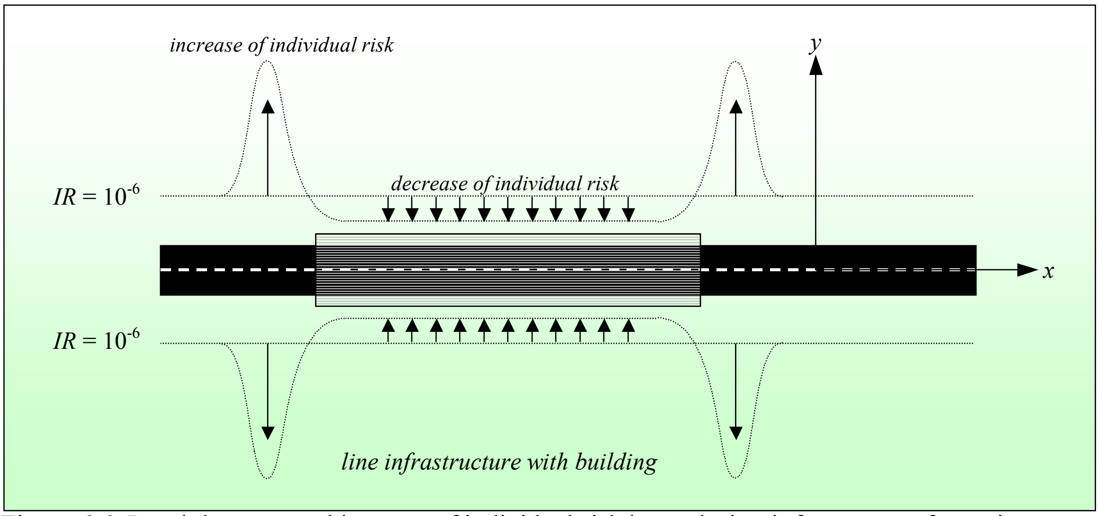

Figure 6.6: Local decrease and increase of individual risk by enclosing infrastructure for toxic gasses.

- *The effect of the height level of the infrastructure*

As stated in section 2.3.2, four different levels of height for infrastructure can be distinguished: underground, subsurface, ground level, and elevated. In figure 2.8, 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 6.4. 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.

Table 6.4: The effect of the level of infrastructure on the damage to the building above the infrastructure and the vicinity.

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	++	++	+	++

6.2.3 Structural safety measures

Structural measures can be implemented on (boundaries of) the building above the infrastructure or on the infrastructure itself.

For instance, buildings above the infrastructure or its structure can be designed free of columns at the footprint of the infrastructure (see figure 6.7). This is of course not a general design solution and mostly the result of architectural considerations. By this, the probability of a collision of a vehicle with the main structure of the building will decrease. Note that if one can utilise independent foundations for the infrastructure, one can reach safety advantages as well. More details on structural safety measures will be discussed in section 6.3.2.

Figure 6.7: Examples of structural measures in buildings; Exchange House in London, UK (left) and the Haagse Poort in The Hague, The Netherlands (right).

6.2.4 Human related safety measures

Safety measures aiming at the evacuation of human beings - which should not be considered as an extra safety measure - are mostly based upon the escape opportunities of people in an emergency situation and the availability and accessibility of emergency response, such as the fire brigade and ambulances. In essence, these measures are mostly measures in the repression class of the safety chain and should be implemented in both buildings above the infrastructure and on the infrastructure itself. An example of a measure in which enough escape possibilities are integrated in the design of the building above the infrastructure is presented in figure 6.8. More research on escape possibilities in the covered infrastructure near railway stations has been done by Langeweg (2003).

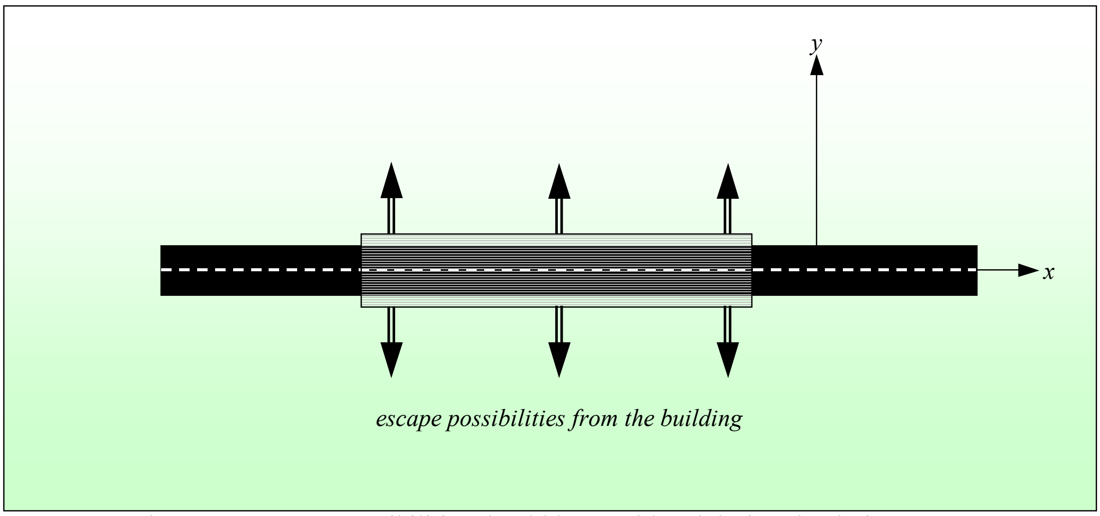

Figure 6.8: Escape possibilities should be considered during the design stage.

6.3 Effect and costs of safety measures for four critical scenarios

6.3.1 Introduction

The effects of measures are unique to each multiple use of space project, depending on the traffic characteristics and local circumstances. A general effect of the measures applicable to all projects can therefore not be generated. Likewise, the costs of measures vary for each type of project. Costs will also differ considerably between measures incorporated during the initial design and building stage and retrofitted measures. The costs are therefore best estimated for each particular case so that the efficiency or cost effectiveness ratio of the measures can be evaluated properly for the specific case. Nevertheless, some measures can be generalised and their risk reducing effect and cost can be determined, leading to particular basic and technical solutions in such projects. It is concluded by Suddle & Wilde (2002) that sufficient investments in safety measures lead into easy realisation of multiple use of space projects in future. It is therefore useful to illustrate some indications of the costs of safety measures. This paragraph gives an overview of both effects and costs of safety measures which can be implemented against the characteristics of the four critical scenarios during exploitation, i.e. fires, explosions, release of toxic gasses, and mechanical accidents. Accordingly, a subdivision of four measure types, which are related to the characteristics of those four main hazards (as presented in the previous chapter), is:

- Measures against fire;
- Measures against peak overpressure;
- Measures against toxic load;
- Measures against mechanical loads.

These measures can be implemented on the infrastructure or the building or on the boundaries of those two. Note that these measures do not emphasise traditional measures, such as detection of fire etc, but strongly originate from a structural and functional point of view. These measures can be found in the paper of Suddle *et al*. (2003)).

6.3.2 Measures against fire

- *Fire protection layer*

Building materials loose their strength and stiffness properties rather quickly when exposed a sufficiently long time (more than say 5-10 minutes) to high temperatures resulting from fires. This may cause severe damage, beyond repair, or even premature collapse. Protection against high temperature levels is a common feature in fire safety engineering. One of the methods is to apply a fire protection layer. As far as safeguarding the structure is concerned, great uncertainty prevails with respect to the choice of the proper protective measures (see Both (2001) & PROMAT (2001)). Fire protection measures are designed for the entire service life of the covered infrastructure and the building above. Since the late eighties, tunnel protection against fire is standard in the Netherlands. The protection is based on a petrol fire. In 1979 the RWS-curve was found during tests in a model tunnel. The temperature measured during the tests rose up to 1350 °C. This high temperature was also found during earlier fire tests elsewhere (also see Tan (1997)). The most important parts of the RWS-curve are the gradient during the first 10 minutes and the maximum temperature level (cf. Both (2001)). The temperature rises so rapidly that the structure has no opportunity to adapt. High thermal stresses develop, and e.g. in concrete, moisture in the concrete becomes steam and causes high pore pressures and as a result, may cause spalling of the concrete. This is not the only problem that can occur.

Apart from the spalling of the concrete, the high temperature can also lead to yield stress, possibly resulting in the collapse of the structure as well. This spalling has a rapid chain effect reaction and can be detrimental. In case of reinforced concrete structures, if the reinforcement is heated, it looses its strength as well and the structure with the building above may collapse. Although the probability of a 300 MW fire which is represented by the RWS-curve is low (it occurred during tests), the structure is protected and designed on the basis of that curve by a *fire-resisting layer*, which has the property to reduce the heating rate in the structure as well as the thermal gradient therein and give the structure a chance to survive the fire. This protecting layer must not collapse during the fire, for between 60 - 90 minutes (VRC (2002)). The fire-resisting layer, an effective measure against immense heat radiation, also called *thermal insulation*, can be implemented on the boundary of the covered infrastructure and the building above, as presented in figure 6.9.

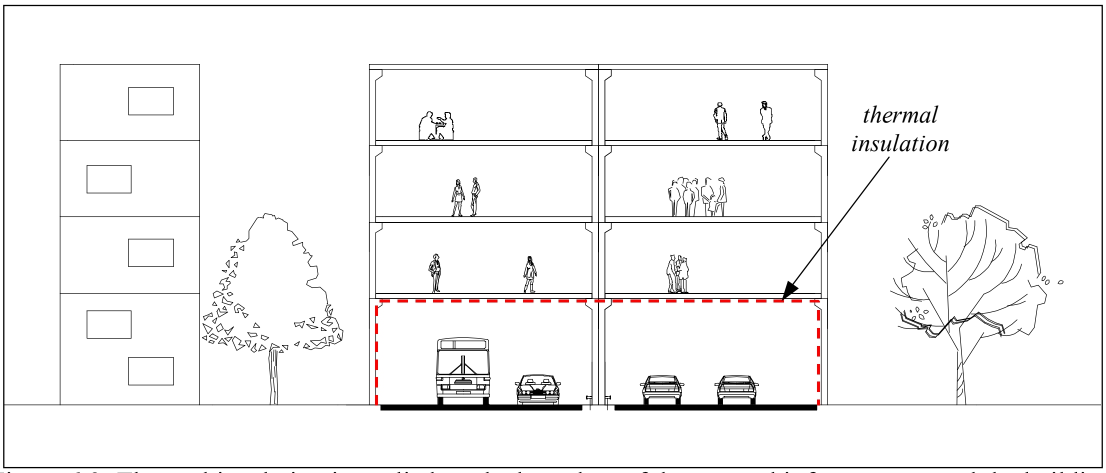

Figure 6.9: Thermal insulation is applied on the boundary of the covered infrastructure and the building above.

The effect of thermal insulation depends on both the scenario occurring in the building or on the infrastructure and the quality of thermal insulation. The quality relies heavily upon insulation capacity (conductivity) but perhaps even more on application details (fixings) and skills of application companies. The thermal insulation covers various methods to protect the concrete. According to PROMAT (2001), the main fire protecting measures of thermal insulation are concrete covering, sprayed covering and board linings. Depending on the type of fire exposure expected, the combination of some fire protecting measures (mostly board linings) can offer a fire performance of up to 240 minutes RWS fire (adapted from http://www.promat-tunnel.com/idprt001.htm), instead of the generally assumed standard 30 minutes fire performance without applying any fire-resistant layers or other measures. In addition, the layers have to be resistant to aggressive environmental conditions such as vehicle fumes, spray water and thawing salt and have to withstand dynamic forces from passing traffic (see also e.g. http://www.cafco.com/). It is also discussed by PROMAT (2001) that good quality thermal insulation can withstand temperatures of 1,350 °C up to 1,700 °C and heat radiations of 100 kWm^{-2}, which can occur during hydrocarbon fires and a BLEVE (CPR 18 (2000)).

Accordingly, one may expect that the resistance to collapse of the structure by (high) fire intensities can be increased by approximately 240 / 30 = 8 times when a fire-resisting layer is used, which is a strong reduction. If the fire is not extinguished in case of a 300 MW fire within half an hour, the probability of collapse of the building above is estimated to be 0.9 (see Appendix A3b).

However, it cannot be assumed that the probability of collapse of the building above infrastructure will decrease by a factor 8, if the resistance of the structure increases with a factor 8. Nonetheless, the effect of the fire-resisting layer, assuming the strong resistance effect of 8 times and the high temperature withstanding properties of the layer, both can be determined. The reduction effects for the probability that the structure of the building above the infrastructure collapses, is estimated to be approximately a factor 10 lower. This means that the probability of collapse of the structure in case of a 300 MW fire occurring on the infrastructure is approximately equal to 10^{-2}. Likewise, the probabilities of collapse of the building above can be assumed for a fire of 20 MW and a 5 MW fire: these are 10^{-3} and 10^{-4} respectively. It should be noted that in case of a fire spread to the building above, these probabilities are higher, because the fire intensity can be much higher than the mentioned 300 MW.

The investments in thermal insulation vary between € 10 / m^2 for the protection from spalling from a maximum fire of 5 MW and € 100 / m^2 for the protection from spalling from a maximum fire of 300 MW (VRC (2002)), which also depends on the concrete quality and the cover. If fire resistant plates are implemented in precast concrete, then the cost will be approximately € 50 / m^2. This value will be used later on in section 6.3.6 for the determination of the risk reducing effect in the integral approach of the safety measures.

Furthermore, it is important to note that maintenance of such a measure is essential for the durable effect of that measure. Although applying thermal insulation is an outstanding measure for the people present in the building above and in the vicinity, no effect of this measure will be gained for people present inside the covered infrastructure. Some experts even feel the measure may adversely affect internal safety, because smoke and hot gases may disperse more rapidly and over longer distances. Fire experts think this is only a secondary effect. In other words, such a measure affects the risk categories [1], [2] and [4] of chapter 1.

- *Additional (concrete) layer*

One may use an additional layer, with a separate foundation, for protecting the building above against fire occurring on the infrastructure beneath and visa versa. In order to prevent the spread of fire from the infrastructure to the building above, the layer should have enough mass. If the height of the concrete layer is set to be 1 meter and it is assumed that a fire on the infrastructure burns for one hour, the approximate calculated temperature increase in the building will be a bit smaller than 100 °C (this temperature can be determined exactly by the method used by Linden (2000)).

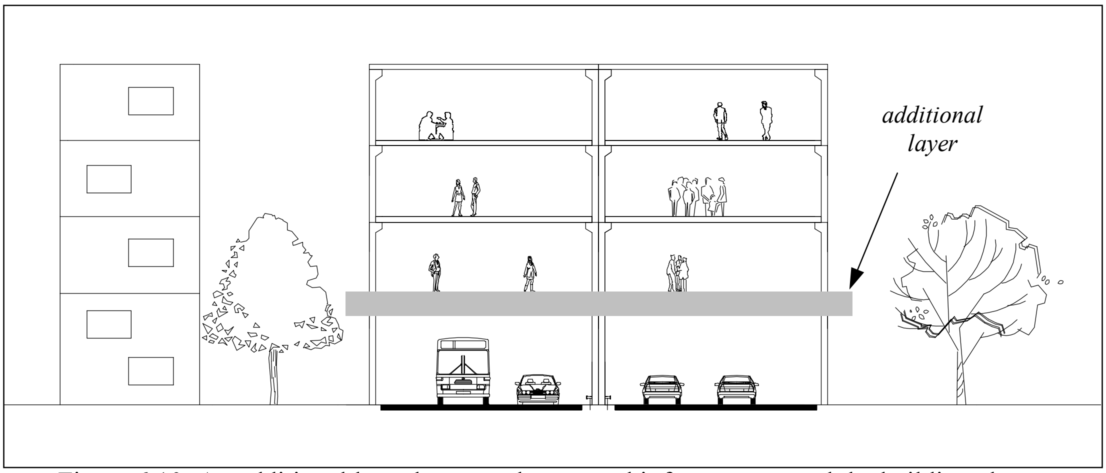

Figure 6.10: An additional layer between the covered infrastructure and the building above.

The effect of this measure is almost the same as the effect of the fire resistant layer. However, the fire resistance is now attainably the massive floor. The disadvantage of this measure is that the massive floor may disrupt the view, which may eventuate in architectural complications. An assumption has been made that the risk reducing effect of this measure is smaller than the effect of a fire-resisting layer. Therefore, it is assumed that the probability of collapse of the building above the infrastructure due to the additional concrete layer is a factor 5 lower than the original situation. This means that the probability of collapse of the building above the infrastructure given a fire of 300 MW fire is approximately equal to $5 \cdot 10^{-2}$. Likewise, the probabilities of collapse of the building above can be assumed for a fire of 20 MW and a 5 MW fire: these are $5 \cdot 10^{-3}$ and $5 \cdot 10^{-4}$ respectively.

The costs of implementing such a measure - including labour costs - are in the order of magnitude of € 500, / m^3 concrete (COBOUW (2003)). For this case € 500, / m^2 of concrete is needed additionally. The extra costs for the foundation activities are not included in that price indication. This measure affects the risk categories [1], [2] and [4].

- *Ventilation of the covered infrastructure*

Contrary to the effect of thermal insulation, the effect of ventilation in covered infrastructure mainly concerns the human risks for people present on the infrastructure. Using ventilation in case of fire at the covered infrastructure could be necessary for preventing smoke accumulation. Ventilation in the covered infrastructure can remove the heat radiation and exhaust gasses from that area in one direction from the fire, enabling people stuck behind the fire to flee from the heat and toxic gasses, into the other direction. In the other direction, the ventilation enables people to flee on foot that are stuck behind the fire from heat and toxic gasses. According to Huijben (2002), there are two main types of ventilation, namely *natural ventilation* and *mechanical ventilation*. The natural ventilation depends on the covering length of the infrastructure. This can be realised functionally by covering the infrastructure in small proportions rather than covering the infrastructure with buildings for long distances (figure 6.11). The space between two buildings should be enough to ventilate adequately. This depends on the wind.

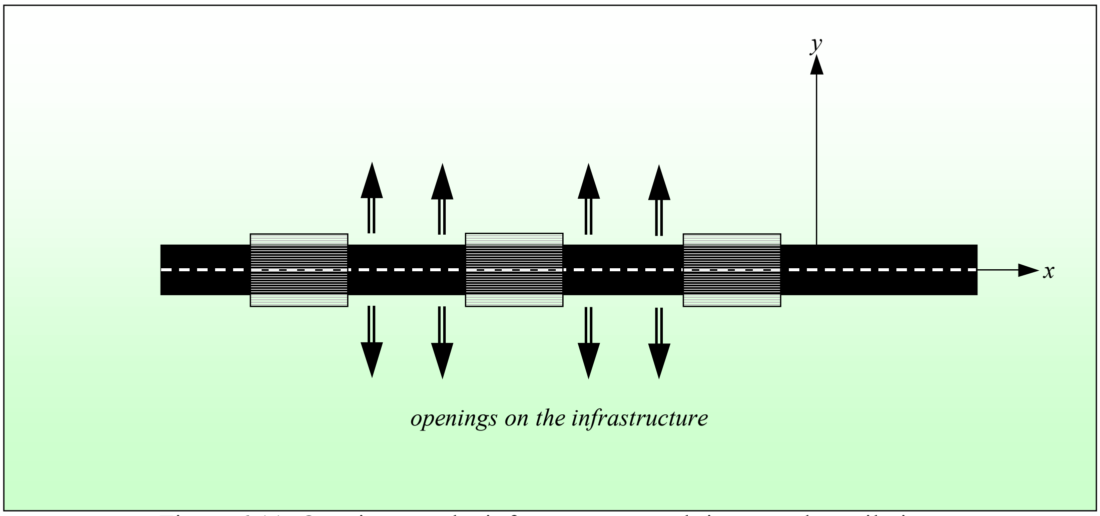

Figure 6.11: Openings on the infrastructure result in natural ventilation.

Applying natural ventilation as a fire safety measure is risky: natural conditions may significantly reduce the foreseen positive effects, it works merely for relatively small fires and relatively low smoke production. For more severe fires above, say, 20 - 50 MW, natural ventilation is felt to be inadequate as an internal fire safety measure in the covered infrastructure. Therefore, it is perhaps better to implement mechanical ventilation in the covered infrastructure, as an investment that should be made. This allows the infrastructure to be covered for long distances. According to the report of VRC (2002)), longitudinal or transversal ventilation in tunnels is suitable for fires of maximum 30 MW. More research on the ventilation of tunnels has been done by Huijben (2002).

The effectiveness of ventilation depends on the stage of the fire. The ventilation might be very effective, when the fire is in an early stage, also called the stratification of smoke. People present in the tunnel will stop and will not move towards the smoke area. For scenarios like a BLEVE, this measure is not effective. Nonetheless, the risk reducing effect of ventilation in the covered infrastructure can be great. It is stated by Kruiskamp (2002) that if the ventilation works, the probability of people killed due to intoxication or (inhaling) heat radiation by smoke in a tunnel, is lowered by a factor 10. One should critically notice that, in some cases, mechanical ventilation could blow or even enlarge the fire in the covered infrastructure.

The costs of implementing mechanical ventilation are approximately € 1,000,000.= / km. This is derived from the study about tunnels in The Netherlands (V & W (2003)), the Drechttunnel in the Netherlands, where 2 x 15 ventilators were implemented in the tunnel. The costs of each ventilator were € 35,000. Per kilometre, the investments for ventilations will be about € 1,000,000.=.

- *Sprinkler System*

Sprinkler systems, both in buildings and in the infrastructure beneath, can be effective, in case of fire occurrence. The sprinkler system - which consists of a water pipe system - sprays water directly onto the fire when detected. Therefore, a complex fire detection system is necessarily required. This decreases the probability of fire spreading from the building above the infrastructure to the infrastructure and visa versa. Sprinkler systems are highly regarded by fire protection professionals in buildings and fire departments because of their long successful history in buildings and on ships. Nonetheless, there is little experience with using sprinklers in tunnels or infrastructure covered by buildings. Although there is only little data (sometimes contradicting) on sprinkler systems, more (field) research is being done by TNO in the UPTUN project[4)]. Arends (2003) presented (dis)advantages for the evaluation of a sprinkler system in tunnels. Generally speaking, it can be stated that there is little scientific data and experience with sprinklers in tunnels (see e.g. DARTS (2002)).

There are indications though that the sprinkler system can be useful to reduce the aggravation of some scenarios. It is reported that a sprinkler system may prevent a BLEVE resulting in a collapse of the tunnel (RWS (2001)) and the building above. Furthermore, it can reduce effects of small fires, particularly when additives are used and it can give the emergency crews more time to enter the tunnel. There are some signs that the sprinkler system may endanger people in the direct vicinity of the huge fire (Arends (2002)). Another serious issue suggested by DTFHA (2000), is the detection system needed for a sprinkler system.

4) UPTON is the abbreviation for a project within the EU's Fifth framework Programme named "Cost-effective, sustainable and innovative UPgrading methods for fire safety in existing TUNnels". The project's two objectives are, firstly, to evaluate existing technologies and, where necessary, to develop innovative and cost-effective technologies and, secondly, demonstrate and promote procedures for the evaluation and upgrading of fire safety levels.

On one hand the reaction time must be very short, thus preferably automatic (RWS (2001)). On the other hand, people close to the fire must have the opportunity to flee before the system is activated. This means that both the detection and the functioning of the sprinkler system must be very accurate. At the moment, none of the detection systems complies with these demands.

Another problem is that the maintenance of sprinkler systems in (underground) infrastructure, is much more difficult than the maintenance in buildings. In this research, the risk reducing effects of the sprinkler system are estimated in a simplified approach as follows: The sprinkler system can prevent a BLEVE, but cannot prevent an instantaneous explosion. Besides, for some fire types like pool fires by burning petrol, the sprinkler system may spread the fire to a large area. Since little is known about the mitigating effects of sprinklers for tunnel fires, this effect is not taken into account (in fact: some authors argue that the use of sprinklers in case of an accident can increase the risks since large amounts of smoke will develop (see e.g. Jonkman *et al.* (2003^B)). Hence, a sprinkler system can prevent 90 % of the BLEVE 's (Arends (2003)). From this point, the probability of collapse of the building above the infrastructure is reduced by 90 %. Another assumption that is made for this research is that the material damage in case of implementing a sprinkler system is 50 % of the original situation.

The costs of a sprinkler system are estimated by Jonkman *et al.* (2003^B), to be approximately € 10^7 / km tunnel. The estimation of these costs is predominantly based on experience data. The costs of a sprinkler system in buildings varies between € 200,000 and € 1,500,000 for a building of 30 x 30 x 50 m^3 (depending on the sprinkler type). The sprinkler system effects the risk categories [1], [2], [3] and [4] of chapter 1.

- *Emergency exits*

In case of an emergency, such as fire occurrence on the covered infrastructure, people will have to flee through emergency exits. The probability of escape can be considered as a function of spacing between exits, which is assumed to exponentially decrease when the space is larger. It can be stressed that the more the distance between emergency exits, the lower the probability that a person can flee from a dangerous situation. In addition, the probability of escaping on infrastructure depends on which scenario occurs on the infrastructure (more details are presented by Person (2002)). It should be noted that emergency exits are very effective against relatively small fires of 5 - 20 MW. In contrast, the effectiveness of emergency exits concerning fires of 300 MW in the covered infrastructure is almost negligible (see figure 6.12).

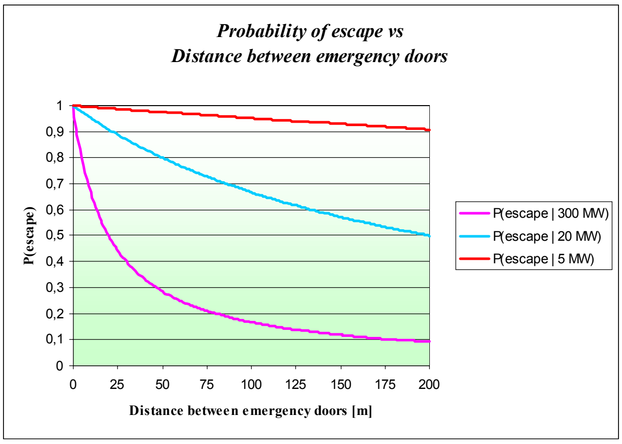

Figure 6.12: The (assumed) probability of escape versus the distance between two emergency exits in case of no ventilation.

The realising costs of emergency exits vary from € 10^4 / exit to € $3 \cdot 10^6$ / exit[5)]. The huge difference between the price is because the first one is assumed to be on the ground level, while the second price is based upon an additional structure for the exit in the underground. Furthermore, it should be noticed that the emergency exits in the covered infrastructure are only effective for people present in the covered infrastructure, and not for the building above (risk category [3] of chapter 1). So, one may consider implementing emergency exits in the functional design of the building above the infrastructure, which is hardly a cost rising measure.

6.3.3 Measures against peak overpressure

Structural measures against peak overpressure are almost never feasible nor practicable. These measures are both structurally and practically almost impossible to realise, because the theoretical dimensions of such measures are enormous. For that reason, the investments in such measures are extremely high, even higher than the total project budget (Suddle *et al.* (2003)). Both explosion resistant and explosion reduction measures, as discussed by e.g. Adeli & Saleh (1998), will thus not be applicable in multiple use of space projects. Calculations, based on AFESC (1989), Baker *et al.* (1983), NASA (1975) and Biggs (1963), show that when packing in the infrastructure in a steel tube to prevent the effects of a detonation towards the building above, the thickness of that profile should be at least 71 mm, costing € 121,800,000.= per kilometre, which is of course absurd and not thus practicable (Suddle *et al.* (2003)). According to Veen & Blaauwendraad (1983), measures against explosions can be taken against a maximum value of $(2.5 - 5.0) \cdot 10^2$ kPa ($\cong$ 2.5 - 5.0 bar). Besides, there is hardly any scientific knowledge or evidence about the practical functioning and applicability of measures, like a clap roof, energy absorbing measures (RWS / OBB (1982)) or water mitigation measures in multiple use of space projects. Only 1:1 scale experiments can predict their feasibility.

Berg & Weerheijm (2004) provide some measures in tunnels against explosions, which are particularly focused on the vessel rather than the tunnel structure. According to Berg & Weerheijm (2004), the most obvious way to prevent a gas explosion is to ignite the gas before a flammable premixture of some size has built up. A fire is easier to control than a gas explosion. Water deluge by a high flow rate sprinkler system cannot prevent a gas explosion but may substantially reduce the pressure effects of an already developing gas explosion. The water deluge should be immediately activated by a flammable gas detection system over the full tunnel length. A promising new development for gas explosion suppression is the micromist device. This technique seems to be able to introduce a sufficient amount of ultrafine water droplets to be able to inert the mixture and to cool the flame. Extinguishing a fire without stopping a source of flammable gas enables a gas explosion scenario. A source of flammable gas after the quenching of a fire may also consist of liquids and solids that evaporate and pyrolise as a consequence of their high temperatures.

An effective measure against the blast of a BLEVE could be to prevent the explosive rupture of a pressure vessel by cooling the vessel with sprinklers, such that the internal vapour pressure of the liquefied gas does not increase beyond a critical limit. The blast of a BLEVE is strongly reduced if the structure of the pressure vessel is designed in such a way that it cannot instantaneously fall apart. If the outflow of liquefied gas is spread over just a time span of about one second, the subsequent blast effects are minor (Berg & Weerheijm (2004)).

[5)] Scource: Rijkswaterstaat, Utrecht; ing. Jelle Hoeksma.

As already stated in section 6.2.2, another safety measure is the separation of transport and the urban activities. Considering the explosion scenario and its large consequences for the vicinity, it can be desired to separate functions of urban development and transport of hazardous materials that cause the explosion scenario, because one should realise that these functions cannot be combined together (Suddle (2003[C])). Still, one needs to deliberate the costs and the benefits of measures to separate them. Only then, a rational and a justified choice can be made.

6.3.4 Measures against toxic loads

- *Covering the infrastructure with use of a water curtain or a barrier on both ends*

Measures against toxic loads can be implemented on the building above the infrastructure, the infrastructure itself, and the vicinity. The group risk, caused by toxic loads, is the result of many buildings in a wide vicinity of infrastructure not having the proper measures, causing people present in those buildings to be the victim due to intoxication. In general, covering the infrastructure for an as long as possible distance, i.e. outside urban contours, is a logic measure to limit the effects of a hazard with transport of toxic materials. Closing barriers or a water curtain is vital at both ends of the covering length. For this to be feasible, an accurate detection system along the covered infrastructure with an alarm system is required.

The effect of such a measure is great. If one can contain the toxic substances within the covered infrastructure, one may have an almost complete exclusion of victims in the building above (risk category [2]) and the vicinity (risk category [4]) due to an accident in which toxic substances are released. It should be noted that the covering length should be as large as possible. The estimation / assumption of the probability of being killed due to such an accident with implementation of the considered measure in the vicinity will decrease with an order magnitude of 2 on a logarithmic scale, which means that the probability of being killed, given that toxic gasses may be released and the wind is assumed of a constant direction, will be 10^{-2}. However, many victims will be present among the people in the covered infrastructure (risk category [3]). It should be noted that evaporation models for release of several toxic gasses are discussed in CPR 18 (2000). Considering the scope of this study, these models are not taken into account for determining the reduction probabilities, but assumptions have been made for these evaporations and the wind. The effect of each measure can be determined exactly, if desired.

The costs of such a measure, based on the detection system in the covered infrastructure and the barrier or a water curtain, are difficult to estimate, since there is hardly an application of such a measure. Covering the infrastructure for a long distance is a measure from an urbanistic point of view rather than a measure to protect people from toxic gasses.

- *Airproof buildings*

In order to make air - possibly polluted with toxic released gasses - impenetrable towards the building above and the vicinity, one must realise air proof buildings. This measure can be applied in particular for the building above the infrastructure rather than the vicinity, because the buildings in the vicinity are usually already established. For most already established buildings in the vicinity, it is not clear that they are airproof untill a certain level. Most buildings are usually not designed to be 100% airproof. In The Netherlands the air volume flow, also called the q_{v10} ratio, deduced from the ratio of pressure and volume flow characteristic in case of a pressure difference of 10 Pa, is a significant parameter that reflects the air permeability of buildings, as discussed in NEN (1989). The q_{v10} ratio is the number of litres outside air penetrating in the building per second ([ls^{-1}]).

Normal buildings are designed on base of a q_{v10} ratio of 80 ls^{-1} (Wiersma *et al.* (2004[A])). Yet, one can yield profit from the air permeability. If one can realise buildings with a q_{v10} ratio of 8 ls^{-1}, one may decrease the effects of toxic gasses with a factor 10. In order to achieve a q_{v10} ratio of 8, one has to implement large concrete façade elements rather than permeable façade elements. Besides, the gaps between these elements should be carefully sealed up. This measure is in particular applicable for buildings above the infrastructure and this measure is against toxic gasses remaining a short time on one occasion (for a full overview see Wiersma *et al.* (2004[A])). The price of such a measure is about € 50 / m^2 façade. This can usually be integrated during the design stage of the project.

- *Airproof buildings with additional ventilation*

In some incidents with release of toxic gasses, the gasses remain for a long time period on one certain location, such as hydrosulphide (H_2S). By this, the probability of fatalities in open air due to intoxication increase considerably. In addition to the previous measure, one can realise 100% airproof buildings, in which an additional (internal) ventilation system is required. Such a system is used in submarines or chemical and biological laboratories. If a building is 100% airproof - i.e. no outside air, possibly toxically polluted, can penetrate the building - an internal circulation of fresh air in the rooms of that building is required. One may achieve this by means of a ventilation system in which the air is refreshed and filtered for instance once a day. The effect of airproof buildings with additional ventilation is enormous, because the combination of airproof building and a ventilation system almost eliminates fatalities through intoxication. Therefore, the effect of implementing the measure in question is estimated to save 99% of the people in the building.

Although the measure reflects a large risk reduction, the measure has some crucial disadvantages. Firstly, the measure is quite expensive. It is shown by Wiersma *et al.* (2004[A]) that the investments for this measure are at least € 2,500,000 per building of 30 x 30 x 10 m^3. Secondly, implementing this measure means that a large number of building surface is lost due to the space needed for the ventilation system.

- *Gasmasks*

Gasmasks are meant to enhance respiratory protection against chemical gasses, etc. Gas masks for emergency services and civilian use costs about € 300 / each. More details can be found at http://www.ukgasmask.co.uk/. In case of an accident with toxic materials one may use the gasmasks in buildings. By this, the released gas is not able to contribute to the number of victims. The effect of gasmasks is theoretically estimated on a risk reduction of 90%, in which it is assumed that there is a good working detection and warning system. Besides, it is also assumed that the people are trained in such situations.

6.3.5 Measures against collisions against the building structure

If a vehicle on the infrastructure collides with a column of the building above the infrastructure, this building may collapse, causing a large number of fatalities in the building. In order to reduce the consequences of mechanical accidents on infrastructure hitting the bearing structure of the building above, one can implement a crash barrier (in case of roads), derailment control (in case of railway tracks), a concrete wall instead of columns or even over-designed columns, combined with independent bearing structures for both building above the covered infrastructure and the covered infrastructure itself. One may also implement an alternative bearing structure in the building, by which the probability of collapse decreases.

One may consider to omit columns on the footprint of the infrastructure. The main advantage of omitting columns on the infrastructure, is that the probability of a collision of a train with the main structure of the building will decrease, let say with a factor 10 (see section 6.2.3). The reduction of damage depends on the traffic type and can be determined exactly. A crash barrier is more effective for car collisions than for collisions with trucks. Therefore the reduction of probabilities is ranked in accordance with the traffic type (see table 6.5). One applies this measure in the design stage of a project.

Table 6.5: The assumed reduction of probabilities and the traffic type.

Traffic Type	Reduction probability crash barrier	Reduction probability derailment control
Car	0.90	-
Bus	0.30	-
Trucks	0.10	-
Trains	-	0.9

The price of a crash barrier, used on motorways, is approximately € 20,000 / km[6)]. The price of derailment control depends on the extra concrete needed to realise this measure. If the extra concrete is 2.0 m^2 on each side, then the costs will approximately be in the order of € 2,000,000 / km.

6.3.6 Integral approach of safety measures

The risk reducing effect per measure have to be compared with the investments in that measure, because of efficiency considerations. In this regard, the cost effectiveness of the safety measures of this chapter is determined for the case study of section 3.5. Although both the effects and investments of measures are unique to each multiple use of space project, depending on several circumstances, some measures can be generalised and their risk reducing effect and cost can be determined, leading to particular basic and technical solutions in such projects. Note that influencing the local circumstances, the cost-effectiveness of safety measures can be inconsistent with the presented results. Moreover, some measures can only be implemented in combination with other measures, rather than implementing individual measures. This may also lead to different results regarding cost-effectiveness of safety measures. The paper of Suddle *et al.* (2003) presents basic probabilities and consequences of scenarios, partly derived from Wiersma *et al.* (2004[A]). Subsequently, the risk reduction per safety measure is determined. Finally, the human risk (decrease) $\Delta E(N_d)$ is compared with the investments C_0 of safety measures, as presented in figure 6.13. This figure should not be used as "the exact cost-effectiveness diagram" for all multiple use of space projects, but as indicator of cost-electiveness of safety measures, because the presented results belong to the specific case of chapter 3. For other cases, these results may differ entirely.

If we consider figure 6.13 in a broader sense, some interesting remarks can be made. From figure 6.13, it becomes evident that measures against toxic gasses are possible, but not cost effectively. Safety measures like fire resistant lining, ventilation in the covered infrastructure and sprinkler systems are very cost effective. From a risk point of view, it is therefore efficient to implement measures without making large investments C_0 resulting in a large risk reducing effect $\Delta E(N_d)$. As a result, measures against fire protection and collisions on the infrastructure are strongly proposed to be implemented in multiple use of space projects.

6) Scource: Rijkswaterstaat, Utrecht; ing. Jelle Hoeksma.

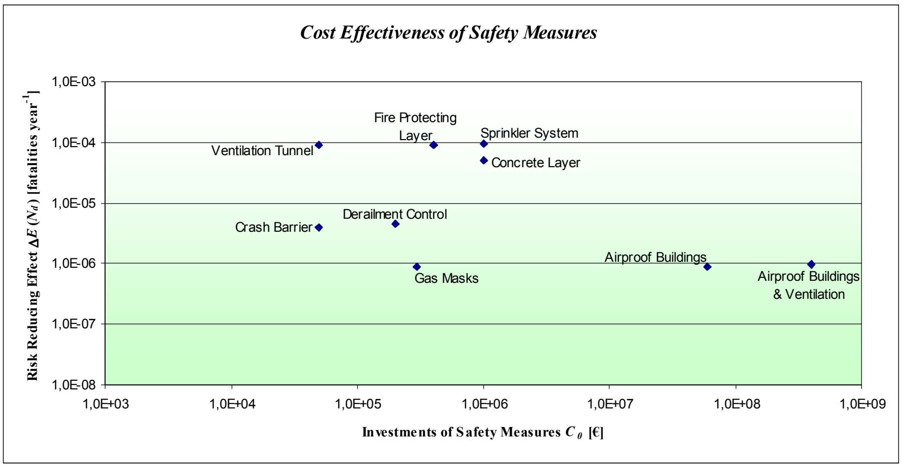

Figure 6.13: Cost Effectiveness of Safety Measures for the case study of chapter 3.

Measures against toxic gasses can be taken, however, these are not cost effective, except gas masks: their risk reducing effect is too marginal in comparison with their relatively large investments. The main reason for this is that although a large number of human lives can be saved, the probability of the release of a toxic gas is relatively small in comparison to other scenarios.

6.4 Conclusions

An overview of the previous sections shows that there are a large number of variations in implementing measures against some kind of scenario in multiple use of space projects. Yet, implementing individual or single measures is mostly expensive and less effective, since individual measures might be beneficial to one scenario, while having no or an opposite effect to another. As a consequence, it is utmost important to consider the implementation of any measure in combination with other measures, e.g. measures from the safety chain, measures against other scenarios such as a fire protecting layer combined with derailment control or crash barriers, or ventilation in the covered infrastructure together with emergency exits. This chapter also illustrates that safety measures against fires, release of toxic gasses and collisions against the main structure of the building above can be realised easily, while measures against explosions are both structurally and financially impossible to realise in practice. Some measures against peak overpressure can be taken to the development of a gas explosion or the vessel itself, e.g. the most obvious and simple way to prevent a gas explosion from developing is early ignition. However, it is questionable whether these mitigating measures will work. If these measures fail to work, a large number of fatalities can occur. Therefore, one should seriously consider that transported materials causing an explosion, such as LPG or ammonia, do not harmonise with urban development near or above such a transport route. In this regard, it is persuasively proposed to separate the transport of hazardous material and urban activities and visa versa, especially in The Netherlands. Furthermore, measures against toxic gasses are less cost effective than measures against fire. Therefore, separation of the transport of toxic gasses through urban development is optional as well. This can accomplish urban development surrounding the infrastructure with less risk. Considering the previous, it can be concluded that multiple use of space projects cannot be realised without taking safety measures. However, one should deliberate the investments of these measures with their probability or risk reducing effect. From this point of view, measures against fire or collisions should be taken during the design stage of such projects.

7

Case Studies

Once all theoretical and practical input of safety issues in multiple use of space projects is known, this knowledge can be put into practice by case studies. This chapter gives an overview of how to deal with safety measures in such projects and how to weigh them with non-financial and non-human risk aspects, as discussed in chapter 2 and 3. In this regard, two case studies in The Netherlands are analysed: the Bos en Lommer project in Amsterdam (buildings above the motorway A10 West) and the tunnelling of the railway track in Delft. These two projects are considered because details on this project are found easily. The elements of the weighted risk analysis, considered in both cases, are the investments C_0*, economical losses* C_j*, economical benefits* $C_{benefits}$*, human risks* $E(N_d)$*, quality risk* $R_{quality}$*, and environmental risk* $R_{environmental}$*. The values of the weighted risk are computed with the monetary values per considered risk* α_j *of section 3.2.3. Finally, it should be noticed that the presented results are indications of amounts of several elements of the weighted risk, rather than an exact presentation of a cost-benefit analysis, through which results may vary considerably.*

7.1 Case Study 1: Bos en Lommer, Amsterdam

7.1.1 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. Due to their position above the motorway and their distinctive architecture, the buildings are extremely eye-catching. The buildings have a total floor space of 20,000 m² distributed over 2 buildings of 6 floors each of 9,000 and 11,000 m² respectively. The 5th 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. What is striking in the design is the visible load-bearing structure and the large degree of transparency. The depth of the buildings is approximately 15 metres (adapted from http://www.multivastgoed.nl). The construction of this project started in 2001 and was finished in end of 2003.

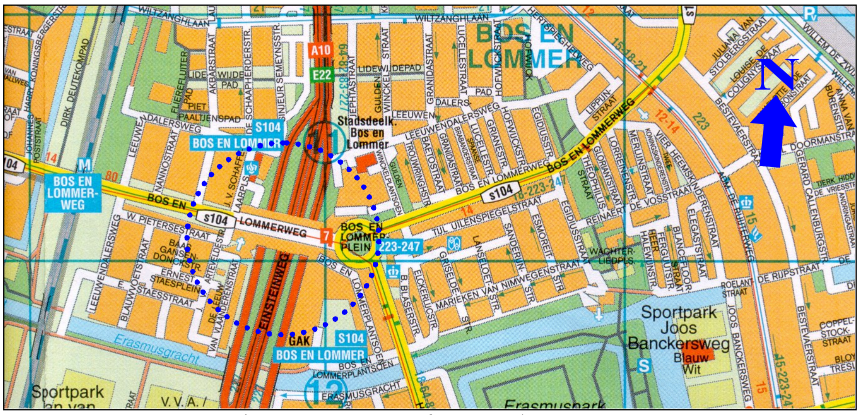

Figure 7.1: Map of Bos and Lommer.

Figure 7.2: An impression of the Bos en Lommer Office buildings with transport of hazardous materials.

7.1.2 Input parameters

The covering length of the buildings is about 90 meters (Hoeksma (2002)). Hoeksma (2002) also presents some basic probabilities of 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 (2002) 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 (2002), toxic liquids and toxic gasses are not transported. The transport of flammable gasses is set to be 3,664. According to Eldonk *et al.* (2001), the average office space use per employee is about 24 m^2 for the year 2000 in The Netherlands. From this, the average number of people working in these buildings can be determined, approximated to be 800 during the day. AVIV (2001) 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 $5.0 \cdot 10^3$ persons per km^2. From AVIV (2001), the fraction of hazardous materials can be derived for the motorway A10 Bos and Lommer Amsterdam as well. Table 7.1 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. An overview of input data is presented in Appendix B.

Table 7.1: The vehicles passed per year with hazardous materials.

Type of Hazardous Materials		Vehicles passed per year
LF	Flammable Liquids	36,501
LT	Toxic Liquids	0
GF	Flammable Gasses	3,664
GT	Toxic Gasses	0

7.1.3 Results risk analysis

The Bayesian Network of chapter 5 (figure 5.6) is used for the risk analysis. First, the individual risk *IR* is computed as described in chapter 5. Subsequently, the group risk *GR* is determined, from which the number of people killed $E(N_d)$ per year is derived. The consequences C_{fi} are assumed per scenario, as it is done in chapter 5.

- *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 $2 \cdot 10^{-5}$ and $2 \cdot 10^{-6}$ respectively (see figure 7.3). Table 7.2 presents the individual risk for the buildings above the infrastructure (per unit building).

Table 7.2: 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	$1 \cdot 10^{-6}$	0.1	$1 \cdot 10^{-7}$
2. Fires	$2 \cdot 10^{-5}$	0.07	$1 \cdot 10^{-6}$
3. Leak of toxic substances	0	0.5	0
4. Explosions	$3 \cdot 10^{-7}$	1	$3 \cdot 10^{-7}$
ΣIR [$year^{-1} \cdot km^{-1}$]			$2 \cdot 10^{-6}$

This means that the risk slightly exceeds the criterion for the individual risk acceptance. From this, the schematic risk contour in the 3rd dimension, as suggested in chapter 5 (see section 5.4), can be depicted in the cross-section. It is assumed that the shape of the contour is a rectangle.

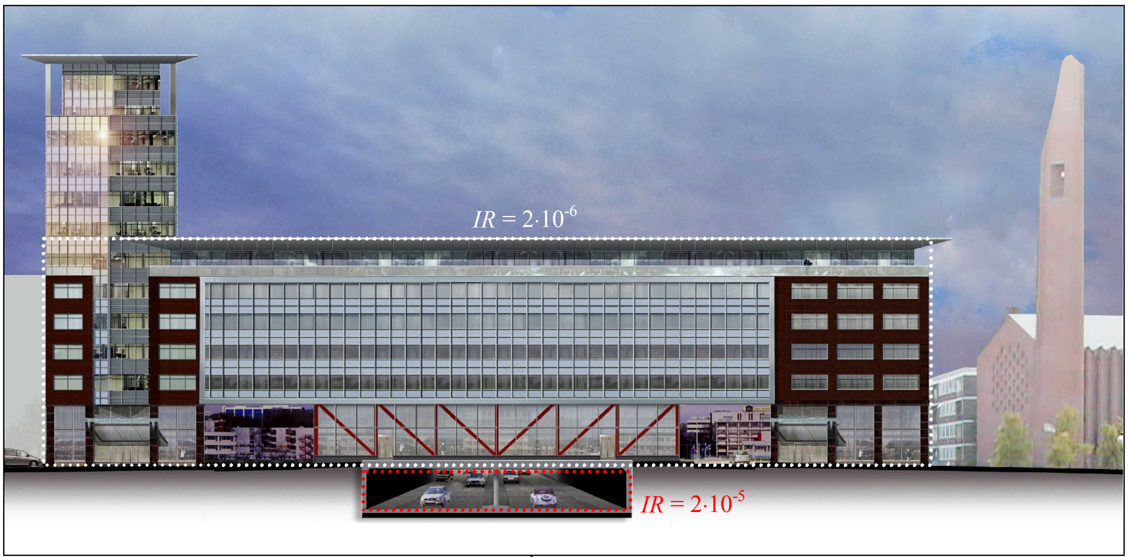

Figure 7.3: The (schematic) IR contours in the 3rd dimension for Bos and Lommer building (Source artist impression: www.multivastgoed.nl).

- *Group Risk*

Likewise, the group risk can be determined for the Bos and Lommer buildings. The FN-curve for this project is presented in figure 7.4.

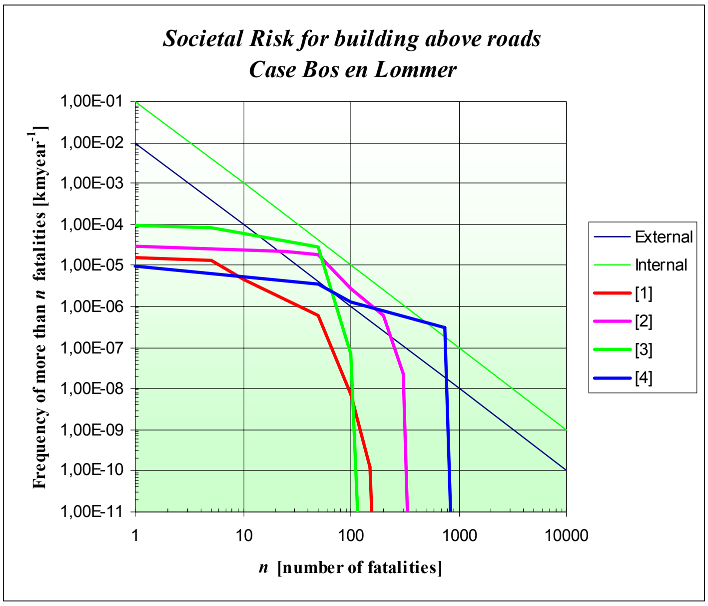

Figure 7.4: The group risk for the Bos and Lommer building and the vicinity per risk categories [1], [2], [3] and [4] of figure 1.2 of chapter 1.

- *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 $E(N_d)$[1], $E(N_d)$[2], $E(N_d)$[3], $E(N_d)$[4] are respectively $1.4 \cdot 10^{-4}$, $1.2 \cdot 10^{-4}$, $2.4 \cdot 10^{-3}$, $4.5 \cdot 10^{-4}$. The total expected number of people killed per year $E(N_d)_{tot}$ is thus equal to $4.2 \cdot 10^{-3}$. Note that the $E(N_d)_{tot}$ depends primarily on both risk category [3] and risk category [4].

- *Economical losses*

The economical risk for the Bos and Lommer building is approximately € 300 per year (table 7.3). Suppose that the monetary value per fatality α is set to be € 1,000,000,=, then the value of $E(N_d)_{total} \cdot \alpha$ is equal to € 4,200, which is higher than the expected economical loss for this case. This comparison will be made when different measures are implemented for this case.

Table 7.3: The economical risk for Bos and Lommer.

Covering Length	**80 m**		
Scenario i	P_{fi}	C_{fi}	R
1. Collisions with the structure of the building	$1 \cdot 10^{-6}$	$1 \cdot 10^{6}$	$1 \cdot 10^{0}$
2. Fires	$2 \cdot 10^{-5}$	$5 \cdot 10^{6}$	$1 \cdot 10^{2}$
3. Leak of toxic substances	0	$2 \cdot 10^{4}$	0
4. Explosions	$3 \cdot 10^{-7}$	$5 \cdot 10^{8}$	$2 \cdot 10^{2}$
Expected economical loss [€·year^{-1}]			$3 \cdot 10^{2}$

7.1.4 Comparison with other measures

- *Measures for regulation of transport of LPG*

The effect of some measures of the safety chain will be determined in the case Bos en Lommer. One of the measures is the ban of transport of LPG on roads. In The Netherlands, there is a strong recommendation to ban the transport of LPG on roads and rails, on a national level. Transporters could benefit from prohibiting urban development adjacent to transport routes. However, banning the transport due to urban planning or banning urban development due to the transport are both not the solution to the external safety problem in The Netherlands. Still, one may accomplish measures with similar effects; such as locally rerouting the LPG traffic through non-urban areas, or realising another transport types e.g. transport pipelines or even transport by ships. An advantage of transport of LPG on ships is that hardly any (densely) populated areas are established near the rivers. All these measures usually demand large investments of different parties or actors using the hazardous material. Logistic measures, such as (1) banning the transport of LPG, (2) rerouting the transport of LPG, (3) LPG through pipelines and (4) LPG transport during the night are taken into account. Investments, maximum economical risks and the number of people killed per year are considered in this part of the case. In Appendix B, a full overview of calculations of investments etc. is presented.

If we can calculate the risk reduction per measure, then the cost effectiveness of measures can be determined. First, the group risk *GR* for the Bos en Lommer project without the transport of LPG is presented in figure 7.5, which is needed to determine the number of people killed per year $E(N_d)$.

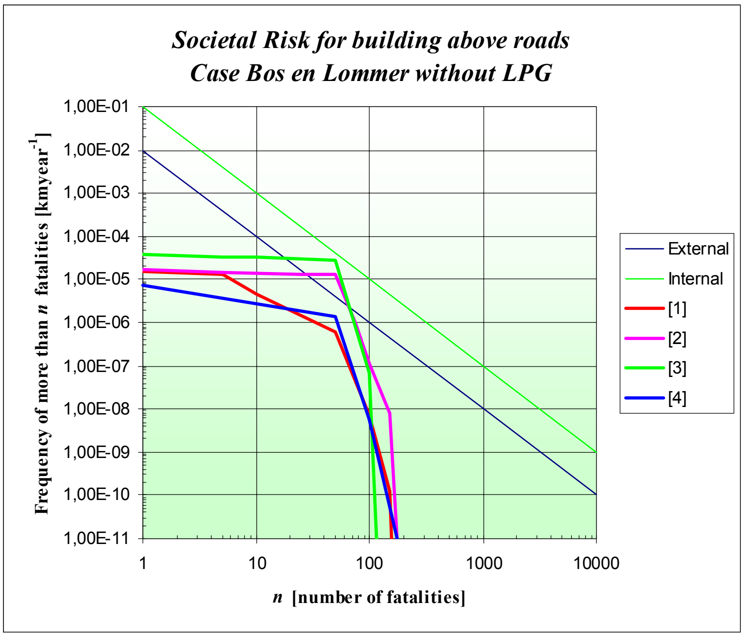

Figure 7.5: The group risk for measure 1, 2 and 3 of table 7.4 per risk categories [1], [2], [3] and [4] of figure 1.2 of chapter 1.

Table 7.4: Comparison of economical risk (per year) for different measures in Bos and Lommer.

Safety Measures	**Investments** C_o	**Economical risk** C_i	**Total costs** C_{tot}	$E(N_d)$
0. Starting situation	-	€ 300	€ 300	$4.2 \cdot 10^{-3}$
1. Banning transport of LPG	-	€ 62,000,000	€ 33,750,000	$2.9 \cdot 10^{-3}$
2. Rerouting transport of LPG (not through urban areas)	€ 55,000	< € 300	€ 55,300	$2.9 \cdot 10^{-3}$
3. Transport of LPG through pipelines	€ 62,500,000	< € 300	€ 62,500,300	$2.9 \cdot 10^{-3}$
4. Transport of LPG takes place during the night	€ 1,062,000	< € 300	€ 1,062,300	$2.9 \cdot 10^{-3}$ - $4.2 \cdot 10^{-3}$

From table 7.4 it becomes evident that measures 1, 2 and 3 lead to the same effect regarding the number of people killed per year $E(N_d)$, where this value for the 4th measure fluctuates in the range of the other measures, because the number of people exposed to that risk will be the only difference. Therefore the risk analysis is not performed for the 4th measure, because the risk reduction of expected fatalities of measure 1, 2, and 3 compared with measure 0 (starting situation) is marginal. Hence, one can expect that the $E(N_d)$ of measure 4 lies somewhere between $2.9 \cdot 10^{-3}$ and $4.2 \cdot 10^{-3}$. The small reduction of the $E(N_d)$ is due to the fact that the probability of the number of fatalities more than 1000 decreases, while the probability of small accidents in which a relatively small number of people is killed, is relative constant. However, the reduction in disasters with large consequences is significant.

So, if the original FN-diagram of measure 0 (figure 7.3) is compared with the FN-diagram of figure 7.4, one sees that scenarios with large numbers of people killed per year decrease strongly. This large reduction, however, is not presented appropriately by the $E(N_d)$, this problem is also discussed by Bedford & Cooke (2001). The FN-diagram of figure 7.5 is valid for the measures 1, 2 and 3. When considering the measures, we see that measure 1 - totally banning the transport of LPG - leads to large economical losses (fired workers and sanitation).

According to the Ketenstudies (2003)[7)], banning the transport of LPG leads to large social losses, i.e. the loss of 4,700 labourers, which is approximately a loss of € 47,000,000.= (see Appendix B). This amount can also be considered as investments for the labourers losing their work. Furthermore, an important notice of applying measure 1 and 3 is that the investments are relatively high, while the risk reduction in terms of $E(N_d)$ is almost negligible. The costs of measure 3 are high, because new infrastructure has to be realised in order to make that measure practicable. In contrast, the costs of measure 2 are relatively low, because rerouting the traffic is taken into account locally. If the investments are computed for an overall rerouting of LPG in the Netherlands, the costs may be millions of euros. The costs of measure 4 are higher than those of measure 2. In section 5.4.5, it has been already stated that the economical risks are of minor relevance compared to the human risks. However, when the investments in safety measures are included in the risk picture, the improvement in human risks is marginal. This phenomenon is controversially emphasised when different monetary values α of human beings are taken into account. Table 7.5 shows that the total costs depend upon the height of monetary value per human being α_{human}. So, the height of monetary value per human being α_{human} is very important for decision-making, because the α_{human} determines the total costs. Furthermore, this case also stresses the problem that the investments in safety measures are relatively high in contrast with their relatively low human risk reduction.

Table 7.5: Comparison of economical and human risk (per year) for LPG regulated safety measures in Bos and Lommer.

Safety Measures	**(Sub)total Costs C_{tot} if$_t$ α = € 0**	**$E(N_d)$**	**Total Costs if$_t$ α = € 1,000,000**	**Total Costs if$_t$ α = € 10,000,000**
0. Starting situation	€ 300	$4.2\cdot10^{-3}$	€ 4,500	€ $420\cdot10^{3}$
1. Banning transport of LPG	€ 62,000,000	$2.9\cdot10^{-3}$	€ 62,002,900	€ $62\cdot10^{6}$
2. Rerouting transport of LPG (not through urban areas)	€ 55,300	$2.9\cdot10^{-3}$	€ 58,200	€ $345\cdot10^{3}$
3. Transport of LPG through pipelines	€ 62,500,300	$2.9\cdot10^{-3}$	€ 62,503,200	€ $63\cdot10^{6}$
4. Transport of LPG takes place during the night	€ 1,062,300	$2.9\cdot10^{-3}$ - $4.2\cdot10^{-3}$	€ 1,065,200	€ $1\cdot10^{6}$

- *Structural and Functional measures*

A full overview of structural and functional safety measures is presented in the previous chapter. In this part, structural and functional measures are implemented in the building (structure) and the effect are determined on the weighted risk. Besides, it is interesting to see whether measures like regulating the LPG are cost efficient with respect to structural measures implemented in buildings.

7) Ketenstudies are performed on behalf of the Dutch Ministry of Spatial Planning, Housing and Environment (VROM) to map out the economical dis(advantages) of hazardous materials such as LPG, chlorine and ammonia.

Structural and functional safety measures in this case can be divided into the following measures: (5) fire protection layer for building above the infrastructure, (6) explosion resistant building above the infrastructure, (7) dimensions of the building above the infrastructure with a small L/D (= implementing a big diameter (a high level for the lowest storey h_o and a bigger span l, (see figure 6.3 and 6.4)), and (8) fire protecting layer for the buildings above and in the vicinity (for 1 km). As before, we can calculate the number of people killed per year $E(N_d)$, the investments C_0 and the economical risks C_j (see Appendix B). The results of these calculations are presented in table 7.6.

Table 7.6: Comparison of economical risk (per year) for functional and structural safety measures in Bos and Lommer.

Safety Measures	Investments C_o	Economical risk C_i	Total costs C_{tot}	$E(N_d)$
0. Starting situation	-	€ 300	€ 300	$4.2 \cdot 10^{-3}$
5. Fire protection layer for building above infrastructure	€ 720,000	< € 300	€ 33,750,000	$2.9 \cdot 10^{-3}$
6. Explosion resistant building above infrastructure	€ 11,000,000	< € 300	€ 11,000,300	$2.9 \cdot 10^{-3}$
7. Building above infrastructure with small L/D	€ 5,316,000	< € 300	€ 5,316,000	$2.9 \cdot 10^{-3}$
8. Fire protection layer for building above and in vicinity	€ 80,000,000	< € 300	€ 80,000,300	$2.5 \cdot 10^{-3}$

Table 7.6 also shows that the total number of people killed per year $E(N_d)$ does not change extremely, because, as mentioned before, this value is dependent of risk category [1], [2], [3] and [4], wherein risk category [3] is dominant over the other categories. Still, the risk reduction can be observed in the FN-diagrams (see figure 7.6). In reality, it does also mean that the $E(N_d)$ for risk category [1], [2] and [4] is much smaller than $2.9 \cdot 10^{-3}$, so, the effect of $\alpha \cdot E(N_d)$ in the weighted risk is almost negligible when an α of € 1,000,000.= is considered.

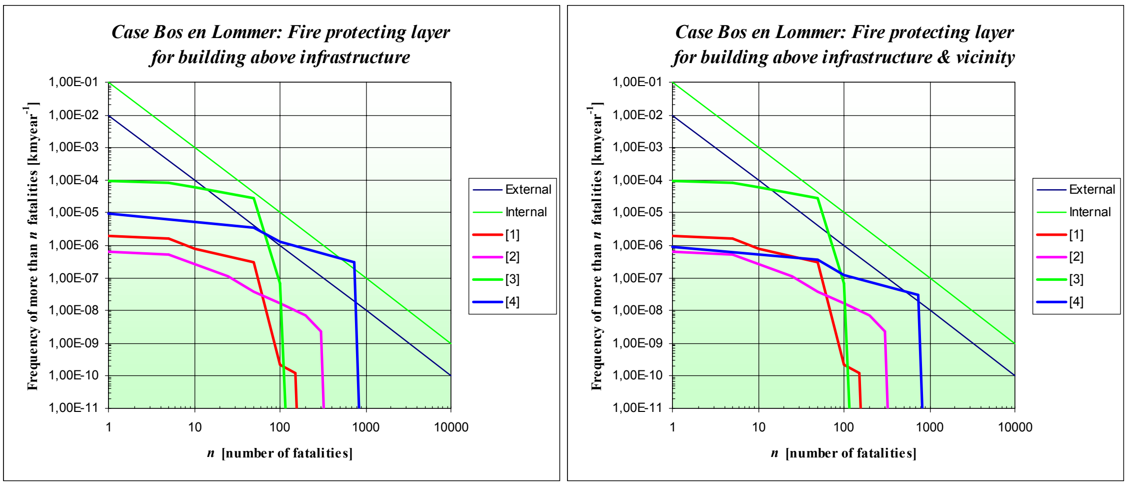

Figure 7.6: The group risk for measure 5 (left) and 8 (right) of table 7.6 per risk categories [1], [2], [3] and [4] of figure 1.2 of chapter 1.

Now, we can compare all these measures from non-human related perspectives with the weighted risk, in which the monetary values of section 3.2.3 will be used for the different components of the weighted risks (see table 7.7).

In table 7.7, the 0-situation is also considered, which represents the situation if the project was not realised on that location, but on the boundary of a city centre. A positive value in table 7.7 presents an absolute risk (loss), a negative value in the table presents an absolute profit / benefit. First of all, it should be concluded from table 7.7 that the safety considerations hardly influence the weighted risk analysis. Even quality and environmental benefits of such a project vanish in the analysis. The reason hereof might be that the monetary values are assumed too low.

Table 7.7: Comparison of weighted risk [€ per year] all safety measures in Bos and Lommer.

Elements of the Weighted Risk R_w for year 1	**Safety Measure**								
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Starting situation	**LPG Ban**	**Reroute LPG**	**LPG through pipe line**	**LPG during night**	**Fire prot. building**	**Expl. Resist. building**	**Small *L/D***	**Fire prot. vicinity**
Investments C_0	0	-	$5.5 \cdot 10^3$	$6.3 \cdot 10^7$	$1 \cdot 10^6$	$7.2 \cdot 10^5$	$1.1 \cdot 10^7$	$5.3 \cdot 10^6$	$8.0 \cdot 10^7$
Economical risk C_i	300	$6.2 \cdot 10^7$	300	300	300	300	300	300	300
Human risk $E(N_d) \cdot \alpha$	$2.9 \cdot 10^3$	$4.2 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$4.2 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$2.5 \cdot 10^3$
Quality risk $R_{quality} \cdot \alpha_{quality}$	$-8 \cdot 10^4$	$-8 \cdot 10^4$	$-8 \cdot 10^4$	$-8 \cdot 10^4$	$-8 \cdot 10^4$	$-8 \cdot 10^4$	$-8 \cdot 10^4$	$-1 \cdot 10^5$	$-8 \cdot 10^4$
Environmental risk $R_{env} \cdot \alpha_{environmental}$	$-1 \cdot 10^4$	$-1 \cdot 10^4$	$-1 \cdot 10^4$	$-1 \cdot 10^4$	$-1 \cdot 10^4$	$-1 \cdot 10^4$	$-1 \cdot 10^4$	$-1 \cdot 10^4$	$-1 \cdot 10^4$
Benefits	$-2 \cdot 10^6$	$-2 \cdot 10^6$	$-2 \cdot 10^6$	$-2 \cdot 10^6$	$-2 \cdot 10^6$	$-2 \cdot 10^6$	$-2 \cdot 10^6$	$-2 \cdot 10^6$	$-2 \cdot 10^6$
R_w [€$\cdot$year^{-1}]	$-2 \cdot 10^6$	$6.0 \cdot 10^7$	$-2 \cdot 10^6$	$6.1 \cdot 10^6$	$-1.1 \cdot 10^6$	$-1.4 \cdot 10^6$	$8.9 \cdot 10^6$	$3.2 \cdot 10^6$	$7.8 \cdot 10^7$

If we consider table 7.7 in detail, it shows that, when considering the weighted risk R_w, the logistical safety measure 2 - rerouting the transport of hazardous materials - is the most effective and beneficial, because the value of the weighted risk R_w is minimised due to relatively small investments in the measure. This is followed by the safety measure ”protecting the building above the infrastructure against fire” (measure 5). Even another logistic measure scores well; transport of LPG, during the night (measure 4). It is therefore kindly appreciated that one should focus on logistical safety measures, such as allowing for a short time period (e.g. 10 minutes) the transport of LPG or other hazardous materials. Surprisingly, the weighted risk analysis shows that if the project was realised without measures (measure 0), even then the value of the weighted risk is negative. This means that according to the weighted risk, such a situation is beneficial as well. Banning the transport of LPG through infrastructure is strongly dissuaded, because the weighted risk is maximised. Measures such as the functional design of the building (measure 7) or explosion resistant building are rather costly and thus not efficient.

7.1.5 Conclusions

First of all, this case presents the fact that the proposed weighted risk analysis methodology is a well ordered, one dimensional quantified tool, which can compare different non-safety related elements. This methodology can support the decision-makers in a broader sense. Focussing on the treated safety measures, this case study accentuates the fact that taking the most progressive safety measure, banning or rerouting the transport of LPG, is not an apparent solution to the external safety problem in The Netherlands. Yet, when the LPG is not transported through urban areas, scenarios or disasters with large number of people killed can be minimised.

This is exactly what the community desires; accidents with large number of fatalities are difficult to accept (see also studies of Vlek (1990; 2001; 2002)). Banning the transport brings out relatively high costs, while rerouting the transport of LPG is relatively cheap and should be paid by the transporters. It should be noticed that according to the study of NEI (2003), the removal of LPG could even result in large profits, i.e. € 453,000,000.= savings in case of avoided redevelopment, which contradicts the Ketenstudies (2003) and VROM (2000[C]), while both are based upon opportunity costs. Rerouting the transport of hazardous materials can also be accomplished by transport of LPG on ships. Most chemical installations are situated near harbours or rivers. Hence, it is clear that rerouting the LPG through areas, which are not densely populated, is possibly the most effective and general measure to tackle the safety problem. In some cases, it could be interesting to set up a new chemical installation next to the place where the hazardous material is processed, if possible. Realising these options, one may accomplish that the transporters almost automatically pay for the investments of this measure. Furthermore, one should stand by the agreement that these transport routes will not be used in the future to establish new projects of urban development. In this case study, it is shown that for the building above infrastructure measures should be taken against fire (fire resistant layer), because these are very cost-effective and within the project budget. Besides, if the proposed model of weighted risk (section 3.2.2) is considered, then the safety component safety may vanish in comparison with both financial and non-financial related aspects such as quality aspects, which may perhaps be the reason behind the realisation of such projects. Finally, one should keep in mind that the proposed weighted risk methodology is a tool for comparing different measures with both financial and non-financial aspects for rational decision-making, rather than an exact expression of a cost-benefit analysis, since the monetary values of the considered weighted risk elements may vary largely.

7.2 Case study 2: Spoorzone Delft

7.2.1 Introduction

The ”Spoorzone” Delft project focuses on the tunnelling of the elevated railway track between Rijswijk and Delft combined with the development of the surrounding area. The aim of this redevelopment programme is to eliminate both the visual and the physical hindrance of the train traffic between Rijswijk and Delft by tunnelling the train traffic in four tracks instead of the current two tracks on the viaduct. Two additional tracks are strategically necessary, since the train traffic on the main route between Rotterdam, The Hague and Amsterdam will increase in the future. Nowadays, more than 350 trains pass every day (Masterplan (2003)). This frequency will increase in the future up to 450 trains per day and so will the transport of hazardous materials on that route.

Figure 7.7: Current Situation, panoramic view (left) and local view (right).

Hence, the railway track forms a bottleneck for urban development in the city centre (see figure 7.7). Additionally, the negative consequences of the train traffic are for example noise hindrance, stagnation of the urban vitality and quality. In this regard, the Masterplan (2003) for tunnelling the railway track Delft and new urban projects in the vicinity of the tunnel, has been launched by the municipality of Delft. However, the realisation of that project depends on several political issues and therefore it is not sure whether this project will be realised at all. Nevertheless, realising that project means that hindrances are minimised, in addition to that the space near and above the tunnel can be utilised and intensified. The construction of this project is planned to start in 2006 and be finished in 2018. Mixing functions, such as residential accommodation combined with a public transport terminal (train and busses) and an excellent ordered traffic structure, will lead to a balanced, modern, and remarkable architectural urban design. It is stressed in the Masterplan (2003) that about 1500 residential accommodations and 54,000 m^2 floor space for offices will be realised. In figure 7.8, the overall map of the project, including the storeys per building, is presented. The length of the tunnel is about 2300 meters. In order to create urban flexibility, a park will be realised over the tunnel for a long distance. At some places above the tunnel, several buildings will be constructed, marked with number 2, 16 and 17 in figure 7.8. Most of the buildings will be realised along the tunnel.

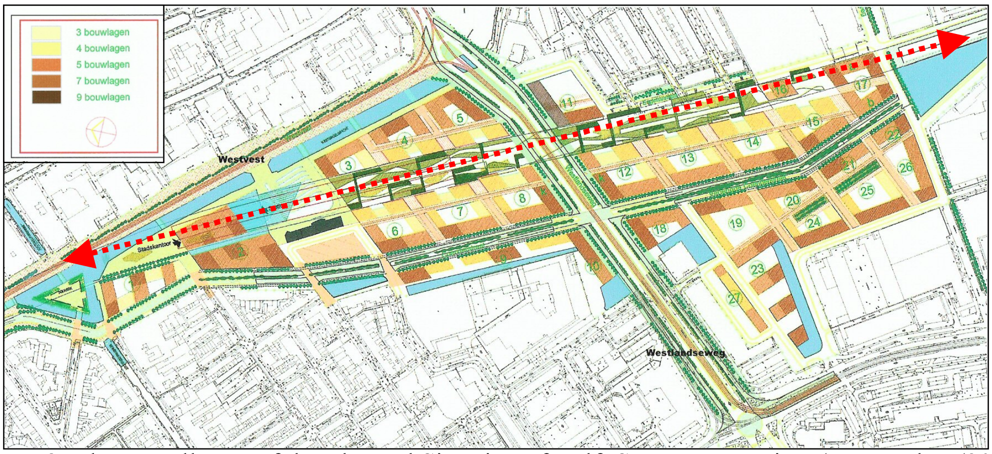

Figure 7.8: The overall map of the Planned Situation of Delft Spoorzone Project (Masterplan (2003)).

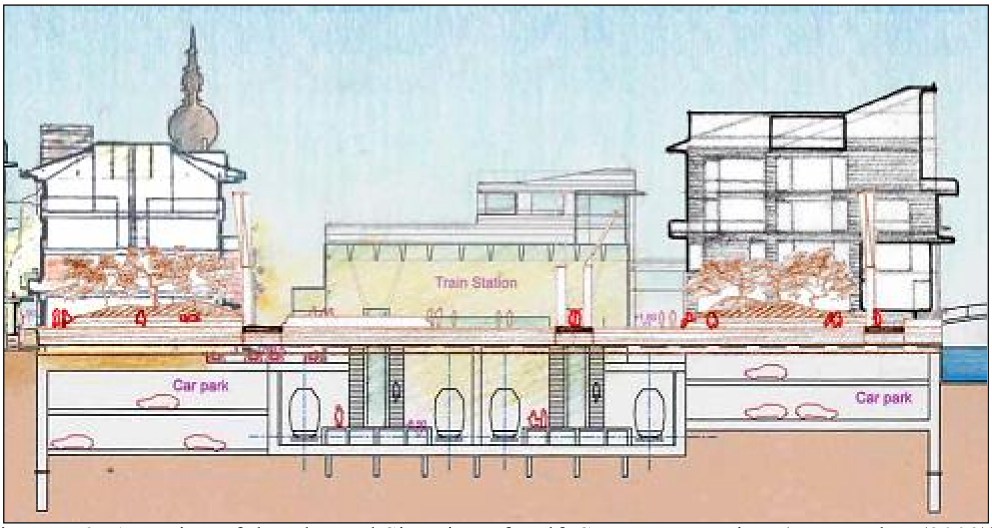

Figure 7.9: A section of the Planned Situation of Delft Spoorzone Project (Masterplan (2003)).

The case Spoorzone Delft was a case to many researchers; it is treated by Heilig (2002), Bruens (2003) and TCE (2003) performed QRAs, in which both effect and risk calculations are made. Bruens (2003) focused in his research on the effect of explosions on buildings above the infrastructure using the modelling technique PLAXIS. Results of these studies are used to evaluate the proposed model of weighted risk, as proposed in section 3.2.2.

7.2.2 Input parameters

Currently, hazardous materials are being transported on the railway track between Delft and Rotterdam. According to the Risk Atlas of DHV (2001), the compulsory notified number of wagons including hazardous materials that pass per year is 200, the so-called autonomous scenario (see table 7.8). Bruens (2002) and TCE (2003) suggest that the railway authorities (ProRail) demand that a so-called category 3a transport of hazardous goods is necessary for the future demands, in which there are two scenarios possible including a strong increase in dangerous goods transport (see also table 7.8).

Table 7.8: The classification of hazardous materials and the number of wagons of these materials transported per year for the Spoorzone Delft (TCE (2003)).

Hazardous Materials			**Example**	**Number of wagons per year**		
				Autonomous Scenario	**ProRail Scenario I**	**ProRail Scenario II**
A	Flammable Gasses	GF	LPG	0	350	350
B2	Toxic Gasses	GT	Ammonia	0	950	1250
B3	Extreme Toxic Gasses	GT	Chlorine	0	300	0
C3	Flammable Liquids	LF	Hexane	150	1500	1250
D3	Extreme Liquid Toxic Liquids	LT	Acrylnitril	50	0	1200
D4	Extreme Liquid Toxic Liquids	LT	HF	0	0	750
Total				200	3100	4800

Both Bruens (2002) and TCE (2003) give some basic probabilities of events for the mentioned three scenarios, which may occur in the tunnel. These probabilities are used in order to determine the individual and economical risk. The parameters of table 7.8 are used as input for the quantitative risk analysis by TCE (2003). The result of the risk analysis is presented in the next section for the individual, group and economical risk. The group risk is adapted from the report of TCE (2003).

However, some comments on the results of QRA of TCE (2003) should be made. First of all, these FN-diagrams do not show the risk curves for the different risk categories [1], [2], [3] or [4] separately. Second, the assumptions underlying the risk analysis, such as conditional probabilities, differ from the conditional probabilities used in the Bayesian Networks of models in chapter 5. Nevertheless, $E(N_d)$ values calculated from these FN-diagrams, will be used to determine their influence and contribution to the weighted risk. For the comparison of results of safety measures, it hardly matters whether the conditional probabilities in a risk analysis contain an error / uncertainty, but it is relevant that comparisons of the $E(N_d)$ values should originate from the same risk analysis model, as discussed in section 5.5. TCE (2003) divided the tunnel into three longitudinal sections, with each a tunnel length of 1 kilometre (two tunnel-ends and one centre section), to determine the effects of hazards in both the tunnel and the vicinity. Furthermore, TCE (2003) considered two types of tunnels for the QRA; a long and a short tunnel. The used tunnel geometry for the QRA is presented in table 7.9. The section of the tunnel is illustrated in figure 7.10.

Table 7.9: The used tunnel geometry in the risk analysis (TCE (2003)).

Geometry of the tunnel	Long Tunnel	Short Tunnel
Tubes	4	4
Partition between tube 1 and 2	Fire protecting layer	Fire protecting layer
Partition between tube 2 and 3	Concrete wall	Concrete wall
Partition between tube 3 and 4	Fire protecting layer	Fire protecting layer
Station	2 island platforms	2 island platforms
Height position of platforms	Underground	Ground level / partly covered
Length tunnel	1496 m	1209 m
Length station / platform	340 m	350 m
Total length	1836 m	1559 m

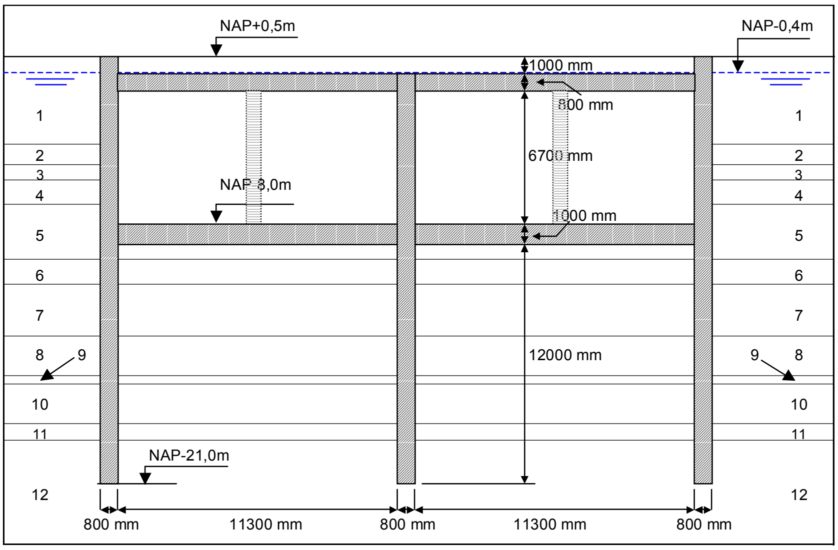

Figure 7.10: A section of the tunnel (adapted from Bruens (2003)).

7.2.3 *Results risk analysis*

- *Individual Risk*

First, the individual risk is computed for three suggested situations by TCE (2003), presented in table 7.10.

Table 7.10: The individual risk [death / year] for the Spoorzone Delft; probabilities adapted from (TCE (2003)).

Scenario of Transported Hazardous Materials	Autonomous Situation			ProRail Scenario I			ProRail Scenario II		
Scenario i	P_{fi}	C_{fi}	R	P_{fi}	C_{fi}	R	P_{fi}	C_{fi}	R
1. Collisions with the structure of the building	$1\cdot10^{-9}$	0.1	$1\cdot10^{-10}$	$1\cdot10^{-9}$	0.1	$1\cdot10^{-10}$	$1\cdot10^{-9}$	0.1	$1\cdot10^{-10}$
2. Fires	$8\cdot10^{-9}$	0.1	$8\cdot10^{-10}$	$1\cdot10^{-8}$	0.1	$1\cdot10^{-9}$	$1\cdot10^{-8}$	0.1	$1\cdot10^{-9}$
3. Leak of toxic substances	0	0.5	0	$3\cdot10^{-9}$	0.5	$3\cdot10^{-9}$	$3\cdot10^{-9}$	0.8	$3\cdot10^{-9}$
4. Explosions	$2\cdot10^{-7}$	1	$2\cdot10^{-7}$	$7\cdot10^{-7}$	1	$7\cdot10^{-7}$	$6\cdot10^{-7}$	1	$6\cdot10^{-7}$
Total ΣIR [$year^{-1}$]			$2\cdot10^{-7}$			$6\cdot10^{-7}$			$6\cdot10^{-7}$

Table 7.10 shows that, if the number of transport wagons with hazardous materials increases, the individual risk will increase as well.

- *Group Risk*

The group risk is also determined by TCE (2003). The FN-curves for external risks for this project are presented in figure 7.11 respectively, in which the ProRail scenarios I & II for both a long and a short tunnel are determined for the distance of 3 km. The external risks are presented for a length of 1 km.

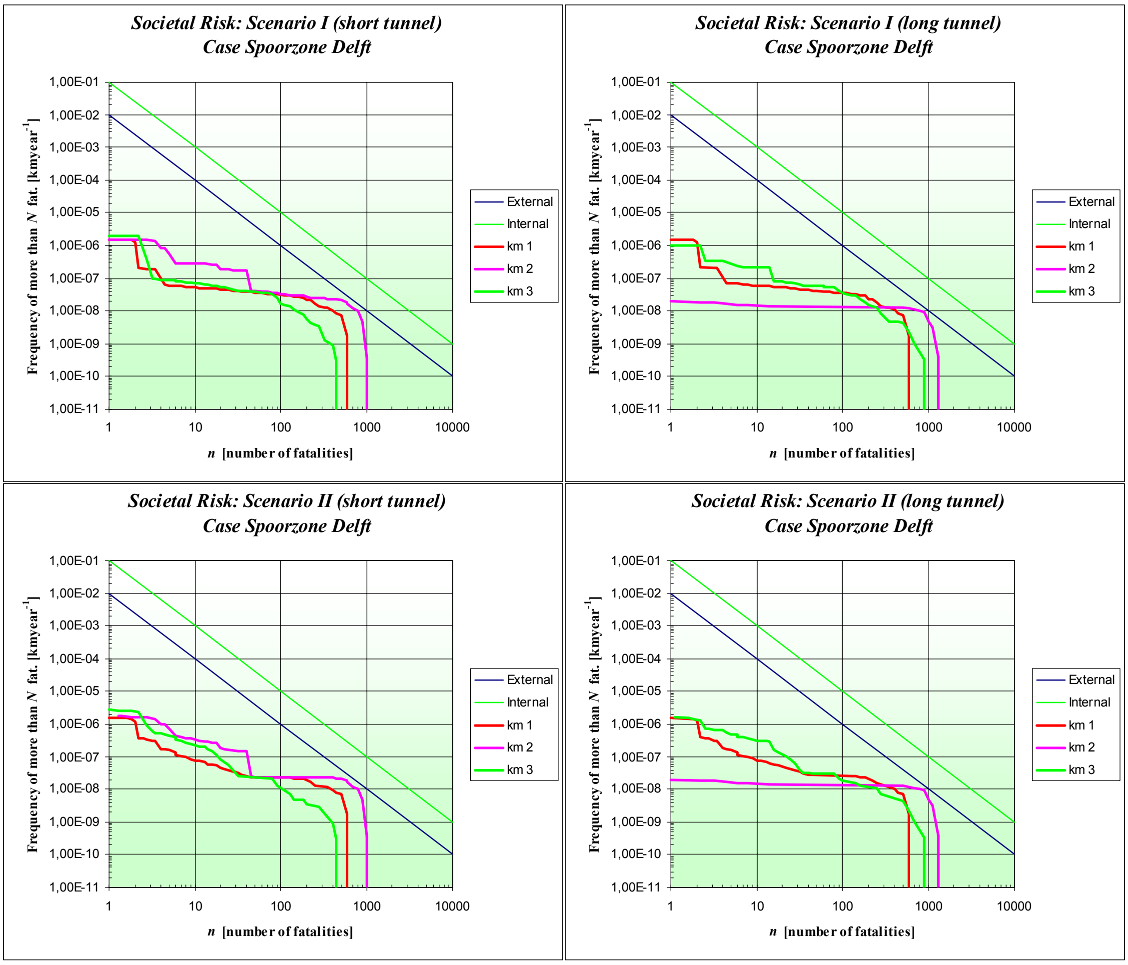

Figure 7.11: Group risks for both a short and a long tunnel for Spoorzone Delft combined with the ProRail scenarios I and II (external risks) (adapted from TCE (2003)).

The FN-curves for internal risks are presented in figure 7.12 and are presented for the total tunnel length.

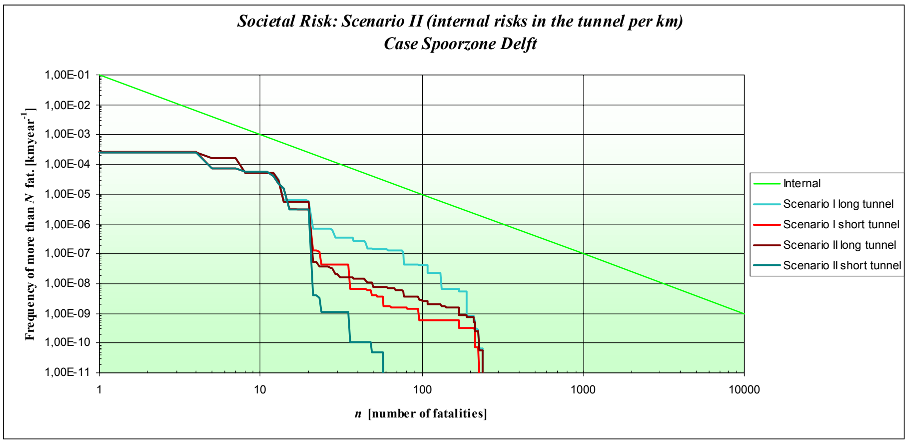

Figure 7.12: Group risks for both a short and a long tunnel for Spoorzone Delft combined with the ProRail scenarios I and II (internal risks) (adapted from TCE (2003)).

- *Expected number of people killed*

As discussed before, the expected number of people killed per year can be determined from the group risk. This case shows that the $E(N_d)_{total}$ mainly depends on the internal risks in the tunnel.

Table 7.11: The expected number of people killed per year for Spoorzone Delft.

Scenario of Transported Hazardous Materials	$E(N_d)$ **External risks**	$E(N_d)$ **Internal risks**	$E(N_d)_{total}$
1. ProRail scenario I (short tunnel)	$5.4 \cdot 10^{-5}$	$6.7 \cdot 10^{-3}$	$6.8 \cdot 10^{-3}$
2. ProRail scenario I (long tunnel)	$4.1 \cdot 10^{-5}$	$7.8 \cdot 10^{-3}$	$7.8 \cdot 10^{-3}$
3. ProRail scenario II (short tunnel)	$5.5 \cdot 10^{-5}$	$6.6 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$
4. ProRail scenario II (long tunnel)	$4.0 \cdot 10^{-5}$	$7.4 \cdot 10^{-3}$	$7.4 \cdot 10^{-3}$

- *Economical losses*

The economical risk for the Spoorzone Delft can also be computed, and it varies from approximately € 1,000.= to € 4,000.= per year. The (conditional) probabilities of scenarios are also derived from the report of TCE (2003).

Table 7.12: The economical risk for Spoorzone Delft.

Scenario of Transported Hazardous Materials	**Autonomous Situation**			**ProRail Scenario I**			**ProRail Scenario I**		
Scenario i	P_{fi}	C_{fi}	R	P_{fi}	C_{fi}	R	P_{fi}	C_{fi}	R
1. Collisions with the structure of the building	$1 \cdot 10^{-9}$	$1 \cdot 10^{6}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-9}$	$1 \cdot 10^{6}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-9}$	$1 \cdot 10^{6}$	$1 \cdot 10^{-3}$
2. Fires	$8 \cdot 10^{-9}$	$5 \cdot 10^{6}$	$4 \cdot 10^{-2}$	$1 \cdot 10^{-8}$	$5 \cdot 10^{6}$	$1 \cdot 10^{-2}$	$1 \cdot 10^{-8}$	$5 \cdot 10^{6}$	$1 \cdot 10^{-2}$
3. Leak of toxic substances	0	10^{6}	0	$3 \cdot 10^{-9}$	10^{6}	$3 \cdot 10^{-3}$	$3 \cdot 10^{-9}$	10^{6}	$3 \cdot 10^{-3}$
4. Explosions	$2 \cdot 10^{-7}$	$5 \cdot 10^{9}$	$1 \cdot 10^{3}$	$7 \cdot 10^{-7}$	$5 \cdot 10^{9}$	$4 \cdot 10^{3}$	$6 \cdot 10^{-7}$	$5 \cdot 10^{9}$	$3 \cdot 10^{3}$
Expected economical loss [€·year^{-1}]			$1 \cdot 10^{3}$			$4 \cdot 10^{3}$			$3 \cdot 10^{3}$

The comparison of economical and human risk is presented in table 7.13.

Table 7.13: Comparison of economical risk (per year) for different scenarios in Spoorzone Delft.

Scenario of Transported Hazardous Materials	Investments C_o	Economical risk C_i	Total costs C_{tot}	$E(N_d)$
0. Autonomous situation	-	€ 1,000	€ 1,000	$6.7 \cdot 10^{-6}$
1. ProRail scenario I (short tunnel)	€ 550,000,000	€ 4,000	€ 550,004,000	$6.8 \cdot 10^{-3}$
2. ProRail scenario I (long tunnel)	€ 800,000,000	€ 4,000	€ 800,004,000	$7.8 \cdot 10^{-3}$
3. ProRail scenario II (short tunnel)	€ 550,000,000	€ 3,000	€ 550,003,000	$6.7 \cdot 10^{-3}$
4. ProRail scenario II (long tunnel)	€ 800,000,000	€ 3,000	€ 800,003,000	$7.4 \cdot 10^{-3}$

Table 7.13 presents the investments in both a short and a long tunnel, without the constructions of the buildings over the tunnel. This table shows that the value of $E(N_d)$, computed for the full tunnel length, hardly differs from the considered scenarios. Assuming the monetary value per fatality α to be € 1,000,000,=, then the $E(N_d)_{total} \cdot \alpha$ is equal to € 7.= for the autonomous situation, which is hardly influential for the realisation of the tunnel. But if the transport of hazardous materials increases, the $E(N_d)_{total} \cdot \alpha$ will increase greatly (€ 7,000.=), which is also of minor relevance in the comparison with economical investments. Hoeven (2001) presents that the investments for realising a tunnel are approximately € 356,000,000.= / km. So the investments for a short and a long tunnel will be in the order of € 550,000,000.= and € 800,000,000.= respectively.

7.2.4 Comparison with other measures

In this section, the obtained results of the case Spoorzone Delft will be used in order to determine the effect on each of the elements of the weighted risk. The effect on the weighted risk will be determined per safety measure of the safety chain and of functional, structural and human related safety measures. In this regard, the following steps are worked out:

First, the weighted risk of the present situation will be determined, in which no tunnel is realised. Second, the realisation of the total project will be evaluated for a long and a short tunnel. Subsequently, the effect of local safety measures will be verified. Full calculations of both the investments and the elements of the weighted risk of each measure are presented in Appendix B.

- *0-situation (without realising project)*

Supposing that the overall project is not realised, the hindrance of sound and lack of spatial quality will still prevail. This means that negative values are assigned for both quality and environment. Besides, it can also be assumed that large benefits from offices will not be attained. These observable facts are presented in table 7.13. In this situation, it is assumed that the profit gained from buildings, which could not be built due to the existing viaduct, are considered in the weighted risk analysis.

- *Short tunnel (measure (1) and (3))*

The main advantage of realising a short tunnel is that the investments for the total project will be smaller compared to the investments for a long tunnel. In contrast, the quality component is negatively affected, because the non-tunnelled part of the infrastructure might lead to local noise hindrance after all, through which environmental benefits are lost as well. The value for environmental benefits is estimated on 70 % of the long tunnel, which is in proportion to the tunnel length of a short and a long tunnel, plus the environmental value of the area of the park realised above the tunnel.

- *Long tunnel (measure (2) and (4))*

In order to minimise the negative discomforts of the train traffic, such as noise hindrance, the infrastructure can be tunnelled for an as long as possible distance. However, the major disadvantage of such a project is its large investments. Besides, the period for realisation will be larger than the realisation of a short tunnel. Nevertheless, one may achieve both quality and environmental benefits if the long tunnel variant is accomplished.

- *Structural safety measures (measure (5))*

In the risk analysis of TCE (2003), two main structural safety measures were analysed, namely the sprinkler system and longitudinal ventilation. The $E(N_d)$ value for these measures is deduced from the group risk of the QRA of MER (2003). These measures are needed to ensure both the safety of people present in the tunnel and the structural integrity and reliability of the tunnel itself. It should be noted that this local and structural measure hardly affects both the environmental and quality (dis)advantages.

- *Human related safety measures (measure (6))*

We saw in the previous case study that the overall computed number of people killed per year was mainly influenced by the internal risks on the infrastructure (risk category [3]). Perhaps it is possible to take measures such as increasing the emergency response and escape possibilities in the tunnel. In this analysis we assume that an extra team of 10 firemen is needed extra, in case of calamities. The costs of this fireman team is about € 1,248,000.= per year (see Appendix B).

Once all ingredients are obtained for the weighted risk, the weighted risk analysis is performed (see table 7.14). Table 7.14 clearly presents that, also in this case study, decisions are based upon the minimum of investments of safety measures rather than the minimum of total costs. In this case, safety considerations, i.e. the effect of the value of a human being α_{human}, are unfortunately weighted lightly in the analysis. But if a disaster with many fatalities takes place, then the value of a fatality α_{human} will rise immediately and progressively (e.g. € 100,000,000.=) due to e.g. sensitive opinion of the community and / or political commotions. By this, the decision will change from an economical one to a human related one. Such a high monetary value of human being will be applicable immediately after an accident, while after a long period this value decreases to its initial "nominal" value of € 1,000,000.=.

Table 7.14: Comparison of weighted risk [€ per year] all safety measures in Spoorzone Delft.

Elements of the Weighted Risk R_w for year 1	**Safety Measure**						
	0	**1**	**2**	**3**	**4**	**5**	**6**
	No project	**Short tunnel**	**Long tunnel**	**Short tunnel**	**Long tunnel**	**Struct. measure**	**Human related measure**
Investments C_0	0	$5.5{\cdot}10^8$	$8{\cdot}10^8$	$5.5{\cdot}10^8$	$8{\cdot}10^8$	$8.3{\cdot}10^8$	$8{\cdot}10^8$
Economical risk C_i	$1{\cdot}10^3$	$4{\cdot}10^3$	$4{\cdot}10^3$	$3{\cdot}10^3$	$3{\cdot}10^3$	$4{\cdot}10^3$	$4{\cdot}10^3$
Human risk $E(N_d){\cdot}\alpha$	6.7	$6.8{\cdot}10^3$	$7.8{\cdot}10^3$	$6.7{\cdot}10^3$	$7.4{\cdot}10^3$	$2.9{\cdot}10^3$	$2.0{\cdot}10^3$
Quality risk $R_{quality}{\cdot}\alpha_{quality}$	$1.9{\cdot}10^5$	$-1.3{\cdot}10^5$	$-1.9{\cdot}10^5$	$-1.3{\cdot}10^5$	$-1.9{\cdot}10^5$	$-1.9{\cdot}10^5$	$-1.9{\cdot}10^5$
Environmental risk $R_{env}{\cdot}\alpha_{environmental}$	$3.7{\cdot}10^4$	$-1.8{\cdot}10^5$	$-2.7{\cdot}10^5$	$-1.8{\cdot}10^5$	$-2.7{\cdot}10^5$	$-1.8{\cdot}10^5$	$-1.8{\cdot}10^5$
Benefits	$2.4{\cdot}10^7$	$-2.4{\cdot}10^7$	$-2.4{\cdot}10^7$	$-2.4{\cdot}10^7$	$-2.4{\cdot}10^7$	$-2.4{\cdot}10^7$	$-2.4{\cdot}10^7$
R_w [€$\cdot$year^{-1}]	$2.4{\cdot}10^7$	$5.3{\cdot}10^8$	$7.8{\cdot}10^8$	$5.3{\cdot}10^8$	$7.8{\cdot}10^8$	$7.8{\cdot}10^8$	$7.8{\cdot}10^8$

The weighted risk analysis shows also that if the tunnel, either a short one, or a long one, is realised, the investments in safety measures cannot be levelled for a period of one year. It is possible if a period of 10 years is considered or financial support by the (local) government is granted. If we consider table 7.14 in detail, it shows that, when considering the minimum weighted risk R_w, measure 0 - not realising the project - is surprisingly the most effective, and beneficial solution for the Spoorzone Delft. In addition to that, no extra investments have to be made. This case also shows that, if safety measures are taken, the decrease of the $E(N_d)$ value is not that much, i.e. the $E(N_d)_{total} \cdot \alpha$ vanishes in the weighted risk analysis, unless a higher monetary value is taken into account. According to this analysis, a short tunnel will be the most attractive solution, because the value of the weighted risk R_w becomes the second lowest.

7.2.5 Conclusions

This case study presents that the proposed weighted risk provides a good estimation of various (in-)direct project related and non-safety related aspects. However, most of them, unfortunately vanish in comparison with financial aspects. Nevertheless, these elements of the weighted risk can be taken into account for a go-no-go decision of a project if the monetary value per element is considered to be higher than presented here. This case presents that the investments are much higher than the benefits for all tunnel variants and safety measures. It may, therefore, be concluded that perhaps there are more safety related issues, which are related to the perception of risks, not considered in the weighted risk analysis. This might be linked to the fact that the monetary value of a human life should be estimated much higher than the used € 1,000,000.=, e.g. € 1,000,000,000.=, because then the R_w begins to be negative. Still, sometimes these measures are taken on an intuitive basis and perhaps the perception related aspects are considered in such an analysis, as discussed by Suddle & Waarts (2003).

8

Conclusions, Summary & Discussion

8.1 Summary & Conclusions

8.1.1 The proposed weighted risk analysis methodology

This Ph.D. dissertation proposes a methodology for dealing with physical safety issues in multiple use of space projects. This method provides sufficient elements to assess, integrate and evaluate physical safety in such projects for both the construction and the exploitation stage. In order to determine the weighted risk in a multiple use of space project, the following methodological steps need to be taken, since the methodology is quite similar for any project:

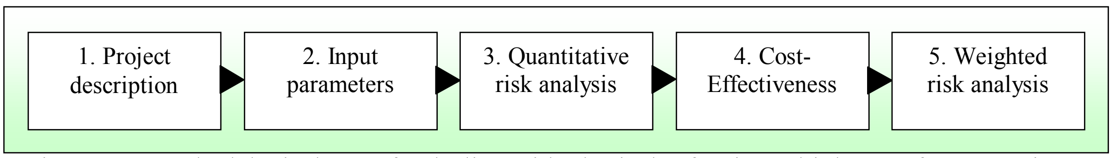

Figure 8.1: Methodological steps for dealing with physical safety in multiple use of space projects.

- Ad 1 Project description
In this stage, the specification or dimensions of the location, on which new urban development will be realised, are described in detail.

- Ad 2 Input parameters
Basic parameters, such as the number and the type of hazardous materials, are determined. These parameters form the basis of the QRA.

- Ad 3 Quantitative risk analysis
A QRA is needed to determine the economical risk C_j, the individual risks *IR*, the group risk *GR* and the expected number of people killed $E(N_d)$.

- Ad 4 Cost-effectiveness
Both costs and effects of safety measures are vital elements for taking cost-effective measures. Therefore, this stage is inevitable in the risk analysis.

- Ad 5 Weighted risk analysis
The cost effectiveness of safety measures can now be deliberated and weighed with both non-safety and non-financial related aspects.

These methodological steps are treated in detail in this thesis.

8.1.2 Summary & Main Conclusions

In this section, the conclusions of this research are presented. These conclusions are mainly based upon the case studies of chapter 3 and the risk analysis models of chapter 4 and 5, where assumptions and average scenarios are taken into account.

First of all, multiple use of space is not always applied on the basis of a shortage of space. Cultural, political, economical, environmental and (spatial) quality aspects can play a decisive role in determining the development and realisation of multiple use of space projects (*chapter 2*). In order to compare and integrate these aspects, from which economical, environmental and quality aspects are considered along with safety aspects, a methodology is proposed: the "*weighted risk analysis*", in which the extension of these aspects can be weighted and deliberated in one dimension, e.g. in terms of money (*chapter 3*). The main advantage of such an approach is that the basis of decision-making on projects or safety measures, which is usually based upon either optimisation of human risks or optimisation of economical risks and sometimes a combination of these two, becomes broader and the effects on several aspects can be shown quantitatively. This methodology supports decision-makers quantitatively to ponder on the effect of measures on different aspects, rather than only determining the risk reducing effect, which is provided by various methods and studies already.

The risks due to falling elements during the *construction stage* in multiple use of space projects were modelled in this research using the risk analysis tool Bayesian Networks. For this to happen, data of falling elements were collected and risk models were analysed. It appears that the falling elements form a major hazard for third parties, such as the users of the infrastructure, because usually the infrastructure is in use when the building above it is being built. Measures against such hazards can easily be taken from a structural point of view - e.g. applying a protection canopy - or logistic point of view - e.g. rerouting the traffic when heavy elements are erected above the infrastructure. If one decides to take structural measures against the falling elements, one should seek for integration in the functional design of the building for the exploitation stage, in order to save costs. Costs are thus saved because the measures do not have to be removed and the measures can even add value to the function or the functional design or aesthetics (*chapter 4*).

Whereas during the construction of these projects hazards related to the "mechanical load" of the falling elements are of main interest, the hazards during the exploitation are also related to the load caused by "chemical" background of hazards.

Also in *chapter 5*, data regarding the main scenarios that may occur on the infrastructure were collected and existing risk analysis were analysed. The scenarios that may occur on the infrastructure are collisions, fires, explosions, and leaks of toxic substances (consecutively decreasing in probability of occurrence and increasing in consequences). One of the conclusions of the risk assessment in the *exploitation stage* for the case study of chapter 3, is that in principle, the scenarios occurring on the infrastructure remain almost the same as when the infrastructure is not covered. In contradiction to this, the effects of these scenarios differ largely. The changes in the effects are caused by the fact that the infrastructure is enclosed and covered by buildings. Physical separation and its dimensions influence both internal and external risks of the infrastructure. In order to model the risk in such projects, a three-dimensional approach of both individual and group risk is vital, in addition to which the collapse of the building above the infrastructure is a significant scenario. Assessing risks of scenarios separately with a three-dimensional approach emphasises the fact that intensifying the space or using the space multiply does not a priori mean that the overall risk will increase. If the infrastructure is covered for a long distance, the vicinity surrounding the infrastructure will be protected from some scenarios (e.g. release of toxic gasses and fires). For scenarios like collisions with the building structure over the infrastructure or explosions in the covered infrastructure, the physical separation may however have an opposite effect. The case studies of chapter 3 also show that when the covering length of the infrastructure increases, the risks of people in the vicinity decrease, while (internal) risks increase. This may become an interesting aspect in the urban designs and developments in relation to multiple and intensive use of space, since the risk acceptance level for people in the covered infrastructure can be assumed to be higher than the external risk acceptance level for the vicinity (*chapter 5*).

The cost-effectiveness assessment of *safety measures* for the exploitation stage in *chapter 6* illustrates that structural safety measures against fires and collisions, can be realised cost-effectively. In contrast, effective measures against the blast effects of an explosion occurring on the infrastructure are both structurally and financially very difficult and impossible to realise. Effective measures within buildings against the effects of release of toxic gasses however can be realised, but are costly. A proactive measure for the exploitation stage can be, if possible, the separation of the transport of hazardous materials from the urban planning activities. In cases where alternative routes have been already established, these logistic measures can be cost-effective in comparison with structural measures in buildings. The obtained risk results from the considered cases in this research may differ totally if other cases would be treated. Therefore, it is recommended that more cases should be treated in the same manner in future research.

In order to evaluate the effect of safety measures with environmental, quality, and economical aspects, two case studies Bos en Lommer (building above roads) and Spoorzone Delft (building above railways) were analysed using the weighted risk analysis methodology (*chapter 7*). Surprisingly, it appears from these cases that if the effect of safety measures is weighed and optimised with economical aspects, such as investments and benefits, the human risks vanish in the weighted risk analysis. Also environmental and quality aspects were less dominant in comparison with the costs / investments of a single safety measure and benefits of the project. For a single building above the infrastructure, the influence of the human risks with other mentioned aspects is negligible. Hence, it can be concluded that usually the costs and benefits are the most influential parameters for a go-no-go decision of either realising a project or taking a safety measure.

In this thesis, the value of a human life is assumed to be the commonly used € 1,000,000.=. Even though the upper limit of the monetary value of a human being is assumed to be € 20,000,000.=, the contribution and effect of human risks in the weighted risk vanishes.

From this point, it can be stated that these monetary values for human beings must be higher in the future in the cost-benefit-analysis or even more aspects than presented in this thesis, are considered for decision-making. If a measure is still applied despite the high costs, it can be stated that the safety is in fact a boundary condition rather than a financial issue. Sometimes decisions on measures are taken on an intuitive basis or political interests, that can be totally unjustified or wrong, even though the purpose of the decision-maker is to guarantee a certain safety level to the society on the one hand and to provide a positive perception regarding safety issues on the other, rather than economical backgrounds. Therefore, one may expect that expendable commodities play an ethical role when taking safety measures.

8.2 Evaluation of the proposed methodology

The scientific contribution of this Ph.D. dissertation concerns several issues:

First of all, the proposed weighted risk analysis methodology is a rational supporting tool for decision-makers, by which safety measures can be evaluated and compared with non-safety related aspects like benefits, quality, economical and environmental aspects. This methodology can be applied to different research problems, such as flood-defence systems and health care management. In this thesis, it has been applied for urban development near or above the infrastructure, over which transport of hazardous materials takes place. When not using this weighted risk analysis methodology, the decision-making on measures is usually based upon either optimisation of human risks or optimisation of economical risks, sometimes a combination of these two aspects and sometimes even on an intuitive base. Often, political interests can play a decisive role. In contrast to previous methods, the weighted risk analysis provides a supporting tool for decision-makers to consider more aspects than optimisations of human and / or economical aspects on an intuitive basis, since the outcome of the methodology can be expressed quantitatively. Expressing the effect of economical, environmental and quality aspects together with human risks quantitatively in one-dimension (i.e. money), scientifically contributes sufficient elements to the existing approach of thinking rationally about new urban developments plans in the future.

Secondly, the scientific contribution is related to the risk assessment in both the construction and exploitation stage of a multiple use of space project with the risk analysis tool Bayesian Networks, in which existing risk analysis models were analysed and data for risk analysis is collected. It provides also a risk assessment tool for assessing the risks for third parties in the construction stage. Often, decision-makers pay less attention to (the quantification of) the risks in the construction stage. Without such an approach, the effect and the risk of scenarios due to falling objects cannot be quantified. The relevance of QRA for the construction stage, as discussed in this thesis, is that the effect of safety measures, which can be implemented to the building above the infrastructure itself, can be assessed. This may result in designing the buildings above the infrastructure from a risk point of view, instead of the currently used approach from an architectural point of view. In addition to that, this thesis provides a basis for integrating safety measures in the design of a project, if applicable, by which the costs of these measures can be reduced. In brief, a quantitative risk analysis during the construction stage can not only provide the decision-maker a more solid basis for decision-making, but also gives opportunities to integrate safety measures at an early stage of building. A fringe benefit is that by doing the last, costs are saved.

Thirdly, a three-dimensional risk assessment approach for both individual and group risk in the exploitation stage is highlighted in this thesis. 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 the third risk dimension of height. The method discussed in this research 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 space or multiple use of space does not a priori mean that the overall risk will increase in all cases. 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.

The fourth main point of scientific contribution is the possibility to evaluate the cost-effectiveness of safety measures in the context of multiple use of space projects. For a decision-maker, it is important to deliberate the costs and effect of a safety measure. Among other things, this dissertation presents some rough indications of both features, which can be used for such projects in general. Without these indications, it is difficult for decision-makers to decide rationally. Since the overview of safety aspects in multiple use of space projects is highlighted from several viewpoints, it is relevant for decision-makers, municipalities, urban planners, risk analysts, railway companies, project developers, architects, structural engineers, safety analysts, transporters of hazardous materials, and policy makers. This study forms an introduction of quantitative risk analysis to these actors and saves investments in safety studies for determining the effectiveness of measures in multiple use of space projects, because now they easily can find out the (methodology for assessing the) costs against the effectiveness of safety measures.

Knowing that physical safety and multiple use of space in city centres are presently one of the hottest items regarding urban development, and many future ”key-projects” are concerned with the safety matter, an important and relevant social difficulty regarding physical safety in multiple use of space projects is being guided. In short, besides the scientific contribution of this thesis, the social contribution of this research cannot be underestimated either.

8.3 Critical notes and future research

Some critical notes on the weighted risk analysis method should be considered carefully. These critical notes are related to future improvements and refinements of the proposed methodology, in order to reach an optimised methodology, for which several additional efforts need to undertaken. First, the case studies indicate that the ultimate result of the weighted risk strongly depends on both the considered aspects and their monetary values. As far as possible, more non-financial aspects, like political issues, can be taken into account in the weighted risk analysis as well. In addition to this, sensitivity analyses should be performed for the height of these values. The monetary value of environmental space can be criticised, since large fluctuations prevail in that value: it ranges between € 4.= per m^2 to € 550.= per m^2. By varying this value, the ultimate result of the weighted risk analysis will change completely. As mentioned in section 3.2.3, the monetary value of a human being ranges between € 1,000,000.= and € 20,000,000.=. If we have a critical look at this value, an ethical decision-maker may estimate this value to be infinitely high, through which the optimisation followed by the decision after all becomes a minimum of human risks. It is questionable whether such large investments in safety measures are justified, since 100 % safety does not exist. Although these monetary values change along with time related aspects like the changing of the perception of people, the proposed weighted risk analysis methodology can still be used to evaluate safety measures.

Likewise, the monetary value for quality can be criticised. Perhaps, subjective elements related to safety should be considered in the monetary value of a human being, through which this value becomes much higher and thus (more) influential. Therefore, it is recommended that the proposed methodology of evaluating the human risk with non-safety related aspects is extended to multiple aspects, such as noise nuisance in terms of quality and political aspects / values.

The background of the decision-maker can be criticised as well. Nyborg (1997) describes the interpretation and aggregation of environmental values of the Homo Economicus and the Homo Politicus. The *Homo Economicu*s is the person who maximizes his or her own well-being subject to the individual budget constraint. In contrast, the *Homo Politicus* puts himself or herself in the role of the ethical observer, and tries to consider what is the best for society. Most decision-makers are apparently working in both fields. Having this all in mind, it can be stated that the interest of the decision-maker, which can be subjective elements of safety, may also play a role in decision-making.

Furthermore, the Bayesian Networks appear to be an effective tool when modelling the risks of falling elements in the construction stage, because the occurring scenarios are relatively small during this stage. In contrast, the opposite was experienced while modelling the exploitation stage. The difficulty here is that the probability distribution tables become enormous, due to the large sets of scenarios. It would probably have been easier and more ordered to model a large risk analysis for the exploitation stage with standard event trees instead of Bayesian Networks. The risk analysis models for scenarios occurring on the infrastructure as presented in this thesis are based upon existing models of AVIV (1997), which are composed up to a certain scale level. For the effect in the third (spatial) dimension, assumptions and average following up scenarios are taken into account. Aspects like the probabilistic behaviour of the emergency response are not considered in the QRA models. For this, refinements in risk analysis models are recommended.

The effect of scenarios regarding psychological behaviour of motorists can be refined in future research, since accident frequencies based on existing literature were used in this research. Injured people can also be considered in the risk assessment, instead of the fatalities used in this study, since these are of great value for emergency rescue. The terrorist attack scenario is not highlighted in this thesis. Still, one should be aware of the fact that such a scenario exists, even though one is unable to take structural measures against such a scenario. In this dissertation, the risks in the construction stage are limited to falling elements. The risks of soil instability or building damage due to ground water regulation etc. can be researched as well.

Finally, both the presented costs and effects of safety measures in this research are estimations. Investments in safety measures depend on various local circumstances and thus vary largely in practice. So, refining and calculating these costs and effects of safety measures is recommended for each particular project.

8.4 Discussion: multiple use of space and transport of hazardous materials

Due to a continuously increasing shortage of space - possibly combined with a high demand for spatial quality -, multiple use of space projects will be realised in the future more often. The development of the transport of hazardous materials is quite uncertain, because several surveys are contradictory to each other. For instance, the survey of the Ketenstudies (2003) shows that on some routes in The Netherlands, the transport of hazardous materials will remain constant or may even decrease in the future.

On the other hand, the railway authorities in The Netherlands (ProRail) suggest that a so-called ”category 3a transport of hazardous goods” is necessary for the future demands, in which it is stated that there will be a strong increase in the transport of dangerous goods (TCE (2003)).

Both the urban development and the transport of hazardous materials are stimulated by the government / community, since these are of great economic value. The general opinion about this issue is that the transport of hazardous materials forms an obstacle for urban development. This is not fully correct, because risks of some materials can be reduced by countermeasures. If urban development and transport of hazardous materials are considered from a helicopter view, the question arises whether it is necessary to plan urban development projects on locations through which transport of hazardous materials takes place. Also, it is questionable whether it is necessary to transport these materials through urban areas, since the transport of hazardous materials does not harmonise with urban development. Line infrastructure for transport of hazardous materials is, however, mostly in use for transport of people as well and therefore often passes through densely populated urban areas. Some transport routes in The Netherlands were initially planned to function as major transport routes of hazardous materials (Ale (2003)).

As the urban development progressed, the development of new projects was forced to be closer and closer to these routes. This is quite contradictory with each other and should therefore have continuous attention. In order to realise urban development near or over the infrastructure, it is desired that the transport of hazardous materials is dissuaded from urban areas, if possible, especially the transport of material causing large fatalities, such as toxic gasses and / or flammable gasses. International multiple use of space projects in London and Paris support this statement. The major advantages of the separation of the transport of hazardous materials and urban development, is that the risks for users of the buildings along the infrastructure decrease and measures against the ”remaining” scenarios, - fires and collisions-, can be taken cost-effectively. The separation will also make the realisation of multiple use of space easier and the transport can be increased without any influence on each other. Therefore, an option might be to separate the transport from the urban development entirely and visa versa. However, the difficulty in The Netherlands is that alternative routes for that transport are sometimes hard to find and to realise, due to a lack of space and large significance of spatial quality. This is even more complex: the chain of transport of hazardous materials is a national issue rather than a local issue. This means that the transport routes cannot be changed easily, simply because of safety. Decision-making on these issues should take into account several aspects like costs and benefits of users and producers of these hazardous materials, and the social value of these materials etc. One may ponder over alternative logistic transport systems, such as the transport on ships.

It should be underlined that decision-making on these alternative routes or alternative systems becomes easier if the proposed weighted risk analysis is used, because several aspects can be compared to each other quantitatively. Without using the weighted risk analysis, the decision on transport routes or systems, or new urban development surrounding these transport routes, will be one-sided. The methodology provides quantitative comparison of several aspects, including safety. In this way, decision-making on urban development and the transport of hazardous materials becomes an interesting step to solve the safety problem in The Netherlands. Note that if one decides for alternative routes, one should stand by the agreement that near these transport routes no new urban projects are to be developed, otherwise the same problems may occur in the future after all. Measures like a set up of a new chemical installation next to the place where the hazardous material is processed, should also be taken on the basis of a weighted risk analysis. In essence, decision-making on measures should be done on the basis of the deliberation of a cost-benefit-safety analysis.

Appendix A: The quantification of basic probabilities

An overview of probabilities for realising buildings above roads

The methodological steps that have been followed to set up a QRA are presented in figure A.1. In order to quantify conditional probabilities[8)] in a methodological way, first, it is important to explore the *basic conditions* (1) to perform a QRA, serving as basic boundary parameters. Subsequently, *basic hazards* (2) followed by *critical scenarios* (3) occurring on both the infrastructure and the building above it, were analysed. Finally, the *consequences* (4) have been modelled for each of those areas. These methodological steps correspond with the Bayesian Network of figure 5.6 of chapter 5.

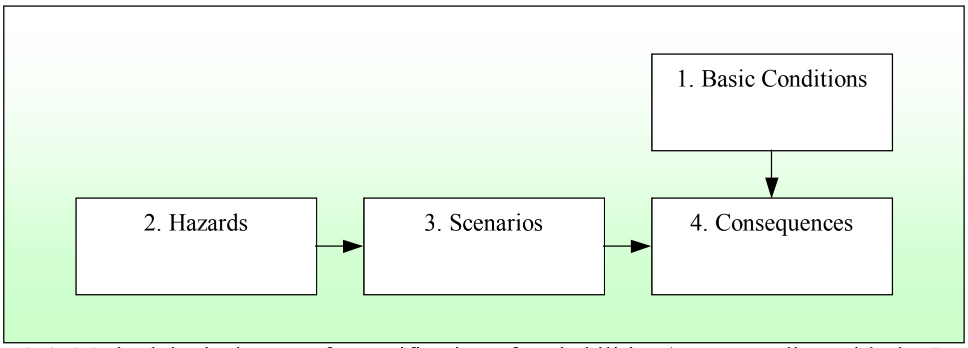

Figure A.1: Methodological steps of quantification of probabilities (corresponding with the Bayesian Network of figure 5.6, chapter 5).

8) More details on conditional probabilities and distribution functions can be found in Heilig (2002).

First, the probabilities in these steps will be determined for constructing above roads. Second, the same steps will be utilised for realising buildings above railways. If we focus on these steps in detail, the following categories for determining probabilities are analysed:

1. *Basic conditions:*
   a. Covering length of infrastructure (see Appendix A1a);
   b. People present in building, covered infrastructure and vicinity (see Appendix A1b).
2. *Hazards:*
   a. Traffic accident (see Appendix A2a);
   b. Transport of hazardous materials (see Appendix A2b);
   c. Following up scenarios of LF, GF, LT and GT (see Appendix A2c).
3. *Collapse of building above infrastructure due to critical scenarios:*
   a. Explosion on covered infrastructure (see Appendix A3a);
   b. Fire in building and covered infrastructure and fire spread (see Appendix A3b);
   c. Collisions affecting the main structure of building above (see Appendix A3c).
4. *Consequences on infrastructure, building and vicinity:*
   a. Fatalities (see Appendix A4a).
   b. Economical losses (main text chapter 5).

- *1. Basic conditions*

- A1a. 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 m, 30 - 100 m, 100 - 1000 m.

- A1b. 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).

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 (see section 5.1.2). 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.1. 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.1. It is assumed that during the night, 10% of the number of people during the day is present in the tunnel.

For *the population density in the vicinity* it is assumed that it is a homogeneous space with an average population density per km^2. Generally, every part of an area is divided into a grid for the vicinity and has to be considered separately in the risk analysis, as discussed by Ale *et al.* (1996). Considering the scope of this study, it is not the purpose to find out the exact effect on every grid. In the node "people [4]" of the Bayesian Network of figure A.16 and in this Appendix, five different classes are considered, namely $1{\cdot}10^3$, $2.5{\cdot}10^3$, $5.0{\cdot}10^3$, $7.5{\cdot}10^3$, or $1{\cdot}10^4$ persons per km^2.

For the considered case of chapter 3, the population density in the vicinity is set to be $7.5 \cdot 10^3$ persons per km^2.

Table A.1: 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).

Number of people present in the building above	Covering length		
	0 - 30m	30 - 100m	> 100 – 1000m
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	**Covering length**		
	0 - 30m	**30 - 100m**	**> 100 – 1000m**
(0 – 10)	0.999	0	0
(10 - 50)	0.001	0.75	0
(50 - 150)	0	0.25	1

❑ *2. Hazards*

- A2a Probability of a traffic accident

The probability of a traffic accident, in most cases the starting point for other scenarios, can be found in literature (cf. Kruiskamp (2002); Weger *et al*. (2001)). The probability of a traffic accident depends on the type of road. In general, both the frequency and the probability of an accident per vehicle kilometre are almost the same (because the probability and the frequency are much less than 1). The used frequencies of an accident per vehicle kilometre are determined using the report of AVIV (1997), see table A.2. In the considered case (of chapter 3), the probability of an accident per vehicle kilometre is set to be $3.60 \cdot 10^{-7}$. In order to calculate the risk of all passed vehicles per year per kilometre, we have to multiply the probability λ with the number of vehicles passed per year n_v and the covering length ratio per kilometre L ($P = nLT\lambda$).

Table A.2: The frequency of an accident per vehicle kilometre per type of road (AVIV (1997)).

Type of road	Frequency of an accident [vehiclekm^{-1}]
Motorway	$8.30 \cdot 10^{-8}$
Outside built-up area	$3.60 \cdot 10^{-7}$
Inside built-up area	$5.90 \cdot 10^{-7}$

- A2b Fraction of transport of hazardous materials

Once an accident has occurred on infrastructure, the following up scenarios depend on the fraction of transport of hazardous materials on that road and thus the traffic type, which can be varied in the Bayesian Network of figure A.16. The average ratio of passing vehicles and heavy traffic is presented in table A.3 (CUR (1998)).

Table A.3: The average ratio of the traffic type on the road (CUR (1998)).

Traffic Type	Ratio
Cars	0.84
Truck traffic	0.15
Busses	0.01

According to Kruiskamp (2002), the average transport of hazardous materials is only 5% of the total truck traffic in The Netherlands. The CUR (1998) also recommends an average ratio of transport of hazardous materials, which can be divided into the classes mentioned in table A.4. Often, a subdivision is made in these classes. Considering the scope of the study, however, it is not relevant to do that. Therefore, the assumed ratio of table A.4 is used for the considered case of chapter 3. It should be noted that this ratio could be varied in the risk analysis (see figure A.2). Normally, hazardous materials of class E (Explosive materials) are also transported on infrastructure. This class is knowingly excluded from the risk analysis, because this class covers a very small part (less than 0.001%) of the total transported hazardous materials.

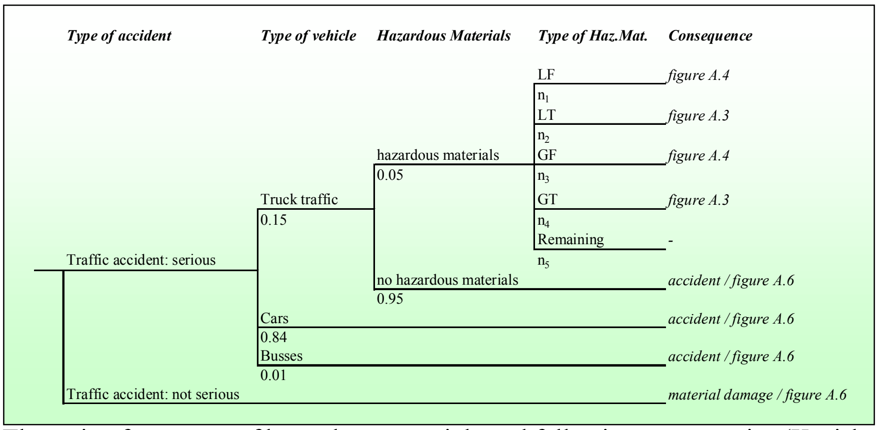

Figure A.2: The ratio of transport of hazardous materials and following up scenarios (Kruiskamp (2002)).

Table A.4: The assumed ratio of hazardous materials.

Hazardous Materials		Example	Ratio
-	Remaining	Margarine	0.14
LF	Flammable Liquids	Benzene	0.60
LT	Toxic Liquids	Propylamine	0.05
GF	Flammable Gasses	LPG	0.20
GT	Toxic Gasses	Chlorine	0.01

- A2c Following up scenarios of LT, GT, LF and GF

The following up scenarios of LT, GT, LF, and GF can be found in literature (cf. AVIV (1997), CPR 18 (2000), Rosmuller (2001), Kruiskamp (2002)). In general, the following up scenarios of release of LT / GT and LF / GF are given respectively in figure A.3 and A.4.

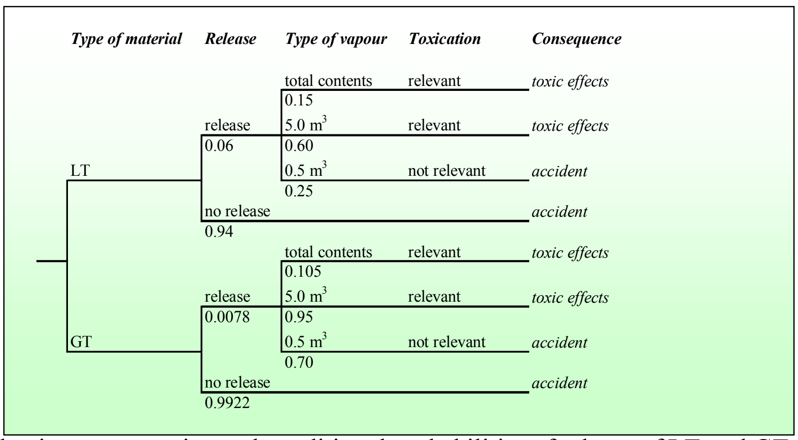

Figure A.3: Following up scenarios and conditional probabilities of release of LT and GT (AVIV (1997)).

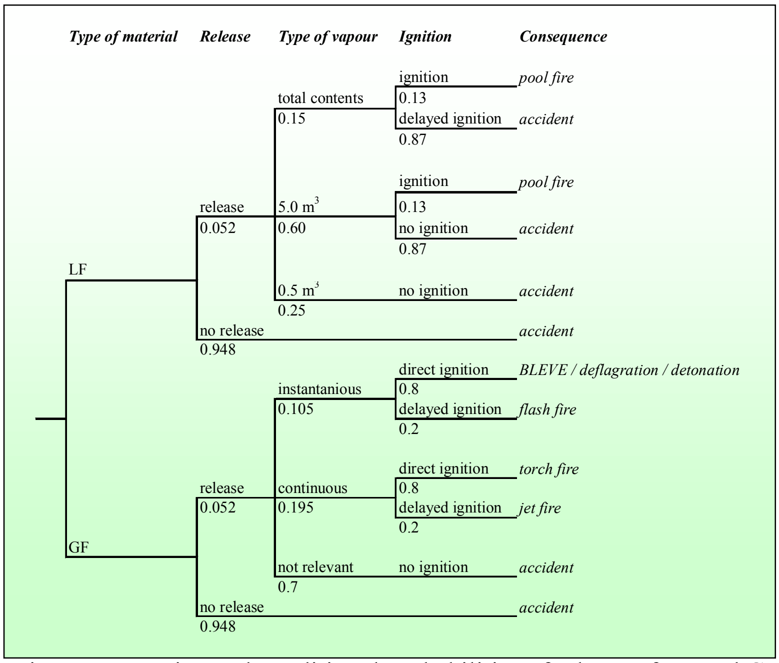

Figure A.4: Following up scenarios and conditional probabilities of release of LF and GF (AVIV (1997)).

The event trees of figure A.2, A.3 and A.4 are transformed into a Bayesian Network:

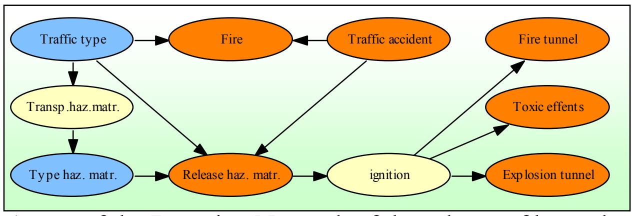

Figure A.5: A part of the Bayesian Network of the release of hazardous materials.

- *3. Collapse of building above infrastructure due to critical scenarios:*

- A3a Covering length of infrastructure and the explosion scenario

Once a gaseous flammable substance is directly ignited, the explosion scenario that occurs depends on the covering length of the infrastructure, as postulated in chapter 5. Assumptions are made for conditional probabilities of the explosion scenario versus the covering length of the infrastructure (see table A.5). Because marginal research has been done on this specific topic, these probabilities are determined by (in house) engineering judgement. According to Berg *et al*. (2001), if the ratio L/D is more than 10, the probability of a detonation in the pipe / tunnel will increase rapidly. Berg *et al*. (2001) 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 meters, instead of a covering length of just 80 meters. 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, 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. 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.

Table A.5: The assumed conditional probabilities of the explosion scenario and the covering length of the infrastructure.

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

- A3b Fire in building and covered infrastructure and fire spread

The probabilities of fire on infrastructure due to an accident can be found in CUR (1998). Note that, in case of a heavy goods vehicle combusting, the presented probabilities may differ from figure A.6. In case of fire with a heavy goods truck, the fire intensity will be higher (e.g. 300 MW) than presented in figure A.6. This is considered in the Bayesian Network of figure A.16.

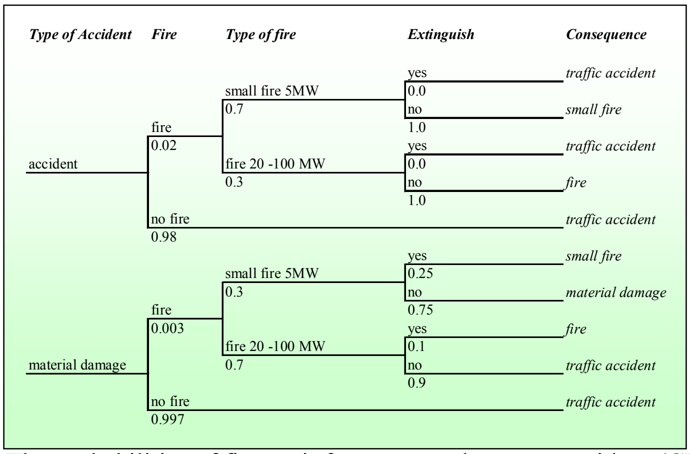

Figure A.6: The probabilities of fire on infrastructure due to an accident (CUR (1998)).

Holborn *et al*. (2002) and Frantzich (1998) investigated risk data of fires in the workplace, in which the probability of fire occurrence in the building depends on the function of that building. In the paper of Holborn *et al*. (2002), the background of the probabilities of fire occurrence is not given, such as the surface of the building etc. Therefore, it is difficult to investigate whether these probabilities are related to a specific building size. Nevertheless, these probabilities are used for the set up of the QRA. It is assumed that the probability of office (no. 7 of table A.6) relates to the mentioned building size of the case study of chapter 3.

Table A.6: The probability of fire occurrence in the building per year for different functions (adapted from Holborn *et al*. (2002)).

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

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.7, 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 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.8). 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.

Table A.7: 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

Table A.8: 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

- A3c Collisions affecting the main structure of building above

The probability of a collision with the main structure of the building can be determined as follows: the total footprint area of the building with a covering length of 30 m and a span of 20 m is equal to 600 m^2. Suppose that the (effect) area of a collision with the main structure of the building is 0.5 m each side multiplied the covering length. This means that the effect area of a collision with the building structure is approximately $0.5 \cdot 2 \cdot 30 = 30$ m^2. By this, the probability of a collision with the main structure of the building can be determined, which is *P*(*hit main structure building* | *an accident*) = 30 / 600 = 0.05 and *P*(*no hit main structure building* | *an accident*) = 1 - 0.05 = 0.95. Besides, hitting the main structure of a building by a car does not automatically result in the collapse of the building. The assumed probabilities for the collapse of the building, given that the vehicle hits the main structure of the building due to an accident, are given below:

Table A.9: 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

- *4. Consequences on infrastructure, building and vicinity:*

- A4a Fatalities

As mentioned in chapter 5, the fatalities in the covered infrastructure, the building above it, and in the vicinity have been determined by a gamma distribution function - formula (5.1) - per scenario by Heilig (2002). Heilig (2002) 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. First of all, the *fatalities on the covered infrastructure* are determined, due to internal risks from the structure enclosing the infrastructure (risk category [3]). The *fatalities on infrastructure* depend on the considered length of the infrastructure (for the case study of chapter 5, this is set to be 100 m). The number of people in 100 meters in the "covered" infrastructure is assumed to be approximately 32. If we focus on the relatively small local traffic accidents, it is assumed that relatively small number of fatalities will occur on the infrastructure (figure A.7).

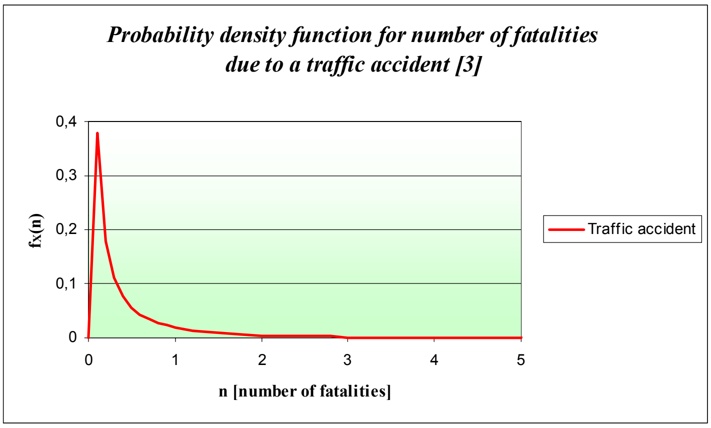

Figure A.7: The assumed probability density function for number of fatalities on the infrastructure due to a non-serious traffic accident (covering length = 100m, risk category [3], adapted from Heilig (2002)).

If a fire spreads from the building to the infrastructure beneath, it may cause fatalities among people present in the infrastructure. Moreover, the occurrence of fire may also be the result of a traffic accident on the infrastructure (due to a possible release of flammable materials). Therefore, an assumption has been made about the consequences of the fire scenario: these are classified according to both the effect distances of several fire scenarios (figure A.8).

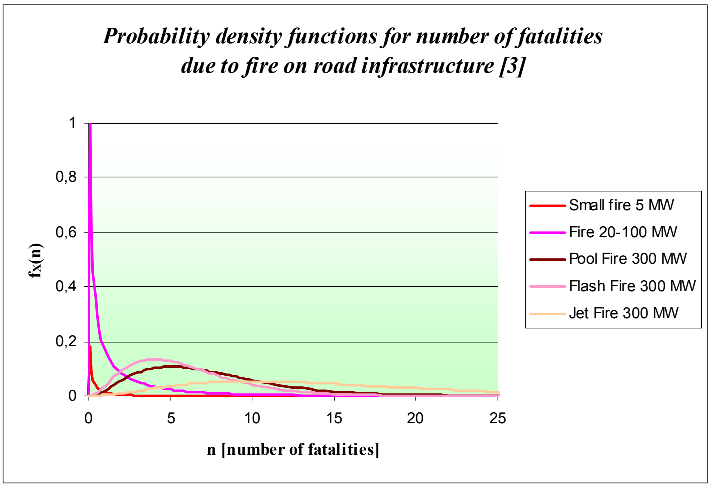

Figure A.8: The assumed probability density functions for number of fatalities due to fire on the covered road infrastructure (covering length = 100m, risk category [3], adapted from Heilig (2002)).

As mentioned earlier, scenarios with a large number of fatalities in a specific area should be treated likewise in a probabilistic manner. Figure A.9 shows the wide range in number of people killed in the covered infrastructure due to different explosion scenarios on the infrastructure. It is obvious that the effect distance depends on the volume transported per tank. In the case studies of chapter 3, the assumption was made that almost everyone present was be killed due to explosion scenarios. However, some nuances in the number of people killed in the covered infrastructure were made for several explosion scenarios. Since the effects of explosions may exceed the boundaries of the covered infrastructure, the number of fatalities on the infrastructure is assumed to be more than 32 in 100 m. Likewise, the assumed conditional probability density functions for number of fatalities due to the release of toxic effects on road infrastructure are presented in figure A.10. Figure A.10 shows the assumed distribution functions for the leak of toxic substances inside the covered infrastructure.

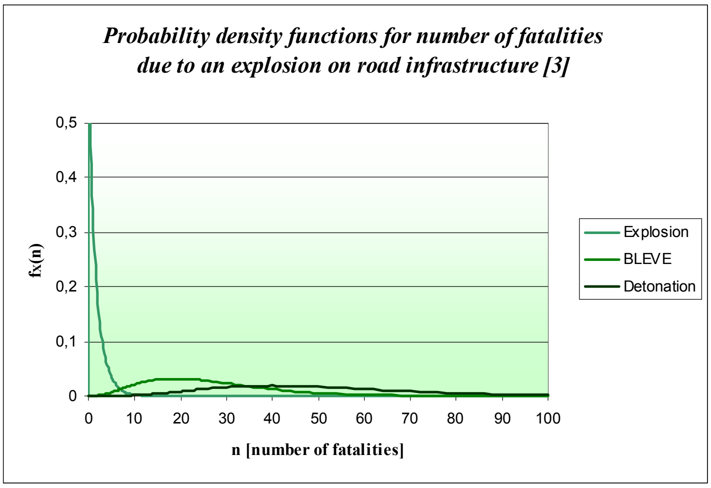

Figure A.9: The assumed probability density functions for number of fatalities due to an explosion on road infrastructure (covering length = 100m, risk category [3], adapted from Heilig (2002)).

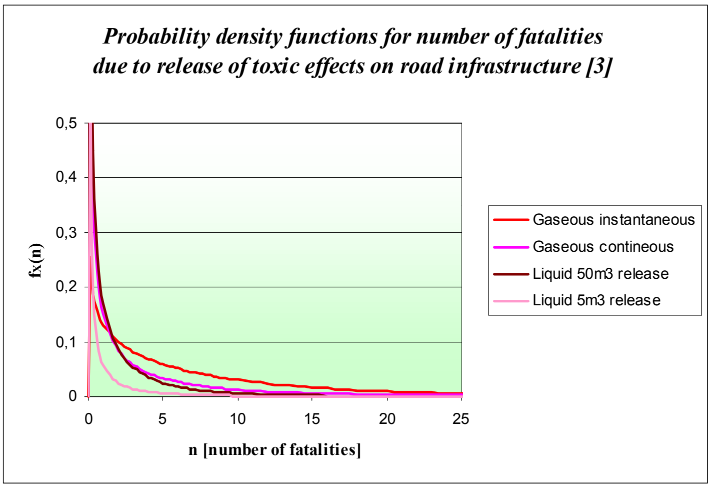

Figure A.10: The assumed probability density functions for number of fatalities due to the release of toxic effects on road infrastructure (covering length = 100m, risk category [3], adapted from Heilig (2002)).

Now, the fatalities in *the building above the infrastructure* is modelled due to the external risks from the infrastructure towards the building above it (risk category [2]).

Fatalities in the building above the infrastructure due to the release of toxic gasses on the infrastructure are assumed to be naught, because it is assumed that the building above the infrastructure does not make use of external ventilation from the covered infrastructure. Fatalities in the building above the infrastructure may occur due to fire and fire spread. These fatalities depend on the people present in the building (see Appendix A1b) and the intensity of the fire. The assumed probability density functions for several fire intensities in the building above the infrastructure (given a fire spread) are shown in figure A.11. It is (logically) assumed that the higher the fire intensity, the higher the number of people killed in the building above the infrastructure.

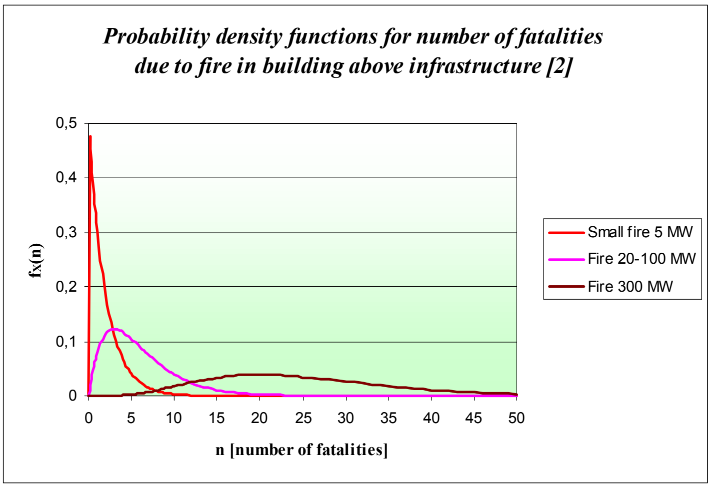

Figure A.11: The assumed probability density functions for number of fatalities due to fire spread from the infrastructure to the building above the infrastructure (risk category [2], adapted from Heilig (2002)).

As stated in chapter 5, the building above infrastructure may collapse due to explosions or accidents on infrastructure. This results in fatalities in the building above. For the considered case, the fatalities depend both on the number of people present and the duration of presence in the building of those people. Furthermore, it is assumed that not all people present in that building are killed due to the collapse of the building. The number of fatalities due to a collapse of a building of 100 m covering length and a height of 50 m is assumed to be as follows:

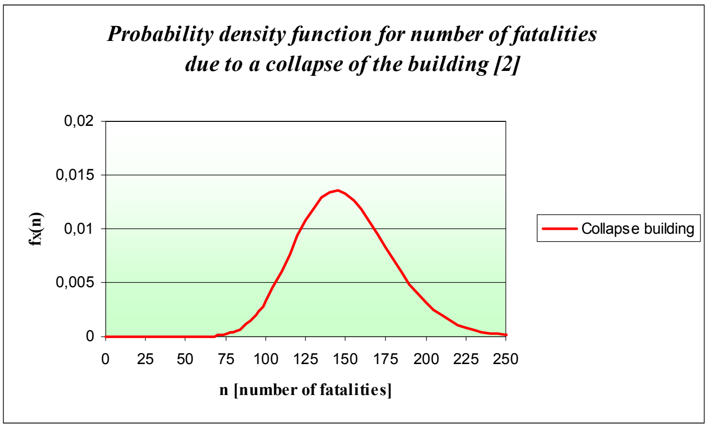

Figure A.12: The assumed probability density function for number of fatalities due to a collapse of the building (risk category [2], adapted from Heilig (2002)).

Now, we will focus on the effects of the scenarios occurring on *the infrastructure towards the vicinity* (risk category [4]). The effects of fires on the vicinity are in some way perceptible. Because the infrastructure is covered with buildings, it may be assumed that both the fire intensity and the effect distance is reduced. In order to investigate the exact decrease of the effect area, a lot of (field) research is needed, which is not the scope of this study, as mentioned in chapter 1. Nevertheless, the reduction of the effect distance can be transformed into assumed conditional probabilities (figure A.13). It should be noted that in case of not covering the infrastructure, the number of fatalities is higher than presented in figure A.13, through which existing QRA models can be applicable.

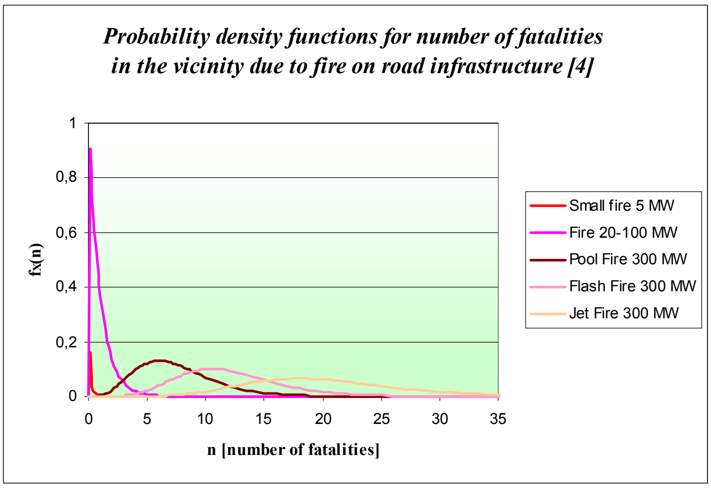

Figure A.13: The assumed probability density functions for number of fatalities in the vicinity due to fire on the covered road infrastructure (population density of $7.5{\cdot}10^3$ people per km^2, risk category [4], adapted from Heilig (2002)).

When considering the effects of the explosion to the vicinity, it can be stated that explosions, specifically detonations, have devastating consequences both for humans and for buildings near the infrastructure. In a relative large grid area of 1 km^2 and a population density of $7.5{\cdot}10^3$ people per km^2, the number of people killed will vary greatly (figure A.14).

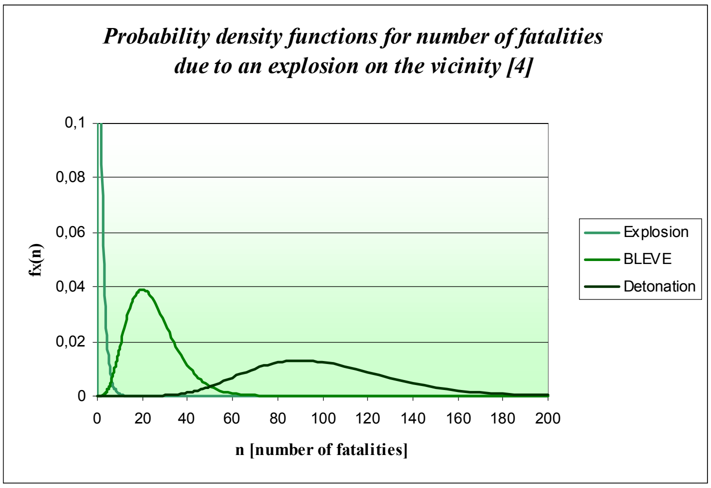

Figure A.14: The assumed probability density functions for number of fatalities due to an explosion in the vicinity (population density of $7.5{\cdot}10^3$ people per km^2, risk category [4], adapted from Heilig (2002)).

Due to the large effect distance (e.g. 5 km), especially of the gaseous toxic materials, the conditional probability density functions for number of fatalities due to release of toxic effects on the vicinity are assumed to be as presented in figure A.15. In fact these probability density functions of the one with a small covering length differ hardly when the infrastructure is not covered, except the case that the infrastructure is covered for a long distance. For a long covering lengths of the infrastructure, the effect distance of the toxic gas may even reduce, resulting in a decrease of fatalities. Suppose that the effect distance for the release of gaseous toxic is instantaneous, then a great number of fatalities may be inevitable, however the probability of this scenario is very small. If the population density increases, the number of fatalities will increase rapidly and can thus be much higher than presented in figure A.15. Once the conditional probabilities and the relations are quantified, they can be transformed into an extensive Bayesian Network, which is presented in figure A.16 and A.17 (for railways).

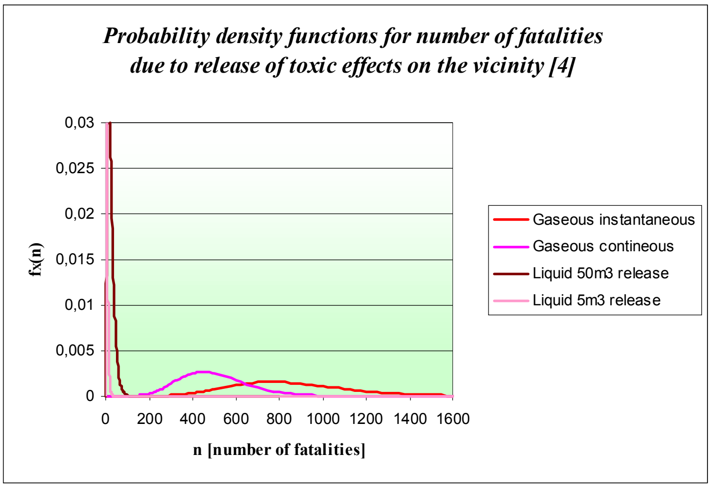

Figure A.15: The assumed probability density functions for number of fatalities due to the release of toxic effects on the vicinity (population density of $7.5 \cdot 10^3$ people per km^2, risk category [4]).

An overview of probabilities for realising building above railways

In essence, the determination of the probabilities for the set-up of QRA of realising buildings above railways does hardly differ from QRA of realising buildings above roads. Therefore, the same methodological steps as for building above roads have been followed to set-up a QRA. As postulated in chapter 5, the hazards, probabilities and basic conditions, integrated in the QRA which will be treated in this part of the Appendix and differ from building above roads, are:

5. *Basic conditions:*
   a. People present in building, covered infrastructure (see Appendix A5a).
6. *Hazards:*
   a. Traffic accident (see Appendix A6a);
   b. Transport of hazardous materials (see Appendix A6b);
   c. Electrocution (see Appendix A6c).
7. *Collapse of building above infrastructure due to critical scenarios:*
   a. Collisions affecting the main structure of building above (see Appendix A7a).
8. *Consequences on infrastructure, building and vicinity:*
   a. Economical losses (see Appendix A8a);

❑ *5. Basic conditions*

- A5a Number of people present at the infrastructure
Due to the great number of people travelling by train, the number of people present at the railway tracks is assumed to be higher than the number of people present in the tunnel when building above roads. An assumption has been made for the number of people present at the tunnel during the night: this is set to be 10% of the number of people present during the day.

Table A.10: The covering length of the building and the assumed number of people present at the infrastructure during the day and in the rush hour, homogenous distribution.

Number of people present at the infrastructure	Covering length		
	0 - 30m	30 - 100m	> 100 – 1000m
0 - 10	0.6	0.5	0.05
10 - 50	0.4	0.4	0.15
50 - 150	0	0.1	0.8

- A6a Probability of a traffic accident
The frequency of an accident in case of derailment, which can be divided into a frequency per wagon kilometre and a frequency per train kilometre, is presented in table A.11 (SAVE (1995$^{A \,\&\, B}$)). It should be noted that these probabilities change when e.g. switches and crossings are taken into account in the risk analysis as well.

Table A.11: The frequency of an accident on railways SAVE (1995$^{A \,\&\, B}$).

Train speed	Frequency of an accident [$wagonkm^{-1}$]	Frequency of an accident [$trainkm^{-1}$]
< 40 kmh^{-1}	$2.2 \cdot 10^{-8}$	$4.4 \cdot 10^{-9}$
> 40 kmh^{-1}	$4.5 \cdot 10^{-8}$	$9.0 \cdot 10^{-9}$

❑ *6. Hazards*

- A6b The ratio of transport of hazardous materials
The ratio of transport of hazardous materials on railways contains a different subdivision than the division of road transport. Nevertheless, these classifications are used for following up scenarios. For the considered case of chapter 3, it is assumed that only 2% of the total number of trains on that track is goods carrying traffic, of which 30% of the transport consists of hazardous materials. The ratio of transported hazardous materials for the considered case is determined as follows: for the case study of chapter 3, it is assumed that every hour 6 trains pass; this results in 105,120 trains per year. The following table presents the distribution of the transported hazardous materials for the considered case of chapter 3.

Table A.12: The classification of hazardous materials and the ratio of these materials for the case study of chapter 3.

Hazardous Materials			Example	Ratio
A	Flammable Gasses	GF	LPG	0.30
A_{mixed}	Flammable Gasses	GF	Propane	-
B2	Toxic Gasses	GT	Ammonia	0.10
B3	Extreme Toxic Gasses	GT	Chlorine	0.20
C3	Flammable Liquids	LF	Hexane	0.20
D4	Extreme Liquid Toxic Liquids	LT	Acrylonitryl	0.20

In fact, the following up scenarios of Toxic Liquids, Toxic Gasses and Flammable Liquids and Gasses are almost the same as presented in figure A.3 and A.4. In some cases however, different conditional probabilities are used (AVIV (1997)).

- A6c Electrocution
Another scenario that may occur when building above railways, is electrical discharge on the railway track. Electrocution can lead to a small fire on the infrastructure. The probability of an electrocution is assumed to be 10^{-6} per location per year.

- *7. Collapse of building above infrastructure due to critical scenarios:*

- A7a Collisions affecting the main structure of building above
In case of collisions with the main structure by trains, the consequences may be disastrous for the building above the railway. The probability that a train derails depends mostly on the switches beneath the building. In this case study, however, an assumption is made that there are no switches beneath the building. But, when the train derails, the main structure of the building can collapse totally or partially. The following probabilities are taken into account (assumptions): *P*(*hit main structure building* | *an accident*) = 0.01 and *P*(*no hit main structure building* | *an accident*) = 0.99. It is assumed that when the train hits the main structure of the building, the building will mostly collapse, because of the high mass and weight of the train, which results in a large impulse towards the infrastructure.

Table A.13: The assumed conditional probability for the collapse of the building of a train type (given the train hits the main the structure of building).

Collapse / No collapse	Vehicle Type: Train
No collapse	0.1
Collapse	0.9

- *4. Consequences on infrastructure, building and vicinity:*

- A8a Economical losses
Determination of economical loss in some way follows the same classification as in the case of building above roads. However, the division into cost-classes is different. It is logically assumed that an accident in the vicinity or at the railway track results in higher economic costs than when building above roads. Mostly, train traffic cannot be rerouted easily and the reconstruction costs of the railway are higher than in case of roads, which results in high economical losses.

Table A.14: Examples of different economical loss classes for building above railways (on a logarithmical scale).

Cost-class	Example of costs
I. No costs	In case of no hazard occurrence
II. < € 1,000,000	Light damage to vehicles and to infrastructure and building, etc.
III. € 1,000,000 - € 10,000,000	Damage to infrastructure and building above combined with and closure of infrastructure for weeks, etc.
IV. € 10,000,000 - € 100,000,000	Heavy damage to infrastructure / building above and buildings in the vicinity combined with close off the road and reroute the traffic for a long period, etc.
V. > € 100,000,000	Complete destruction of both infrastructure and buildings (above and in the vicinity)

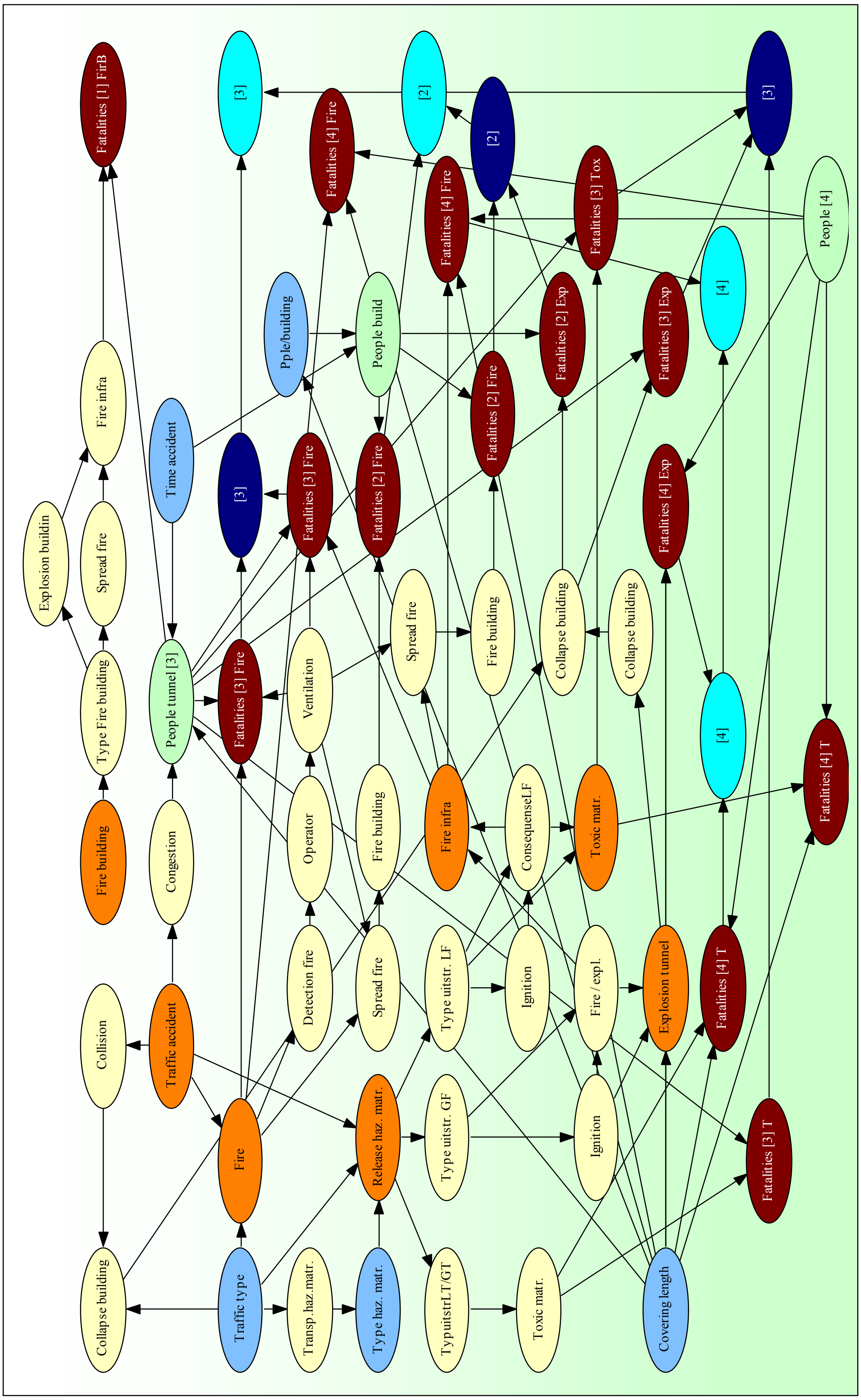

Figure A.16: Bayesian Network for building above roads.

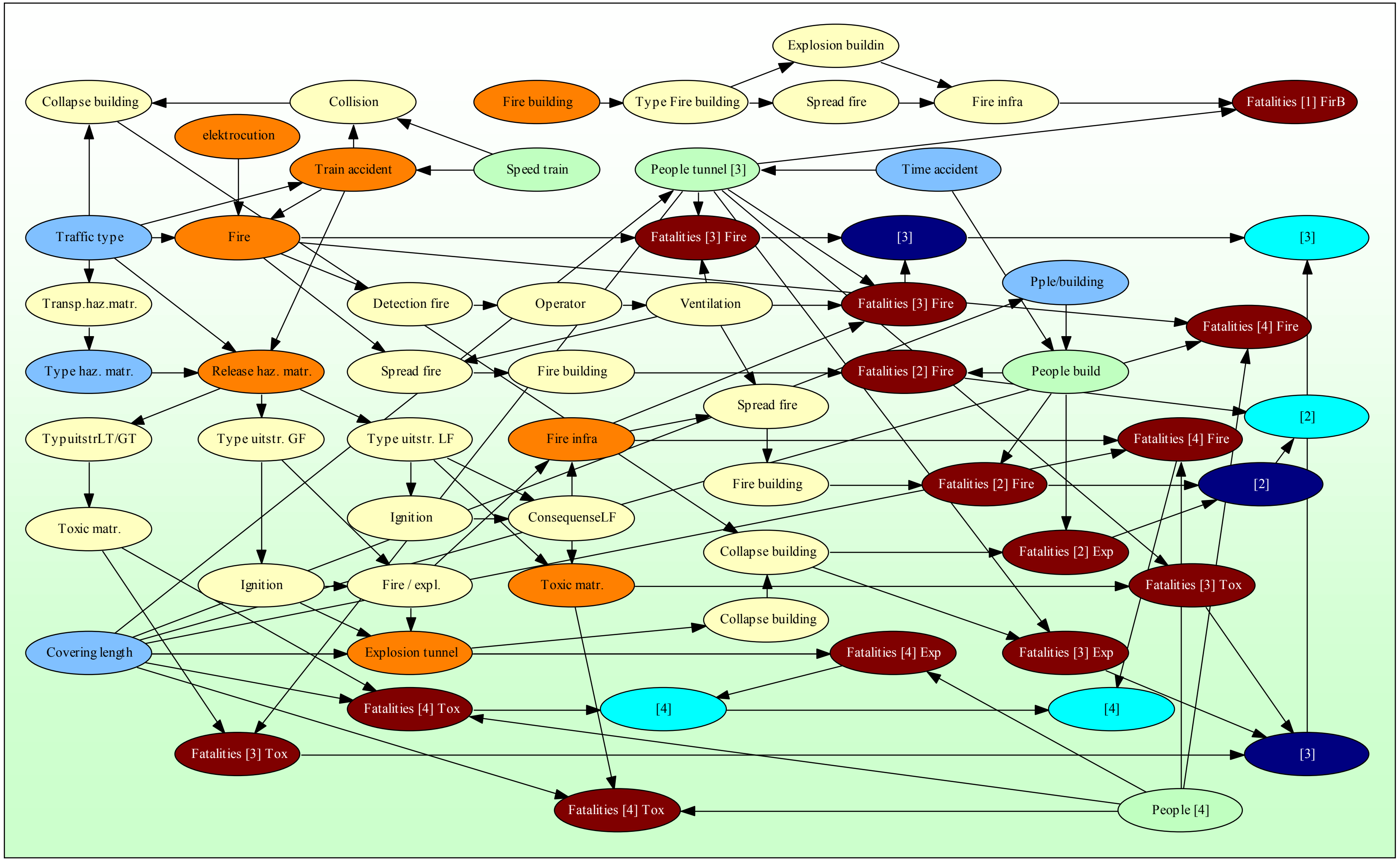

Figure A.17: Bayesian Network for building above railways.

Appendix B: Calculations of effects and costs of safety measures

Effects and costs of safety measures of chapter 6

Table B.1: Effects and costs of safety measures of chapter 6 (Suddle *et al*. (2003)).

Safety Meausres i	**Fire Protecting Layer**			**Concrete Layer**			**Sprinkler System**			**Airproof Buildings**		
Scenario n	*red.*	$P(i)_{red}$	$R(i)_{red}$	*red.*	$P(i)_{red}$	$R(i)_{red}$	*red.*	$P(i)_{red}$	$R(i)_{red}$	*red.*	$P(i)_{red}$	$R(i)_{red}$
1. Collisions with structure building $P_f(1) = 1.0 \cdot 10^{-7}$ $C_f(1) = 50$ $R_0(1) = 5.0 \cdot 10^{-6}$	-	-	-	-	-	-	-	-	-	-	-	-
2. Fires $P_f(2) = 1.0 \cdot 10^{-6}$ $C_f(2) = 100$ $R_0(2) = 1.0 \cdot 10^{-4}$	0.1	$1.0 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$	0.5	$5.0 \cdot 10^{-7}$	$5.0 \cdot 10^{-5}$	0.1	$1.0 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$	-	-	-
3. Toxic gasses $P_f(2) = 1.0 \cdot 10^{-9}$ $C_f(2) = 1000$ $R_0(2) = 1.0 \cdot 10^{-6}$	-	-	-	-	-	-	-	-	-	0.1	$1 \cdot 10^{-10}$	$1.0 \cdot 10^{-7}$
4. Explosions $P_f(4) = 1.0 \cdot 10^{-8}$ $C_f(4) = 500$ $R_0(4) = 5.0 \cdot 10^{-6}$	-	-	-	-	-	-	0.1	$1.0 \cdot 10^{-9}$	$5.0 \cdot 10^{-6}$	-	-	-
R_{totnw} [fat./year]	$2.1 \cdot 10^{-5}$			$6.1 \cdot 10^{-5}$			$1.7 \cdot 10^{-5}$			$1.1 \cdot 10^{-4}$		
$\Delta E(N_d)$ [fat./year]	$9.0 \cdot 10^{-5}$			$5.0 \cdot 10^{-5}$			$9.5 \cdot 10^{-5}$			$9.0 \cdot 10^{-7}$		
C_0 [€]	$4.0 \cdot 10^{5}$			$1.0 \cdot 10^{6}$			$1.0 \cdot 10^{6}$			$6.0 \cdot 10^{7}$		

Table B.2: Effects and costs of safety measures of chapter 6 (Suddle *et al*. (2003)).

Safety Measures i	**Derailment Control**			**Crash Barrier**			**Ventilation Tunnel**		
Scenario n	*red.*	$P(i)_{red}$	$R(i)_{red}$	*red.*	$P(i)_{red}$	$R(i)_{red}$	*red.*	$P(i)_{red}$	$R(i)_{red}$
1. Collisions with structure building $P_f(1) = 1.0{\cdot}10^{-7}$ $C_f(1) = 50$ $R_0(1) = 5.0{\cdot}10^{-6}$	0.1	$1.0{\cdot}10^{-8}$	$5.0{\cdot}10^{-7}$	0.2	$2.0{\cdot}10^{-8}$	$1.0{\cdot}10^{-6}$	-	-	-
2. Fires $P_f(2) = 1.0{\cdot}10^{-6}$ $C_f(2) = 100$ $R_0(2) = 1.0{\cdot}10^{-4}$	-	-	-	-	-	-	0.1	$1.0{\cdot}10^{-7}$	$1.0{\cdot}10^{-5}$
3. Toxic gasses $P_f(2) = 1.0{\cdot}10^{-9}$ $C_f(2) = 1000$ $R_0(2) = 1.0{\cdot}10^{-6}$	-	-	-	-	-	-	-	-	-
4. Explosions $P_f(4) = 1.0{\cdot}10^{-8}$ $C_f(4) = 500$ $R_0(4) = 5.0{\cdot}10^{-6}$	-	-	-	-	-	-	-	-	-
R_{totnw} [fat./year]	$1.1{\cdot}10^{-4}$			$1.1{\cdot}10^{-4}$			$2{\cdot}10^{-5}$		
$\Delta E(N_d)$ [fat./year]	$4.5{\cdot}10^{-6}$			$4.0{\cdot}10^{-6}$			$9{\cdot}10^{-5}$		
C_0 [€]	$2.0{\cdot}10^{5}$			$5.0{\cdot}10^{4}$			$7.5{\cdot}10^{4}$		

Resume of the monetary values of the elements of the weighted risk

The used monetary values of the elements of the weighted risk are: human beings α_{human} = € 1,000,000.= / fat.; quality $\alpha_{quality}$ = € 100.= / person / year; environment $\alpha_{environment}$ = € 4.= / m^2.

Case Study Bos en Lommer

The input parameters for the QRA of Bos en Lommer are presented in table B.3:

Table B.3: Input parameters for the case Bos en Lommer QRA.

Input parameters for case Bos en Lommer			
Characteristics of the road		*Characteristics of the building above the road*	
Type of road	3 x 2 lane motorway	Function of the building	Offices
Number of vehicles passed per day	159,000	Floor space of the buildings	20,000 m^2
Ratio of traffic type on the road	91% cars 8% truck traffic 1% busses	Length of the building	79.5 m
		Width of the building	85 m
		Height of the building	20 m
Transport of hazardous materials per year	36,501 LF trucks 3,664 GF trucks	Maximum people in the building	800
Ratio transport of hazardous materials per year	0.122807 no traffic 0.729123 LF 0.14807 GF	*Characteristics of the vicinity*	
		Population density	50 persons/ha
Covering length	79.5 m		
Frequency of an accident	$8.30{\cdot}10^{-8}$		
Maximum people in the covered infrastructure	100		

The investments of the measures regulating LPG transport are determined for the following measures (V & W (1996)): (1) banning transport of LPG; (2) Rerouting transport of LPG (not through urban areas); (3) transport of LPG through pipelines and (4) transport of LPG takes place during the night;

- Banning transport of LPG (measure 1)
According to the Ketenstudies (2003), banning the transport of LPG could lead to large social losses, such as the loss of 4,700 labourers. Suppose that labour costs € 20,000.= per year for a truck driver and 50 % of the fired employees is not able to find work. This means that the government has to pay 0.5 · 4,700 · 20,000 = € 47,000,000.=. So, this measure leads to economical losses. Suppose, if the economical loss becomes € 10,000,000.= per year and costs for sanitation are € 5,000,000.=; the total economical loss will be about € 62,000,000.= per year.

- Rerouting transport of LPG (measure 2)
Assume that every LPG truck has to take a detour of 50 km per day corresponding with about 10 litres petrol (€ 1.50 / litre) then the investments per year of this measure are: 1.50 · 10 · 3,664 = € 55,000.=.

- Transport of LPG through pipelines (measure 3)
The investments of a pipeline are € 250,000.= / km (VROM (2000^C)). Suppose a pipeline of 250 km has to be realised, i.e. from The Netherlands to Germany, then the investments will roughly be € 62,500,000 per year.

- Transport of LPG takes place during the night (measure 4)
No extra material investments are required, but the extra hourly wage of a truck driver during the night should be taken into account. Suppose that his hourly wage during the night is 200% (€ 35 per hour extra) of the normal hourly wage, then the costs will be roughly 3,664 · 35 · 8 = € 1,026,000.= per year.

Investments of structural and functional safety measures are determined for the following measures: (5) fire protection layer for building above infrastructure, (6) explosion resistant building above, (7) implementing a big diameter (a high level for the lowest storey h_o and a bigger span l), and (8) fire protecting layer for the buildings above and in the vicinity (for 1 km).

- Fire protection layer for building above infrastructure (measure 5)
Suppose the fire protection layer costs € 100 / m^2; then the total costs of this measure will be approximately 90 · (100 · 60 + 4 · 100 · 5) = € 720,000.=.

- Explosion resistant building above (measure 6)
For an explosion resistant building, we need a steel structure with a large deformation capacity. In the paper of Suddle *et al.* (2003), the costs of such a structure are presented. The investments for this measure will be about 0.09 · 121,800,000 ≅ € 11,000,000.=.

- Implementing a big diameter to the building (measure 7)
The costs of this measure are difficult to determine. Suppose we need a large bearing structure for the building and we elevate the building to 40 meters above the current situation. So, we may need 40 · 3 · 90 / 5 = 2160 extra column length, which costs about 2160 · 100 = € 216,000.=. Suppose we need an extra structures for building stability, let say € 100,000.=. The construction of this building will be also expensive, let say € 5,000,000 extra in comparison with the initial situation. The total costs of this measure will be about € 5,316,000.=.

- Fire protecting layer for the buildings above and in the vicinity (measure 8)
The costs will be about 2 · 1000 · 2 · 200 · 100 = € 80,000,000.= per year.

- Quality risk
The quality risk $R_{quality} \cdot \alpha_{quality}$ for 800 people computed as follows: € 100 · 800 = € 80,000.= (-) per year.

- Environmental risk
The environmental risk $R_{env} \cdot \alpha_{environmental}$ is computed by using the GAP as follows: € 4 · 30 · 90 = € 10,800.= (-) per year.

- Benefits
The benefits can be easily determined, using the rent prices: € 200 · 20,000 = € 2,000,000.= (-) per year.

Case Study Spoorzone Delft

The input parameters for the QRA of Spoorzone Delft are presented in the main text of chapter 7. The investments of the following measures are determined for the Spoorzone Delft case: Short tunnel (measure (1) and (3)), long tunnel (measure (2) and (4), structural safety measure (5), and human related safety measure (6).

- 0-situation (without realising project)
The quality component of the weighted risk can be calculated as follows; we know from the Masterplan (2003) the number of people working in offices on top the tunnel are the total floor space divided by the value of Eldonk *et al.* (2001) (the surface needed per employee): (29000 + 3765 + 13063) / 24 ≅ 1910 people. This means that $R_{quality}$ = 100 · 1910 ≅ € 191,000.= per year. $R_{environmental}$ = (6200 + 753 + 2341) · 4 ≅ € 37,000.= per year. The loss of benefits will about 54000 · 200 +1500 · 9,000 ≅ € 24,300,000.= per year.

- Short tunnel (measure (1) and (3))
The value for environmental benefits is estimated on 70 % of the long tunnel, plus the environmental value of the area of the park realised above the tunnel; let say that the park is 25 meters in width. This is thus $R_{environmental}$ = 0.7 · 37000 + 25 · 1559 · 4 ≅ € 182,000.= (-) per year. $R_{quality}$ = 191000 · 0.7 ≅ € 134,400 (-) per year.

- Long tunnel (measure (2) and (4))
For this measure, the $R_{environmental}$ will be about 37000 + 25 · 2300· 4 ≅ € 267,000.= (-) per year. $R_{quality}$ will be approximately € 191,000 (-) per year.

- Structural safety measures (measure (5))
The investments of this measure will be in the range of 2.3 · (10,000,000 + 1,000,000) ≅ € 25,000,000.= for the long tunnel.

- Human related safety measures (measure (6))
Suppose we need a extra team of 10 firemen. The costs of this fireman team is about 10 · 60 · 8 · 5 · 52 ≅ € 1,248,000.= per year.

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Dutch Summary (Samenvatting)

Fysieke Veiligheid bij Meervoudig Ruimtegebruik

Door een gebrek aan beschikbare ruimte, zijn in West-Europa projecten gerealiseerd waarbij intensief met ruimte is omgegaan. Binnen beperkte ruimte worden verschillende functies bij of boven elkaar gerealiseerd: meervoudig en intensief ruimtegebruik. De veiligheid van dergelijke gebieden wordt vooral bedreigd door het transport van gevaarlijke stoffen door deze gebieden. Dit heeft tot gevolg dat nieuwbouwplannen op dergelijke locaties niet worden uitgevoerd, of - in sommige gevallen - ondanks het dreigende gevaar toch worden verwezenlijkt. Dit nationale veiligheidsissue gaat soms gepaard met risico's op projectniveau: door het stapelen van transport- en verblijffuncties, zoals infrastructuur en bebouwing, kan een klein ongeluk leiden tot een ramp. Bovendien is de publieke opinie met betrekking tot veiligheid op scherp gesteld door een aantal recente (inter-) nationale rampen. Derhalve is veiligheid bij meervoudig en/of intensief ruimtegebruik een zeer relevante speerpunt. Dit proefschrift behandelt een methodiek voor het beoordelen van veiligheidsaspecten bij meervoudig en intensief ruimtegebruik, voor zowel de bouwfase als de exploitatiefase (*hoofdstuk 1*). In het onderzoek wordt de interactie tussen de interne veiligheid in de overkapping en de externe veiligheid behandeld.

Meervoudig ruimtegebruik is niet altijd het gevolg van ruimtetekort; ook culturele, politicologische, economische, milieutechnische en kwaliteitsaspecten kunnen een rol spelen bij het realiseren van dergelijke projecten (*hoofdstuk 2*). In feite kan men het risicoreducerend effect van maatregelen, dat betrekking heeft op veiligheid, afwegen tegen de genoemde aspecten. In dit proefschrift wordt hiervoor een zgn. *gewogen risicoanalyse*-methodiek voorgesteld.

In de kostenoptimalisering kan, met behulp van dit gewogen risico, het gevaar voor verlies van mensenlevens kwantitatief worden afgewogen tegen economische, milieutechnische en kwaliteitsaspecten. Het gewogen risico kan uitgedrukt worden in één risicodimensie (bijv. geld). Hierdoor kan de besluitvorming en het nemen van maatregelen bij deze projecten plaatsvinden op een veel bredere, effectieve en gegronde basis dan alleen op basis van de normen voor het individueel- en groepsrisico, zoals nu het geval is (*hoofdstuk 3*).

In *hoofdstuk 4* wordt ingegaan op de gevaren tijdens de bouwfase van dergelijke projecten. Een belangrijk onderdeel in dit hoofdstuk heeft betrekking op het vinden van specifiek voor dit toepassingsgebied toegesneden rekenmodellen, rekenmethoden en bijbehorende data zoals, statistiek van vallende objecten bij bouwactiviteiten, etc. Geconcludeerd wordt dat vallende voorwerpen de veiligheid van derden in gevaar brengen. Dit komt meestal doordat de onderliggende infrastructuur tijdens de bouw van het gebouw in gebruik is. De kwantitatieve risicoanalyse, gemodelleerd met Bayesiaanse Netwerken, toont aan dat kosteneffectieve maatregelen tegen deze vallende voorwerpen ofwel constructief - zoals het toepassen van een opvangvloer -, ofwel logistiek van aard - zoals het omleiden van het verkeer - kunnen zijn. Constructieve maatregelen kunnen dikwijls ingepast worden in het functionele of architectonische ontwerp van dit gebouw, waarmee tevens kosten kunnen worden bespaard.

Hoofdstuk 5 behandelt de risico's tijdens de exploitatiefase bij meervoudig ruimtegebruik-projecten. Ook zijn in dit hoofdstuk rekenmodellen, rekenmethoden en bijbehorende data, met betrekking tot ongevalfrequenties, statistiek van intensiteit en duur van branden, effecten van explosies etc. onderzocht. De mogelijk optredende scenario's tijdens de exploitatiefase zijn: aanrijdingen, branden, explosies en het vrijkomen van toxische gassen (afnemend in kans van optreden en toenemend in gevolg). Gesteld wordt dat het optreden van deze scenario's niet afhangt van het al dan niet overbouwd zijn van de infrastructuur. Echter, de gevolgen van deze scenario's kunnen totaal verschillend zijn, waardoor het resulterende risico alsnog kan verschillen. De overbouwing van de infrastructuur beïnvloedt de interne en de externe risico's van de infrastructuur. Derhalve is bij een modellering van individueel- en groepsrisico bij het stapelen van functies een driedimensionale risicobenadering onontbeerlijk. Bij deze benadering is het bezwijken van het gebouw boven de infrastructuur een cruciaal scenario. Met behulp van de driedimensionale risicobenadering wordt aangetoond dat het stapelen van functies niet per definitie leidt tot een groter risico. Zo kunnen ter plaatse van de overbouwing de externe risico's afnemen, terwijl deze intern sterk kunnen toenemen. Het effect van een bijv. explosie kan zich vertalen in het bezwijken van het gebouw boven de infrastructuur. Terwijl bij het vrijkomen van toxische gassen deze omsloten kunnen worden in de tunnelgedeelte.

In *hoofdstuk 6* passeert de set van mogelijke maatregelen voor de exploitatiefase bij dergelijke projecten en de kosteneffectiviteit hiervan de revue. Geconcludeerd wordt dat maatregelen tegen brand en aanrijdingen op kosteneffectieve wijze kunnen worden genomen. Maatregelen aan gebouwen tegen toxische gassen kunnen weliswaar uitgevoerd worden, maar blijken duur te zijn. Maatregelen tegen explosies zijn, zowel in constructief als in financieel opzicht, zeer moeilijk te realiseren. Het scheiden van verblijfs- en transportfunctie kan een kosteneffectieve en een logistieke maatregel zijn, indien er mogelijkheden zijn voor het vervoeren van gevaarlijke stoffen op alternatieve transportroutes.

Tenslotte wordt in *hoofdstuk 7* de voorgestelde "gewogen risicoanalyse"-methode toegepast in een tweetal cases: Bos en Lommer (bouwen boven wegen) en Spoorzone Delft (bouwen boven sporen). In deze casestudies is het effect van de veiligheidsmaatregelen in de (gewogen) risicoanalyse marginaal ten opzichte van de kosten van deze maatregelen.

Uit het gewogen risico blijkt dat de waarde toegekend aan milieutechnische en kwaliteitsaspecten c.q. maatregelen weinig invloed heeft op de totale kosten en baten van een project. Variatie in de inputvariabelen voor bijvoorbeeld de nominale waarde van een mensenleven leidt niet tot een substantiële verbetering in de effectiviteit van maatregelen in de gewogen risicoanalyse. Hieruit kan geconcludeerd worden dat de kosten en baten van een project de doorslaggevende factoren zijn voor de besluitvorming omtrent het al dan niet realiseren van een project of het treffen van een maatregel.

Het feit dat het verlies van mensenlevens nauwelijks meeweegt in het gewogen risico kan erop duiden dat in de toekomst hogere monetaire waarden worden gebruikt voor het verlies van een mensenleven of dat meer aspecten worden meegenomen bij het beslissingsproces dan de aangenomen economische, milieutechnische, menselijke en kwaliteitsaspecten. Echter, het treffen van veiligheidsmaatregelen, ondanks hun marginale effect, duidt erop dat veiligheid meer een randvoorwaarde is dan een financieel aspect. Beslissingen op grond van intuïtie of politieke achtergrond kunnen weliswaar totaal effectloos zijn, maar hebben het doel om een bepaald veiligheidsniveau te garanderen en om een positief gevoel over de veiligheid te geven. De gewogen risico-methodiek heeft dan een ondersteunende rol bij het besluitvormingsproces. In de toekomst kan deze methode de input vormen voor een toetsingskader voor fysieke veiligheid bij ruimtelijke ordeningsprojecten. De monetaire waarden per aspect kunnen echter verschillen in de tijd. Door het variëren van deze waarden van het model kan inzicht gekregen worden in de invloed hiervan. De gewogen risico-methodiek zorgt voor een afgewogen, effectieve beslissing. De kracht van het gewogen risico schuilt dus in het feit dat relevante aspecten, tot op een zekere hoogte, gekwantificeerd worden, wat tot een gegronde besluitvorming leidt.

Shahid Iqbal Suddle

Acknowledgements

After three years of research, the wonderful moment has come to express my gratitude to some special persons and to reveal a few things about myself. It is obvious that without a pen, it is difficult to write. Likewise, without the dedicated support of the supervisors, it is almost impossible to succeed for a Ph.D. researcher. Hence, I would like to use this opportunity to distinguish my supervisors for their contribution in this work. First of all, I would like to express my deepest gratitude to Prof. Jan Vamberský, who gave me the opportunity to conduct this research project at Delft University of Technology. He did not only guide me as my supervisor, but he has also refined my skills of Structural Engineering at Corsmit Consulting Engineers in Rijswijk. His every minute encouragement was an outstanding impulse for my development as a scientist. Secondly, I would like to thank Prof. Ton Vrouwenvelder very much, who taught me to be always as exact as possible, which is necessary for completing a Ph.D. study. I will always remember our scientific discussions during my research time. He taught me that safety is not quantifiable, and I really understand it now. This thesis is also the result of his significant and extremely valuable advises and effective comments.

Writing this thesis was induced by a number of people, especially the non-official supervisors. Dr. Paul Waarts advised me monthly during my research period. I would like to thank him for his helpful suggestions. I appreciate the cooperation with Prof. Ben Ale, a man with a very special style, who provided me an exclusive way of thinking about risks: ”it will not happen to us”. I would like to thank Dr. John Stoop and Dr. Pieter van Gelder for their support in this study and review of this thesis. In order to deal with the lack of expertise in many scientific fields in this research, it was indispensable to involve individuals of companies with great practical experience.

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It is not correct for one to suppose that the total time needed for this research was less than three and a half years. I ”officially” worked part-time in Delft. However, from the second year of my research I unofficially worked mainly in the evening hours and at weekends, during which I received inspiration from my family. My lovely father Sahibzada Inayat Ullah Suddle and my lovely mother Razia Begum Suddle have always been great to me. My parents’ inspiration and support in many respects has led to this manuscript. The deep gratitude I feel for my parents is beyond all words. You gave too much to me. Once again, thank you very, very much. I am proud of my sisters Arifa Tunveer - and her husband Adil -, Kashifa and Fozia Tunveer, who were willing to listen to anecdotes about all my research activities. Thanks for the fun and laughs we had during my breaks. I would like to thank Kashifa twice, because of her interest in my research progress, our long discussions and her review and suggestions on this thesis.

Unfortunately, apart from all mentioned positive response on my research, I had a tough time as well. In fact, life is extremely complex and in my opinion, the pearls of life are created on the principle that everything is composed in balanced pairs: e.g. the higher the desired success level, the more undesired difficulties that are to be gone through. At least, that was one of my great experiences in many respects during my research time. I saw for instance that success is in someway overshadowed by dark events.

Nevertheless, this thesis is strong evidence that I rescued: I have always been inspired and guided by the spiritual stimulation of my beloved Grandfather Hazrat Baba-Ji Sakhi Saif Ullah Noori Al-Quadri Noshahi. I am convinced that even a single word of this thesis is one of the miracles of this life that He provided. Therefore, I would to like to express my deepest gratitude to Hazrat Saif Ullah Noori for everything He has given to me. And I am pleased that today I hopefully contributed to your celebrity in a positive way. I am proud that it was the decision of God for me to be your grandchild. I am so glad that you gave me so much. At last, but not at least: God is Great. As final words of this thesis, I would like to thank God for creating this universe, and in particular for His help in completing this research.

Shahid Iqbal Suddle
September 2004, Schiedam

About The Author

(Mohammad Asif) Shahid Iqbal Suddle was born on March, 9th, 1975 in Sialkot City, Pakistan. In 1977, he moved with his parents to The Netherlands (Rotterdam), where he attended primary school. In 1989, he started secondary school with a Lower Technical Education (LTS) at the Beukelsburg in Rotterdam. Being highly interested in science and mathematics, he continued his education in 1992 at the Wolfert van Borselen high school in Rotterdam. There, he successfully passed his MAVO examinations, followed by the HAVO. In 1996, he received his Atheneum (VWO) diploma at the same high school. After that, he studied Civil Engineering at Delft University of Technology, with the specialisation Building Engineering and Structural Engineering. He obtained his Masters of Science degree in May 2001. His M.Sc. thesis concerned the safety of construction in multiple use of space. From the 1st of May 2001, Shahid Suddle worked part time on his Ph.D. research project at the Faculty of Civil Engineering and Geosciences of Delft University of Technology within the section of Building Engineering and Structural Engineering. Apart from his Ph.D. research, he worked part time as a structural engineer and designer at Corsmit Consulting Engineers in Rijswijk, where he was involved in numerous projects regarding structural design of buildings and safety assessment studies. During his Ph.D. period, the author was also a guest lecturer of the NIBRA (Netherlands Institute for Fire Service and Disaster Management). He also gave a guest lecture at the University of Engineering and Technology in Lahore in Pakistan. From September 2004, the author has continued his career as a policy advisor on external safety and spatial planning at Stadsgewest Haaglanden in The Hague. The author has presented his work at numerous national and international conferences and workshops, and has published in journals.

When knowledge strikes on the heart, it becomes a helper.
When knowledge strikes upon the body, it becomes a burden.
(The Mathnawi of Jalal-Ud-Din Rumi)

INVITATION

You are cordially invited to attend the public defence of my doctoral dissertation entitled

Physical Safety in Multiple Use of Space

with propositions.

This ceremony takes place on Wednesday **October 13th 2004** at **10.30** in the Senaatzaal of the Aula of Delft University of Technology, Mekelweg 5, Delft.

Prior to the official session, I will give an explanation on the contents of the thesis between **10.00** and **10.15**.

You are also invited for the reception after the defence.

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Paranymphs: Arifa Suddle & Kashifa Suddle

UITNODIGING

Hierbij nodig ik u van harte uit om de openbare verdediging van mijn proefschrift getiteld

Physical Safety in Multiple Use of Space

met stellingen bij te wonen.

Deze ceremonie vindt plaats op woensdag **13 oktober 2004** om **10.30** uur in de Senaatzaal van de Aula der Technische Universiteit Delft, Mekelweg 5 in Delft.

Voor de officiële zitting geef ik een toelichting op de inhoud van het proefschrift van **10.00** tot **10.15** uur.

Na afloop van de promotie bent u welkom op de receptie.

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Stellingen

behorende bij het proefschrift

Physical Safety in Multiple Use of Space

door

Shahid Iqbal SUDDLE

1. Veiligheid is niet te kwantificeren.

2. Het systematisch fout toekennen van kansen in een kwantitatieve risicoanalyse kan desondanks tot gevolg hebben dat de vergelijking van de resultaten van veiligheidsmaatregelen alsnog valide is.

3. De kans op een onzekerheid in een risicoanalyse is even groot als de complementaire kans op het kerngezond zijn van een levend wezen.

4. Beslissingen met betrekking tot veiligheid zijn op basis van een gewogen risicoanalyse rationeler dan beslissingen op basis van de normen voor het individueel- en groepsrisico.

5. Het transporteren van gevaarlijke stoffen door bebouwde gebieden of het realiseren van bebouwing langs transportroutes met het vervoer van gevaarlijke stoffen, duidt erop dat ons geheugen relatief kort is of dat wij het risico a-priori accepteren.

6. De kloof tussen een deterministische risicoanalyse en een probabilistische risicoanalyse is groter dan de kloof tussen de vakgebieden van sociale psychologie en kwantitatieve risicoanalyse.

7. Bij de bestrijding van terrorisme dient uit ethische overwegingen de gewogen risicoanalyse methodologie toegepast te worden.

8. Het vak veiligheid hoort in het lesprogramma van een technische opleiding, met name als men bedenkt dat het vak ethiek reeds een onderdeel hiervan is.

9. Het beschikbare budget voor een vierjarig promotieonderzoek is kleiner dan de jaarlijkse maatschappelijke schade veroorzaakt door één junk.

10. Bij het schaakspel zijn onveilige stellingen gewenst.

11. Nanotechnologie heeft ook toekomst in constructies.

12. Kennis is relatief.

13 Oktober 2004

Deze stellingen worden verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren, Prof.Dipl.-ing. J.N.J.A. Vamberský en Prof.ir. A.C.W.M. Vrouwenvelder.

Propositions

as a supplement to the Ph.D. dissertation

Physical Safety in Multiple Use of Space

by

Shahid Iqbal SUDDLE

1. Safety cannot be quantified.

2. Even if the probabilities in a quantitative risk analysis are systematically misjudged, the comparison of the results of safety measures may still be valid.

3. The probability of an uncertainty in a risk analysis is equal to the complementary probability of a living creature being perfectly healthy.

4. Decisions on the basis of a weighted risk analysis with respect to safety are more rational than decisions on the basis of the risk acceptance criteria for individual and group risk.

5. Transporting hazardous materials through urban areas or realising buildings adjacent to transport routes along which hazardous materials are transported, argues that our memory is relatively short, or that we accept the risk level a priori.

6. The gap between a deterministic risk analysis and a probabilistic risk analysis is larger than the gap between the fields of social psychology and quantitative risk analysis.

7. The weighted risk analysis methodology should be applied from ethical considerations for the fight against terrorism.

8. Safety should be a part of the engineering curriculum, especially when considering that ethics is already a part of that programme.

9. The available budget for a four years PhD-project is less than the annual social damage caused by a single junkie.

10. On a chessboard, unsafe positions are desirable.

11. Nanotechnology also has a bright future in structures.

12. Knowledge is relative.

13 October 2004

These propositions are considered defendable and as such have been approved by the supervisors, Prof.Dipl.-ing. J.N.J.A. Vamberský en Prof.ir. A.C.W.M. Vrouwenvelder.