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The weighted risk analysis

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ABSTRACT

Safety and risk assessment are characterised by aspects, like subjectivity and objectivity. In this paper, relations between safety and risk are described. 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 environmental, quality, and economical aspects, a weighted risk analysis methodology is proposed in this paper. This paper also provides a theoretical background regarding the scope of safety assessment in relation to the decision-making in complex urban development projects adjacent to or above transport routes of hazardous materials. In Western Europe, such projects are realised due to shortage of space. The weighted risk analysis is an interesting tool comparing different risks, such as investments, economical losses and the loss of human lives, in one-dimension (e.g., money), since both investments and risks could be expressed solely in money. Finally, the weighted risk analysis approach is applied in a case study of Bos and Lommer, Amsterdam.

1. Introduction

Safety is nowadays one of the main items on the agenda during the planning, realisation and management of most large-scale projects, particularly in infrastructure and building projects in intensively used areas such as multiple use of space projects. Buildings above roads and railways are examples of multiple use of space. With a population density of 475 people/km^2 in The Netherlands, a particular concern is to preserve the remaining "empty" areas as long as possible if alone to provide recreational area's for the inhabitants of the congested cities. Accordingly, future projects preferably are to be realised within the present urban contours, utilising existing urban spaces more efficiently and effectively. Multiple use of space projects are thus realised due to a shortage of space on one hand and a high demands set on spatial quality on the other. This may lead to conflict situations where the use of space is being intensified near or even above locations where hazardous activities are taking place (e.g., industrial activities and transport routes or storage of hazardous materials); any accident may result in increasing serious consequences (Suddle and Ale, 2005). Some buildings in The Netherlands are realised above transport routes of hazardous materials. Therefore, it is vital to assess the safety aspects at an early possible stage of the project, since safety is one of the critical issues for such projects. In this regard, quantitative risk analyses (QRA) can be undertaken to investigate what safety measures that are required to realise these projects. The QRA should examine the construction stage, the exploitation stage and the demolition stage.

The results of these analyses can also be compared to risk acceptance criteria, if they are applicable. In The Netherlands, regulations for land-use planning in the vicinity of major industrial hazards are explicitly risk-based. In risk-based regulation, not only potential adverse physical effects are considered but also the probability of failure. Three main elements constitute the Dutch regulatory framework: (i) quantitative risk assessment, (ii) the adoption of individual and societal risk as risk-determining parameters and (iii) acceptability criteria for individual and societal risk (Bottelberghs, 2000). Besides these criteria, the ALARA-principle is adopted. Also when the risk criteria are met, risks should be reduced to levels that are as low as reasonably achievable. Whether additional investments in risk reduction are reasonable is determined by implicit or explicit societal cost-benefit analysis. In The Netherlands, there are explicit criteria for acceptability of individual risk and societal risk. Note that the risk acceptance criteria are targets, rather than the conditions to ensure complete safety.

When a risk analysis is performed, it is important to realise that decision-making about (accepting) 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. Sometimes, expensive safety measures are necessary to realise multiple use of projects,

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particularly in cases where buildings are realised above transport routes of hazardous materials. There are several measures that can be implemented in such projects, which will reduce either the probability or the consequences of an incident in the building or infrastructure. The risk reducing effect regarding safety measures for human risks is usually depicted in FN-diagrams for the group risk. The risk reducing effects of safety measures can be determined quantitatively, presenting the effect of reduction in the number of expected fatalities. From a risk management point of view, it is desired that the implemented measures are cost-effective. Hence, this implies that the effect of safety measures for human risks is both implicit and explicit compared with economical grounds. As mentioned before, rather more aspects than economical grounds should be taken into account during the decision-making process. Cultural, political, economical, environmental and (spatial) quality aspects can also play a decisive role in determining the decision regarding safety measures related with the development of such projects. Having this all in mind, the following question arises: Can different decision-making aspects compared quantitatively – preferably in the same (cost) units – with the effect of safety measures? This question contains implicitly whether investments of safety measures can be efficient in comparison with other non-safety related aspects. Moreover, 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. Additionally, comparison of effects of safety measures with non-safety related aspects, such as environmental and spatial quality aspects, are more difficult to find in literature (e.g., Bottelberghs, 2000; Wiersma et al., 2004; Vrouwenvelder, 2001).

This was the reason for undertaking a Ph.D. research project at Delft University of Technology, carried out by Suddle (2004). In this paper, this question is answered by proposing the "weighted risk analysis" (WRA) methodology as an additional tool in the decision-making process, in which the effect of safety measures is optimised with aspects, such as environmental, quality, and economical aspects. Furthermore, the approach of the optimisation is not only based on effects of economical and human risks of measures, but also a deliberation of non-safety related aspects. Finally, the weighted risk analysis methodology is applied in a case study of Bos and Lommer, Amsterdam.

2. Safety and risk

2.1. Introduction

Safety is a wide notion. Vrouwenvelder (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). Social safety constitutes mainly of the (perception) behaviour among persons (Suddle, 2004). Crime incentive factors, spatial factors, institutional factors and social factors of an area are characteristics of social safety (Durmisevic, 2002). 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 into a social or a physical part. The subdivision within physical safety divides into internal safety and external safety (see, e.g., Hale, 2000). The following subdivision, here ranked according to increasing benefit to the persons at risk is frequently found (Suddle, 2004) (see Fig. 1).

2.2. 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 Fig. 2. Subjective safety is related to psychological aspects (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. A maximum level of safety corresponds with no risk, while a low safety level guaranteed corresponds with a risk of almost 100%. The advantage hereof is that risk can be quantified and judged whether it is acceptable or not, while safety itself cannot. Risk can thus be measured with loss per year, while safety cannot.

2.3. 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, 1996) 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 and Stallen (1980), Bohnenblust and Slovic (1998), Slovic (1987, 1999), Adams (1995), Coombs (1972), and Libby and Fishburn (1977). An integral approach of both mathematical and psychological definitions is treated by Suddle and

Safety		
Social Safety	*Physical Safety*	
Crime incentive factors Spatial factors Institutional factors Social factors	*Natural & Man-made hazards*	
	Internal Users Passengers Personnel	**External** Third parties

Fig. 1. Subdivision of safety (Suddle, 2004).

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

Fig. 2. Aspects of behaviour.

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 paper. 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 (Suddle, 2004; Vrijling et al., 1998). In essence, it comes down to the following expression (the most frequently used definition in risk analysis), see also ISO 31000 (2002):

$$R = P_{\mathrm{f}} \cdot C_{\mathrm{f}} \tag{1}$$

in which *R is the* risk (fatalities per year or money per year); P_{f} is the probability of failure (year^{-1}) and C_{f} is the consequence of the unwanted event (fatalities or money).

According to Kaplan and Garrick (1981), risk consists of three components; (1) scenario, (2) probability of that scenario and (3) consequence of that scenario. Kaplan and 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:

$$R = \sum_{i=1} P_{\mathrm{f}_i} \cdot C_{\mathrm{f}_i} \tag{2}$$

Consequences C_{f} to be taken into account include among others:

- injury, or loss of life, due to structural collapse;
- reconstruction costs;
- loss of economic activity;
- environmental losses;
- time loss;
- and so on...

It should be noticed that it depends on the level of the decision-maker which type of consequences C_{f} are taken into account. It should be noted that if one likes to implement the concept of risk aversion in that formula, one can take the consequences to a second power. This concept is applied for the criteria of risk acceptance of the societal risk (see, e.g., Bottelberghs, 2000). Most of the time, there is an inverse relation between the probability that a hazard will occur and the consequences of that hazard.

Finally, it should be stated that considering the scope of this paper and considering the case study, in which the transport of hazardous materials is forming a major hazard to buildings above the infrastructure, the mathematical definition of risk is used to determine both the individual risk and group risk. So, both internal and external safety risks are worked out in this paper, since these are the most useful to determine both the individual risk and group risk.

3. Risk management process

3.1. 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 (Suddle, 2004). 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 and 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 Fig. 3 (see, e.g., Høj and Kröger, 2002; ISO 31000, 2002). Note that different stakeholders are involved in the risk management process. Usually, QRA models reach the level of risk evaluation.

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.

3.2. 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. 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 Fig. 4).

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 (Suddle, 2004; Vlek and Stallen, 1980; Coombs, 1972; Libby and Fishburn, 1977). 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, 2004; Suddle and Waarts, 2003):

$$R_{\mathrm{w}} = \sum_{j=1} \alpha_j \sum_{i=1} P_{\mathrm{f}_{ij}} \cdot C_{\mathrm{f}_{ij}} \tag{3}$$

$$R_{\mathrm{w}} = \sum_{j=1} \alpha_j \sum_{i=1} R_{ij} \tag{4}$$

in which R_{w} is the weighted risk (cost unit per year); α_j *is the* (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 (Suddle, 2004). Furthermore, the term weighted is discussable, since different risks are also aggregated. Bohnenblust and 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) and (4) can be specified into particular risk components (Suddle, 2004; Suddle and Waarts, 2003):

$$R_{\mathrm{w}} = \alpha_1 \sum_{i=1} R_{\mathrm{human},i} + \alpha_2 \sum_{j=1} R_{\mathrm{economic},j} + \alpha_3 \sum_{k=1} R_{\mathrm{environment},k} + \alpha_4 \sum_{l=1} R_{\mathrm{quality},l} + \cdots \tag{5}$$

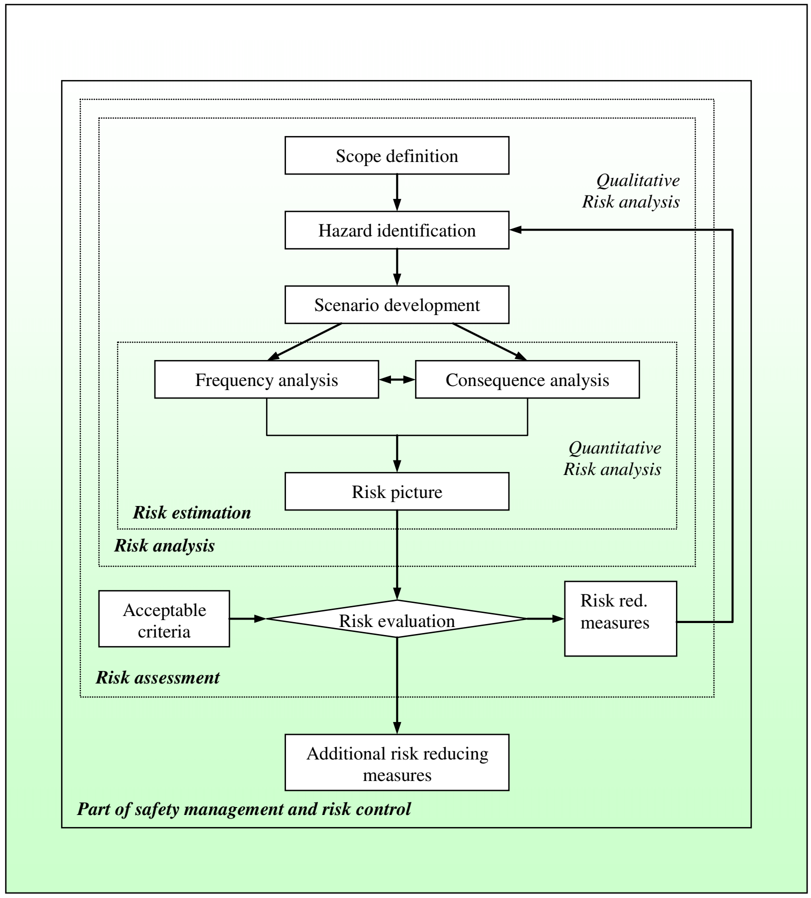

Fig. 3. A part of the risk management process (Høj and Kröger, 2002).

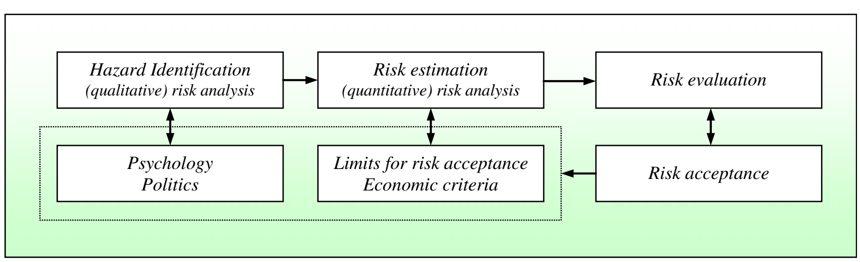

Fig. 4. Risk analysis and risk acceptance (Suddle, 2004).

in which α_1 is the (monetary) value per fatality or injury (cost unit); α_2 is the (monetary) value per environmental risk (cost unit); α_3 is the (monetary) value per economical risk (cost unit) (mostly $\alpha_3 = 1$), α_4 is the (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. However, usually these are taken into account during the phase of risk evaluation (Suddle and Waarts, 2003). Furthermore, all mentioned elements may have dependencies between them. However, within the scope of this paper these are not taken into account. According to Lind (1994), 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:

$$\text{Minimise}: \quad C_{\text{tot}} = C_0(y) + \sum_{j=1} \frac{R_{\text{w}j}}{(1+r)^j} \tag{6}$$

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

Eq. (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. Since the proposed Eq. (6) is a multidisciplinary approach than decision-making on targets for risk acceptance, the WRA becomes a more justified supporting tool in decision-making. Note that ethical aspects are involved implicitly in such comparisons and should, therefore, be carefully considered. Only considering these ethical aspects is the proper way to validate decision-making about risks.

3.3. Monetary values of elements of the weighted risk

The elements of the weighted risk, considered in this paper, 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. It should be noted that these values are depending on local circumstances, which themselves depending on cultural and political aspects of the local policy. Furthermore, these components of the weighted risk analysis may vary very largely. This paper is illustrate how to bring different consequence indicators and, by that, different kinds of risks together.

3.3.1. Monetary value per human saved

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 and 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., de Blaeij, 2003). According to the environmental protection agency, the value of a citizen in the US is approximately €5,600,000. According to Vrouwenvelder (2001), a reasonable value seems €1,000,000, which will be the figure employed as the basis in this paper. de 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 and €11,400,000. An analysis of the valuation of a human life is also discussed by Vrijling and van Gelder (2000). Another method to determine this value is using the so-called life quality index (LQI) (see Lind, 1994; Rackwitz, 2002).

3.3.2. Monetary value for a set of qualities

Rodenburg (2005) 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 paper, however, this condition is eliminated.

3.3.3. Monetary value for environmental space saved

Nyborg (2000) discusses a model of Schkade and Payne (1993), presenting that, based on CVM (contingent valuation) respondents, one would spend about $1000.= (≅€800) per year, per person to protect environmental quality. van den Dobbelsteen (2004) quotes an indicator for the green area preserved (GAP), which is about €4.= per 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 (2000) 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 paper $((€900 - 200) \times 10^6)/(8.5 \times 10^3 \times 150) \cong €550.=$ per m^2.

3.3.4. Monetary value for rent prices

Jones Lang La Salle (2002) provides prime rent prices for offices in multiple use of space projects. These prices vary from €1350.= to €300.= per m^2 per year for Broadgate and Lehrter Bahnhof, respectively. Since the project of the case study of Section 4 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 €9000 per year (see Table 1).

3.4. The weighted risk analysis methodology

Since the approach of Figs. 3 and 4 is particularly associated with the QRA and not with comparing risks with non-safety related elements, this approach is extended with the WRA. This method provides sufficient elements to assess, integrate and evaluate physical safety in complicated 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 (Suddle and Ale, 2005) (see Fig. 5).

3.4.1. 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.

3.4.2. 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.

Table 1
Monetary values of the weighted risk analysis

Aspects of the weighted risk analysis	Monetary values of α_j	Literature
Fatality (α_{human})	€1,000,000–€20,000,000/person	Vrouwenvelder (2001) and de Blaeij (2003)
A set of qualities ($\alpha_{quality}$)	€100/person/year	Rodenburg (2005)
Environmental space saved ($\alpha_{environmental}$)	€4/m^2	By Vogtländer (2001)

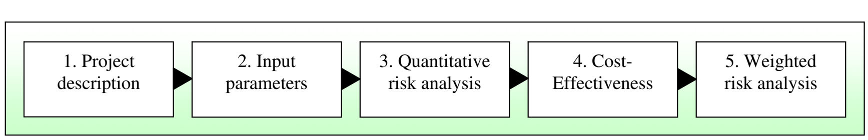

Fig. 5. Methodological steps for dealing with physical safety in multiple use of space projects.

3.4.3. 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 $E(N_d)$.

3.4.4. 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.

3.4.5. 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 the thesis of Suddle (2004) and are demonstrated in the case study of the next section.

4. Case study

4.1. Introduction

This section gives an overview of how to weigh the effect of safety measures with non-financial and non-human risk aspects in the case Bos and Lommer project in Amsterdam (buildings above the motorway A10 West). The elements of the weighted risk analysis, considered in this case, 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 $R_{\text{environmental}}$. The values of the weighted risk are computed with the monetary values per considered risk α_j of Section 3.3. The case study used in this paper contains some data, statements and results of the QRA of the paper presented by Suddle and Ale (2005). The main results of the QRA of the Suddle and Ale (2005) paper were necessary used in this section to conduct eventually the QRA by proposing mitigating safety measures. 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.

4.2. Case study Bos and Lommer

4.2.1. Introduction

The Bos and Lommer office development is part of the development scheme, which centres on the Bos and Lommerplein and the surrounding area. The buildings have a total floor space of 20,000 m^2 distributed over two buildings of six floors each of 9000 and 11,000 m^2, respectively. The fifth floor has been designed as a set-back level with balconies. Commercial functions were planned for the ground floor of the building first (employment agency, travel agents, etc.). The depth of the buildings is approximately 15 m. The construction of this project started in 2001 and was finished 2003. A detailed description of the case can be found in Suddle and Ale (2005) (see Figs. 6 and 7).

According to the QRA approach of Suddle (2004), four interrelations (risk categories) of the different areas should be assessed in multiple use of space projects, influencing the overall safety level and presenting both individual and group risk per risk category (see Fig. 8):

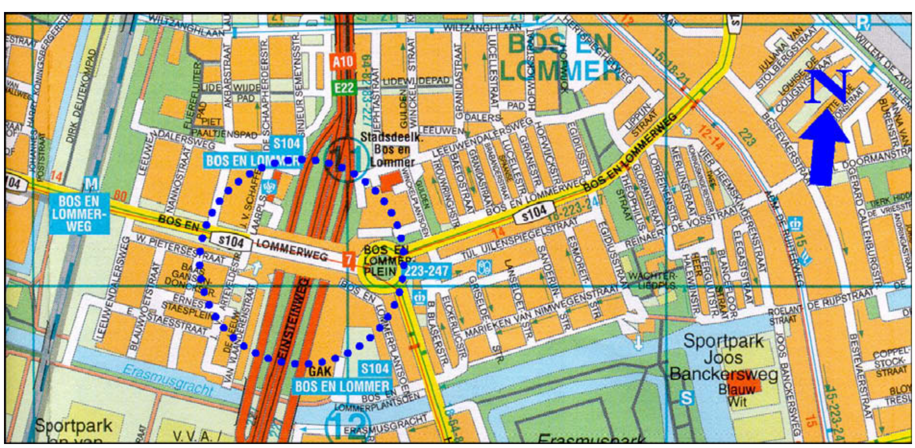

Fig. 6. Map of Bos and Lommer.

Fig. 7. An impression of the Bos and Lommer office buildings with transport of hazardous materials.

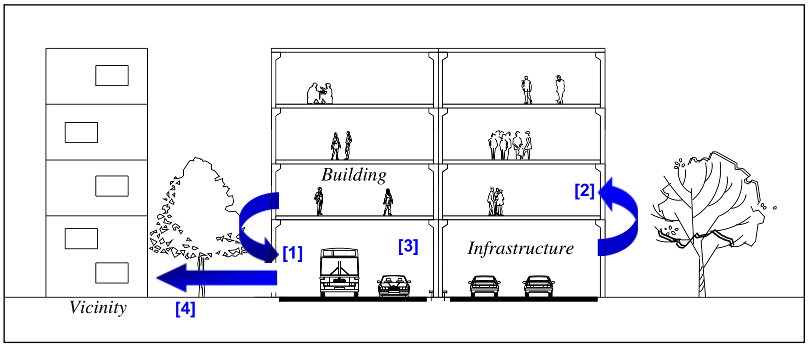

Fig. 8. The four risk interaction categories in multiple use of space projects.

- *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).

4.2.2. Input parameters

Input data for the QRA such as the basic probabilities of events that may occur on the infrastructure with transport of hazardous materials and the quantities of transport of hazardous materials were derived from Hoeksma (2002). The average population density in the vicinity could be determined from AVIV (1997). Table 2 shows the input parameters for the QRA of Bos and Lommer (Suddle and Ale, 2005). The result of the risk analysis is presented in the next section for the individual, group, and economical risk, needed to conduct the WRA.

Table 2
Input parameters for the case Bos and Lommer QRA (Suddle and Ale, 2005)

Input parameters for case Bos and Lommer	
Characteristics of the road	
Type of road	3 × 2 lane motorway
Number of vehicles passed per day	159,000
Ratio of traffic type on the road	91% cars
	8% truck traffic
	1% busses
Transport of hazardous materials per year	36,501 LF trucks
	3664 GF trucks
Ratio transport of hazardous materials per year	0.122807 not hazardous traffic
	0.729123 LF
	0.14807 GF
Covering length	79.5 m
Frequency of an accident	8.30×10^{-8}
Maximum people in the covered infrastructure	100
Characteristics of the building above the road	
Function of the building	Offices
Floor space of the buildings	20,000 m^2
Length of the building	79.5 m
Width of the building	85 m
Height of the building	20 m
Maximum people in the building	800
Characteristics of the vicinity	
Population density	50 persons/ha

4.2.3. Results risk analysis

First, the individual risk IR is computed. Subsequently, the group risk GR is determined, from which the number of people killed $E(N_d)$ per year is derived. The consequences C_{fi} are assumed per scenario. The targets used for the risk are related to IR and GR. These targets are the Dutch criteria for risk acceptance (see, e.g., VROM, 2006). The target for IR is 10^{-6} contour. The target for GR is the GR is rather an indication criterion with a so-called orientation value as decision standard. This criterion is presented in Fig. 10 as the two diagonal lines for external and internal safety.

4.2.3.1. Individual risk. The individual risk can be divided into IR for people present on the infrastructure and IR above the covered infrastructure, which is about 2×10^{-5} and 2×10^{-6}, respectively (see Fig. 8). Table 3 presents the individual risk for the buildings above the infrastructure (per unit building), where the conditional probability of a person being killed due to an "average" scenario is presented (see Fig. 9).

4.2.3.2. Group risk. Likewise, the group risk can be determined for the Bos and Lommer buildings. The FN-curve for this project is presented in Fig. 10.

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

4.2.3.4. Economical losses. The economical risk for the Bos and Lommer building is approximately €300 per year (Table 4). Suppose

Fig. 9. The (schematic) IR contours in the third dimension for Bos and Lommer building (source artist impression: www.multivastgoed.nl).

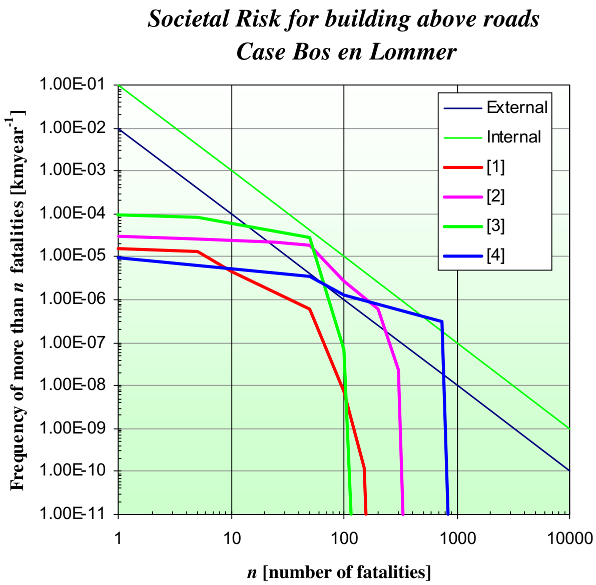

Fig. 10. The group risk for the Bos and Lommer building and the vicinity per risk categories [1], [2], [3] and [4] of Fig. 8 (Suddle and Ale, 2005).

Table 3
The individual risk (death/year/km) for Bos and Lommer (Suddle and Ale, 2005)

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

Table 4
The economical risk for Bos and Lommer (Suddle, 2004)

Covering length	80 m		
Scenario i	P_{fi}	C_{fi}	R
1. Collisions with the structure of the building	1×10^{-6}	1×10^{6}	1×10^{0}
2. Fires	2×10^{-5}	5×10^{6}	1×10^{2}
3. Leak of toxic substances	0	2×10^{4}	0
4. Explosions	3×10^{-7}	5×10^{8}	2×10^{2}
Expected economical loss (€ per year)	3×10^{2}		

that the monetary value per fatality α is set to be €1,000,000.=, then the value of $E(N_d)_{tot} - \alpha$ is equal to €4200.= which is higher than the expected economical loss for this case. This comparison will be made when different measures are implemented for this case.

4.2.4. Cost-effectiveness of safety measures

4.2.4.1. Measures for regulation of transport of LPG. The effect of some measures of the safety chain will be determined in the case Bos and 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. A full overview of calculations of investments etc. is presented in thesis of Suddle [4]. 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 and Lommer project without the transport of LPG is presented in Fig. 10, which is needed to determine the number of people killed per year $E(N_d)$.

From Table 5 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 fourth 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 fourth measure, because the risk reduction of expected fatalities of measures 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 2.9×10^{-3} and 4.2×10^{-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 (Fig. 10) is compared with the FN-diagram of Fig. 11, 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 and Cooke (2001). The FN-diagram of Fig. 11 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)[1], banning the transport of LPG leads to large social losses, i.e., the loss of 4700 labourers, which is approximately a loss of €47,000,000.= (see Suddle, 2004). This amount can also be considered as investments for the labourers losing their work. Furthermore, an important notice of applying measures 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. This case also shows 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 6 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 (saved) α_{human} is very important for

[1] 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.

Table 5
Comparison of economical risk (per year) for different measures in Bos and Lommer

Safety measures	Investments C_0	Economical risk C_i	Total costs C_{tot}	$E(N_d)$
0. Starting situation	–	€300	€300	4.2×10^{-3}
1. Banning transport of LPG	–	€62,000,000	€33,750,000	2.9×10^{-3}
2. Rerouting transport of LPG (not through urban areas)	€55,000	<€300	€55,300	2.9×10^{-3}
3. Transport of LPG through pipelines	€62,500,000	<€300	€62,500,300	2.9×10^{-3}
4. Transport of LPG takes place during the night	€1,062,000	<€300	€1,062,300	2.9×10^{-3}–4.2×10^{-3}

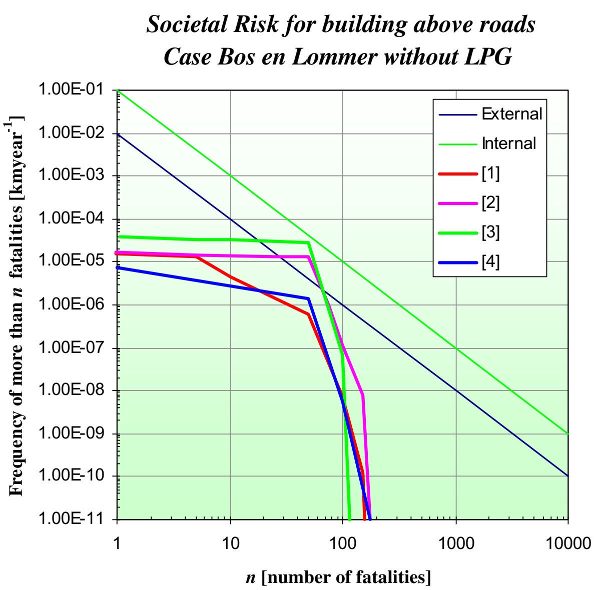

Fig. 11. The group risk for measures 1, 2 and 3 of Table 5 per risk categories [1], [2], [3] and [4] of Fig. 8.

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.

4.2.4.2. Structural and functional measures. 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. 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 larger distance between the infrastructure and the lowest storey and a bigger span, 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 Suddle, 2004). The results of these calculations are presented in Table 7.

Table 7 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 categories [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 Fig. 12). In reality, it does also mean that the $E(N_d)$ for risk categories [1], [2] and [4] is much smaller than 2.9×10^{-3}, so, the effect of $\alpha_{human} \times E(N_d)$ in the weighted risk is almost negligible when an α_{human} of €1,000,000.= is considered.

4.2.5. The weighted risk analysis

Now, we can compare all these measures from non-human related perspectives with the weighted risk, in which the monetary values of Section 3.3 will be used for the different components of the weighted risks (see Table 8). In Table 8, 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 8 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 8 that the safety considerations hardly influence the weighted risk analysis. Even quality and

Table 6
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	4.2×10^{-3}	€4500	€420×10^{3}
1. Banning transport of LPG	€62,000,000	2.9×10^{-3}	€62,002,900	€62×10^{6}
2. Rerouting transport of LPG (not through urban areas)	€55,300	2.9×10^{-3}	€58,200	€345×10^{3}
3. Transport of LPG through pipelines	€62,500,300	2.9×10^{-3}	€62,503,200	€63×10^{6}
4. Transport of LPG takes place during the night	€1,062,300	2.9×10^{-3}–4.2×10^{-3}	€1,065,200	€1×10^{6}

Table 7
Comparison of economical risk (per year) for functional and structural safety measures in Bos and Lommer

Safety measures	Investments C_0	Economical risk C_i	Total costs C_{tot}	$E(N_d)$
0. Starting situation	–	€300	€300	4.2×10^{-3}
5. Fire protection layer for building above infrastructure	€720,000	<€300	€33,750,000	2.9×10^{-3}
6. Explosion resistant building above infrastructure	€11,000,000	<€300	€11,000,300	2.9×10^{-3}
7. Building above infrastructure with small L/D	€5,316,000	<€300	€5,316,000	2.9×10^{-3}
8. Fire protection layer for building above and in vicinity	€80,000,000	<€300	€80,000,300	2.5×10^{-3}

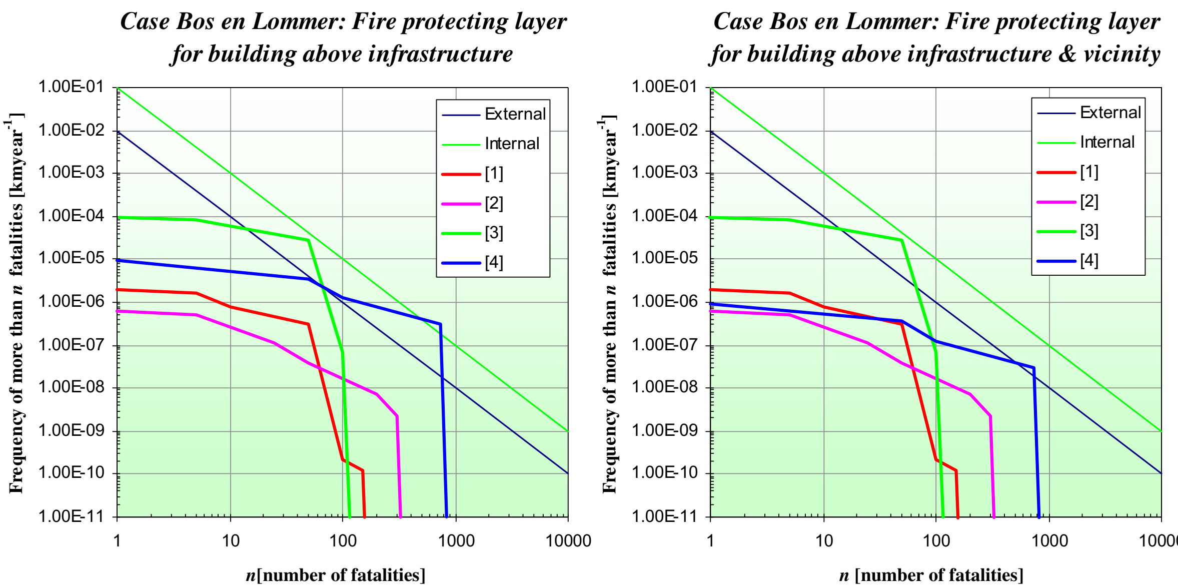

Fig. 12. The group risk for measures 5 (left) and 8 (right) of Table 7.6 per risk categories [1], [2], [3] and [4] of Fig. 8.

Table 8
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 Starting situation	1 LPG Ban	2 Reroute LPG	3 LPG through pipe line	4 LPG during night	5 Fire protection building	6 Explosion resistant building	7 Small *L*/*D*	8 Fire protection vicinity
Investments C_0	0	–	5.5×10^3	6.3×10^7	1×10^6	7.2×10^5	1.1×10^7	5.3×10^6	8.0×10^7
Economical risk C_i	300	6.2×10^7	300	300	300	300	300	300	300
Human risk $E(N_d) \times \alpha$	2.9×10^3	4.2×10^3	2.9×10^3	2.9×10^3	4.2×10^3	2.9×10^3	2.9×10^3	2.9×10^3	2.5×10^3
Quality risk $R_{quality} \times \alpha_{quality}$	-8×10^4	-8×10^4	-8×10^4	-8×10^4	-8×10^4	-8×10^4	-8×10^4	-1×10^5	-8×10^4
Environmental risk $R_{env} \times \alpha_{environmental}$	-1×10^4	-1×10^4	-1×10^4	-1×10^4	-1×10^4	-1×10^4	-1×10^4	-1×10^4	-1×10^4
Benefits	-2×10^6	-2×10^6	-2×10^6	-2×10^6	-2×10^6	-2×10^6	-2×10^6	-2×10^6	-2×10^6
R_w (€ per year)	-2×10^6	6.0×10^7	-2×10^6	6.1×10^6	-1.1×10^6	-1.4×10^6	8.9×10^6	3.2×10^6	7.8×10^7

environmental benefits of such a project vanish in the analysis. The reason hereof might be that the monetary values are assumed too low.

If we consider Table 8 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 min) 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 still negative. This means that according to the weighted risk $R_w = -2 \times 10^6$€·per year, such a situation is beneficial as well in relation to other proposed measures. In fact, the weighted risk $R_w = -2 \times 10^6$€ per year is the highest in comparison with the weighted risk of other measures. 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.

4.2.6. Conclusions

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, 1996) and Vlek and Stallen (1980)). 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 Keten-studies (2003), 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. Therefore, one may assume that the monetary values of the considered elements of the weighted risk analysis might be much higher than used in this case. 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.

5. Conclusions and discussion

First of all, this paper 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. 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. 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. This is made clear by utilising the WRA methodology for the case Bos and Lommer.

Surprisingly, it appears from this case 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 paper, 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 paper, 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.

Other 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 study indicates 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. This could be a very complex task, because the values of the WRA consist of large uncertainties, depending on the scale of the WRA. The monetary value of environmental space can be criticised, since large fluctuations prevail in that value: it ranges between €4.= per m^2 and €550.= per m^2.

By varying this value, the ultimate result of the weighted risk analysis will change completely. As mentioned before, 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. Furthermore, all mentioned elements of the weighted risk analysis may have dependencies between them. However, within the scope of this paper these are not taken into account, but should be investigated in future research.

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