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The Risk Management of Third Parties During Construction in Multifunctional Urban Locations

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Buildings above roads, railways, and existing buildings themselves are examples of multifunctional urban locations. The construction stage of those buildings is in general extremely complicated. Safety is one of the critical issues during the construction stage. Because the traffic on the infrastructure must continue during the construction of the building above the infrastructure, falling objects due to construction activities form a major hazard for third parties, i.e., people present on the infrastructure or beneath it, such as car drivers and passengers. This article outlines a systematic approach to conduct quantitative risk assessment (QRA) and risk management of falling elements for third parties during the construction stage of the building above the infrastructure in multifunctional urban locations. In order to set up a QRA model, quantifiable aspects influencing the risk for third parties were determined. Subsequently, the conditional probabilities of these aspects were estimated by historical data or engineering judgment. This was followed by integrating those conditional probabilities, now used as input parameters for the QRA, into a Bayesian network representing the relation and the conditional dependence between the quantified aspects. The outcome of the Bayesian network—the calculation of both the human and financial risk in quantitative terms—is compared with the risk acceptance criteria as far as possible. Furthermore, the effect of some safety measures were analyzed and optimized in relation with decision making. Finally, the possibility of integration of safety measures in the functional and structural building design above the infrastructure are explored.

KEY WORDS: Bayesian networks; construction sites; multifunctional urban locations; quantitative risk analyses; safety

1. INTRODUCTION

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 used at a growing rate in city centers. These multifunctional urban locations bring with them several safety risks when buildings are being constructed above infrastructure and existing buildings. Activities during the construction stage of such projects form a hazard for people present on infrastructure beneath—called *third parties*—such as drivers, passengers, and other people present on the road beneath, as shown in Fig. 1.[1,2] The reason that third parties are exposed to the risk of construction activities is that the infrastructure under the building is mostly in use while construction activities

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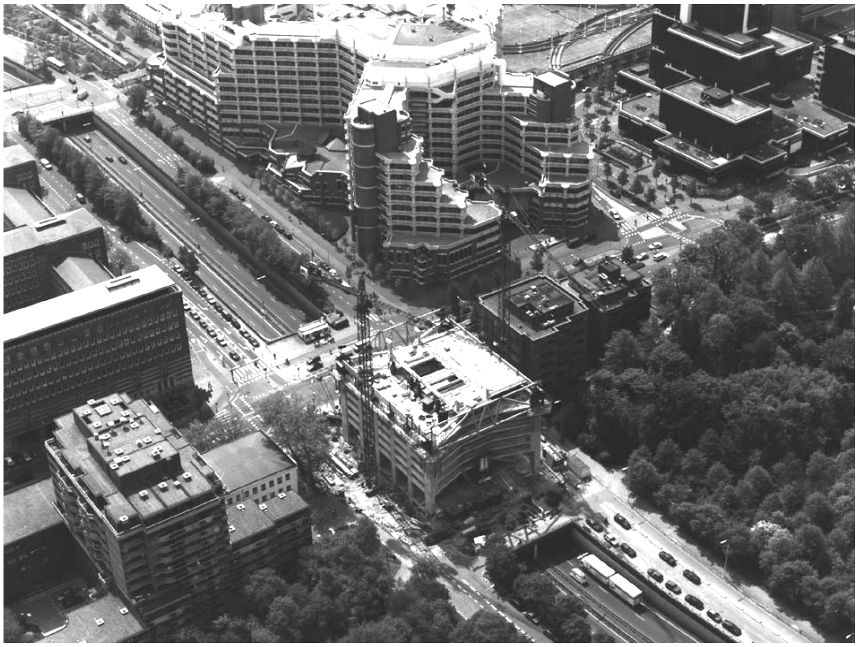

Fig. 1. Construction of the Malie Tower in The Hague.

take place above the infrastructure. These problems are addressed in a detailed case study of multifunctional construction sites by Meijer and Visscher,[2] focusing particularly on process management aspects resulting in safety protocols in multifunctional urban locations, in which the problems with safety aspects in such surroundings were addressed for the first time in organizational terms. In such cases, the safety protocols remain qualitatively based arguments through which the decision making on risks is based upon subjective grounds, since there isn't any insight into the severeness of risks of construction activities. In order to support adequate safety protocols, it is vital to find a workable methodology for assessing the risks quantitatively of third parties due to falling elements in such conditions. This can particularly be handy for decisionmakers because the decision making based on quantitative grounds can be more objective than in case of decision making based on qualitative grounds, through which the decision making can be more rational. In this regard, the cost effectiveness of safety measures can be compared mutually, and subsequently the optimized construction method can be applied in such complex projects. This might lead to different conclusions on which safety measures are preferable. However, if we focus on the safety of third parties during construction activities, neither explicit quantitative risk analysis models nor norms could be found in literature, especially for such projects where building are being built above the motorway.

This was the reason for undertaking an empirical M.Sc. research,[1] which was a part of the Ph.D. research project of Suddle,[3] at Delft University of Technology, in which the methodology of risk assessment of third parties in such conditions during the construction stage was empirically developed, and the quantifications of risks due to falling elements were observed in detail.[1] In this study, probabilistic and quantitative risk analyses were undertaken to assess the safety level and to investigate what safety measures are needed to realize these projects within the boundaries of acceptable risk, as far as these are applicable in such conditions. In the research of Suddle,[1,3] the following risks were considered: human risks (loss of human lives and injuries) and financial risks. Thus, the observations of Meijer and Visscher[2] formed the departure point for a fundamental and empirical investigation of risks due to falling elements in surrounding multifunctional urban locations.[1]

There was little background literature that addressed the problem, i.e., physical safety during construction. Durmisevic[4] addressed the social safety aspects for underground spaces during the exploitation stage. Gambatese *et al.*[5] describes the design's role in construction accident causality and prevention, in which a research is conducted revealing a link between construction site fatalities and the design for construction safety concept. Abudayyeh *et al.*[6] investigated the management's commitment to construction safety, in which the construction-related injuries and illness of construction workers is correlated. Additionally, most studies[5–7] on construction safety focus on regulation and site fatalities rather than quantification of probabilities of falling elements. So, neither studies nor methodologies could be found in the literature assessing physical safety risks quantitatively, nor safety measures for combinations of buildings constructed over infrastructure—a three-dimensional safety system—in densely populated areas, during the construction stage. Visscher *et al.*[8] also provides insight on how to deal with safety issues during general construction projects.

This article will particularly focus on the methodological setup of the QRA model for third parties in multifunctional areas. For this, quantifiable aspects influencing the risk for third parties were analyzed, followed by estimating the conditional probabilities of these aspects by historical data or engineering judgment (Section 2). Subsequently, those conditional probabilities—now used as input parameters for the QRA—were integrated in a Bayesian network, representing the relation and the conditional dependence between the quantified aspects. The outcome of the Bayesian network is the calculation of both the human and financial risk in quantitative terms. In Section 3, the results of the QRA are compared with the proposed risk acceptance criteria. Section 4 discusses the verification of the QRA parameters by means of sensitivity analysis. Section 5 focuses on the effects and costs of safety measures and the decision making on the base of financial backgrounds. These measures can be integrated in the functional, architectural, and structural design of the building (Section 6). Finally, the conclusions are set out in Section 7.

2. QUALITATIVE RISK ANALYSIS

In order to quantify the risks in such projects and to determine the effect of variable parameters on the entire risk, it is essential to set up virtual and schematic case studies. The height position of the infrastructure situated at the ground level is an assumption made for the risk analysis models (see Fig. 2). The standard case will be used as a central object in this article and is drawn up for realizing buildings above roads. It is assumed that the building above the road consists of 10 storys and is built above a 2 × 2 lane motorway. The span (width) and the length in the linear direction of the building are 20 and 50 m, respectively (see Fig. 2). The following subsection presents the methodology of risk assessment for third parties due to falling elements in multifunctional urban locations.

2.1. Qualitative Risk Analysis

A qualitative risk analysis for the safety of third parties has been performed by failure mode and effect analysis (FMEA) techniques, representing a complete overview of hazards and consequences for the construction of a building above a motorway. Normally, a FMEA contains an evaluation of effects of failure like cost increase, time loss, loss of quality, environmental damage, and loss of human life. For this study, both the risk regarding cost increase and the risk regarding loss of human life are taken into account. Vrouwenvelder[9] suggests that the FMEA should be performed for all activities during the construction stage, such as ground excavations, fabrication of elements, transport of elements, removal of temporary structures, etc. In this research, however, because of the risk assessment of these activities to third parties, only particular activities on the construction site are considered in the FMEA. A section of the FMEA is presented in Table I. It can be concluded from the FMEA that the main risks to third parties during construction is due to *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, organizational failures, problems with soil stability, and so forth. However, these scenarios were not taken into account, considering the scope of this article.

2.2. Quantitative Risk Analysis

The observation of falling elements, which may cause casualties among people present at the infrastructure and in some cases economic risks as well, was analyzed in detail by a quantitative risk analysis using Bayesian networks for the case study of Fig. 2.[1] A Bayesian network is a graphical tool that represents the relationship between a set of variables and a set of directed connections between variables,[10,11] which can then be divided into events

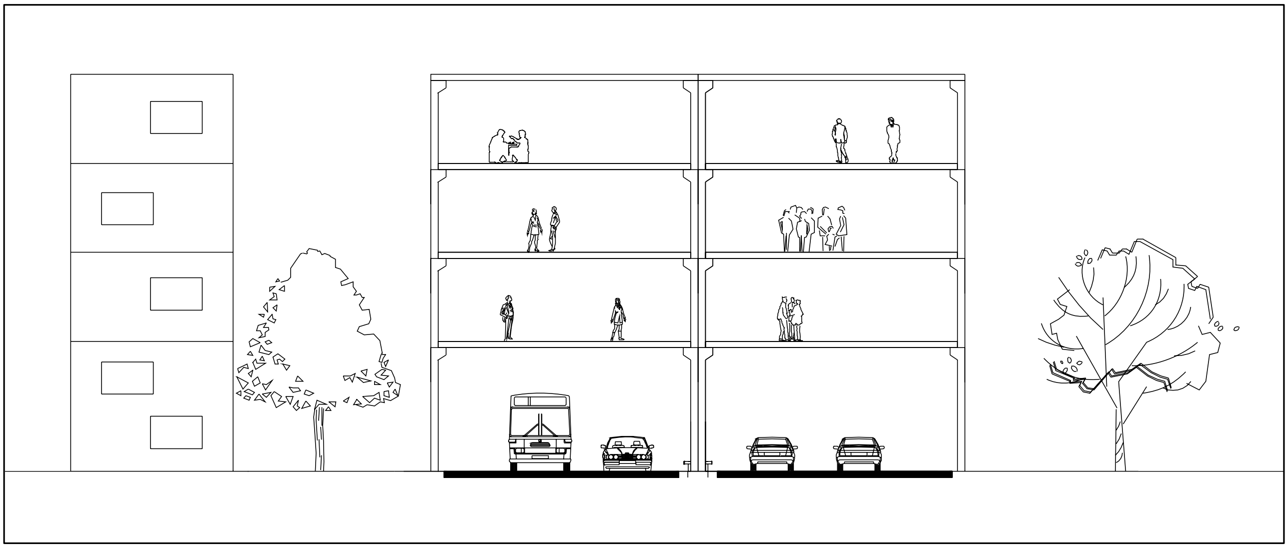

Fig. 2. Case study; building above 2 × 2 lane motorway.[2]

Table I. An Example of a Section of the FMEA for Safety of Third Parties During Construction (Adapted from Reference 3)

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

and consequences. A Bayesian network consists of a set of nodes and a set of directed arrows, each node representing a probability distribution. The major advantage of Bayesian networks is that these networks can replace and compact both traditional fault trees and event trees in one model.[12] According to Friis-Hansen,[13] the potential of a Bayesian network is that it is an intuitive modeling tool, partly based on artificial intelligence but adding transparency and consistency to the models, therefore making it an interesting tool for this research. 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 and the FMEA (Table I). These quantifiable aspects, considered in Bayesian networks, are as follows:

(1) the position where the element falls (inside or outside the building);
(2) the situation below the building;
(3) (design) errors;
(4) the weight of the falling element;
(5) the actions of elements in relation with installation of elements;
(6) the collapse of the main structure of the building caused by falling elements;
(7) the probability of elements falling;
(8) the height from which the element is falling;
(9) fatalities; and
(10) economic risk.

Each of those aspects represents a node in these networks (see Fig. 3). Each node is divided into categories corresponding with events of that node. The

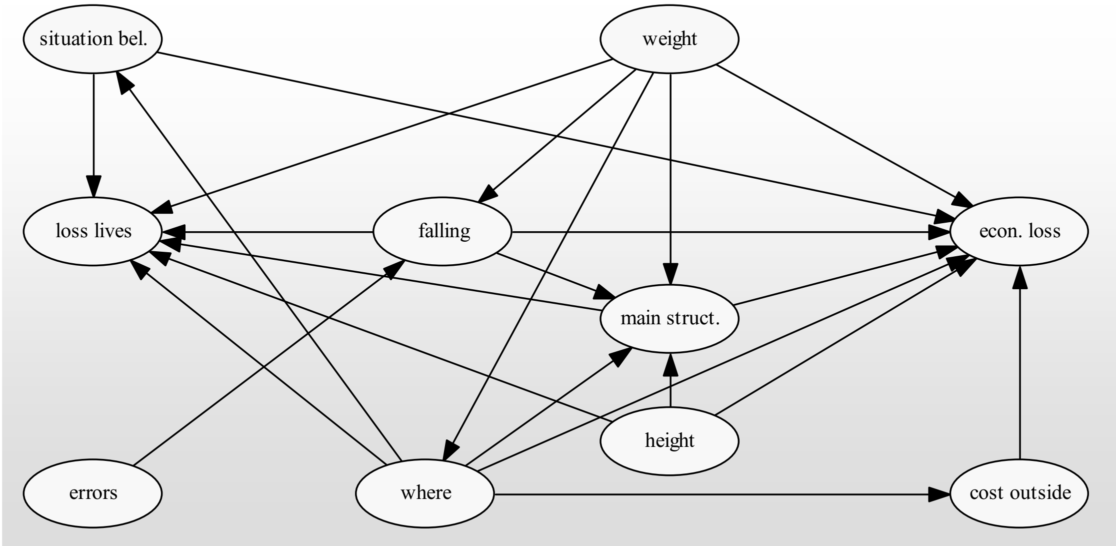

Fig. 3. Bayesian network for building above roads for construction stage.

Table II. 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}

relationships between the nodes are connected with directional arrows, which specify the probable influence between these nodes. Fig. 3 shows the relationship 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 relationship 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 judgment. In some cases, especially cases for which historical data are unavailable—such as the probability of elements falling—an expert opinion or an (in-house) engineering judgment is used. The failure probability is determined using the likelihood of the occurrence of hazardous events along with different probabilities (see Table II). The determination of consequences of hazardous events is based upon either calculations or the order of magnitude of severities of events. The next section will give an overview of how the conditional probabilities are determined. It is assumed for the case studies that the duration of the project is exactly one year. More details on the quantification of these probabilities can be found in Suddle.[3] Some data of Abudayyeh *et al.*[6] are used for the setup of the QRA. It must be noticed that quantifying the effect of safety measures can also be implemented in and verified by the Bayesian network of Fig. 3 by adding a node (e.g., protection canopy/shelter) or changing conditional probabilities between these nodes. Logically, changes exert influence on the economic risk as well as the risk for loss of human lives.

2.3. Quantification of Probabilities

2.3.1. *(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 II.

2.3.2. *The Situation Below the Building and the Probability of Hitting a Car*

When computing the probability that a third party is hit by a falling element, it is relevant to know the situation below the building. The situation below the building corresponds to 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 $A_{cars}/A_{building}$ (see Fig. 4). The assumption is based upon the condition in which the cars fit under the building in normal conditions at daytime. In the considered case, an assumption has been made that there are 15 cars present on average below the building and each car is 13 m^2 ($\approx 15 \times 13 = 195$ m^2). Also, $A_{building}$ is equal to $20 \times 50 = 1{,}000$ 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. These conditional probabilities depend on the place where the element falls; this may be under the building (due to progressive collapse of the building) but also at the begining or the end of the building. The ratio of element hitting in the center of the building and at the both ends of the building is discussed in the following section.

2.3.3. *The Position Where the Element Falls (Inside or Outside the Building)*

The position where the element falls depends on the footprint area 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 Fig. 3, the analysis comes to the following: the value of risk zones outside the building is estimated to be 2 m outside of the façade of the building (see Fig. 4). By this, the value of $A_{outside1,2}$ can be calculated: this is $2 \times (2 \times 50 + 2 \times 20) = 280$ m^2. The area of the footprint of the building $A_{building}$ is equal to $20 \times 50 = 1{,}000$ m^2. Hence, the probability *P*(*element falls outside or inside the building* | *element falls*) is equal to 280/(1,000 + 280) = 0.21875. If only the risk of people present on the infrastructure has to be taken into account, then $A_{outside1}$ is equal to $2 \times (20 \times 2) = 80$ m^2. The probability *P*(*element falls outside or inside the building* | *element falls*) is in this case equal to 80/(1,000 + 80) = 0.0741.

2.3.4. *The Weight of the Falling Element*

In order to investigate the effect of a falling element, five different weight classes (of falling elements, that are used in the building) are formulated (Table III). These five different weight classes

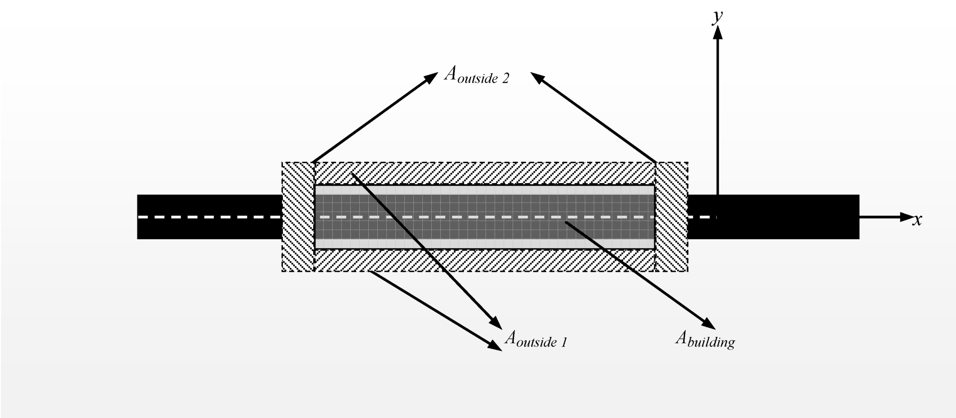

Fig. 4. The building footprint area and the footprint area of risk zones outside the building.

Table III. 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. 100–1,000 kg	Structural elements for the façade construction, equipment, etc.
IV. 1,000–10,000 kg	Structural elements, beams, hollow core beams, heavy equipment, etc.
V. >10,000 kg	Heavy structural elements, main structure of the building, etc.

are chosen on the basis of a logarithmic approach, which is common in risk analysis, as discussed and demonstrated by Vrouwenvelder.[9] It should be noticed that small elements of the weight class I (<5 kg) are generalized to simplify mathematically the QRA. In this regard, extreme small elements—such as dust or grain of sand—are not even considered in the QRA. For the considered case, the elements of the building are classified into these weight classes.

2.3.5. The Actions with Elements in Relation with the Assembly of Elements

It is not only the weight class but also the actions per element of the weight class that determines the risk to third parties, 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 Fig. 1, in which the classification of Table III is used. Extremely small elements can be found during construction. However, not all small elements always have large consequences; for example, a concrete part of 1 mm. On the other hand, a falling screw, e.g., may result in serious injury or even death, while having average less number of actions per element. Therefore, limited risky elements are taken into account for the setup of the QRA, especially for the weight class <5 kg. Large elements of the weight class > 10,000 kg (main bearing structure) are not much implemented in the project, but have more actions needed for installing such an element in the building. Subsequently, this distribution is transformed into the distribution of the actions per element of each weight class (see Table IV and Fig. 5, left). 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 story of the building. It is assumed that elements of the façade structure are prefabricated elements of 1×1 m^2.

2.3.6. 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. Ten experienced professionals 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 II). The experts varied from scientists specialized in construction technology in multifunctional urban projects to construction workers. Their opinions regarding the probability of failure correlated with each other; the smaller the element, the higher the probability that an element falls (an inverse exponential increase). This is presented in Fig. 6. Subsequently, since there was a strong correlation between the probabilities of the experts, the average probability of elements falling per weight class per project is derived as shown in Fig. 7.

Table IV. Distribution of Elements and Distribution of Actions per Element[1]

Weight Class	The Number of Risky Elements per Story	Total Number of Elements	Distribution of Elements	Actions per Element	Total Actions	Distribution of Actions per Element
I. <5 kg	500	5,000	0.1753	1	5,000	0.055
II. 5–100 kg	1,520	1,5200	0.5330	3	45,600	0.498
III. 100–1,000 kg	700	7,000	0.2454	3	21,000	0.229
IV. 1,000–10,000 kg	129	1,290	0.0452	15	19,350	0.211
V. >10,000 kg	3	30	0.0011	20	600	0.007

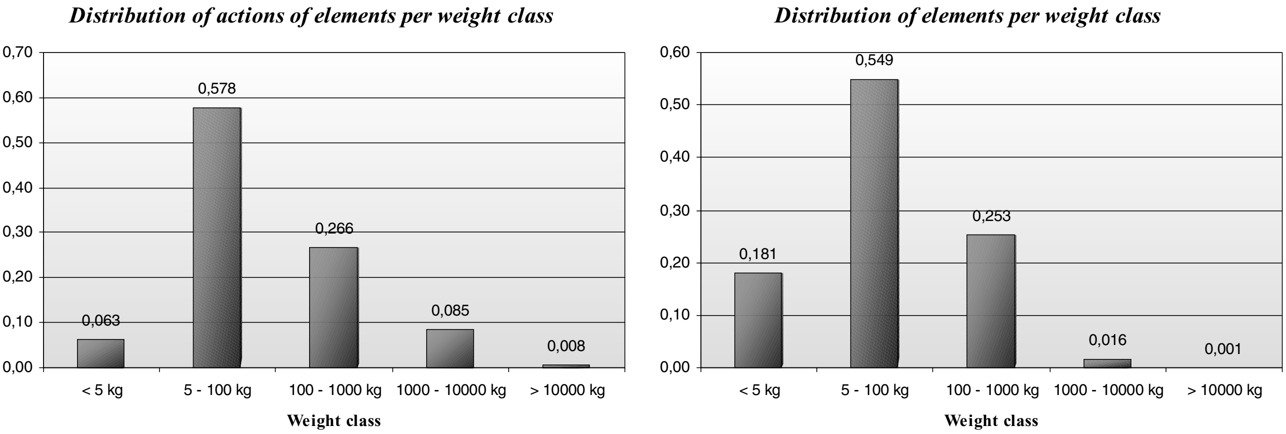

Fig. 5. Distribution of elements and distribution of actions per element.(1)

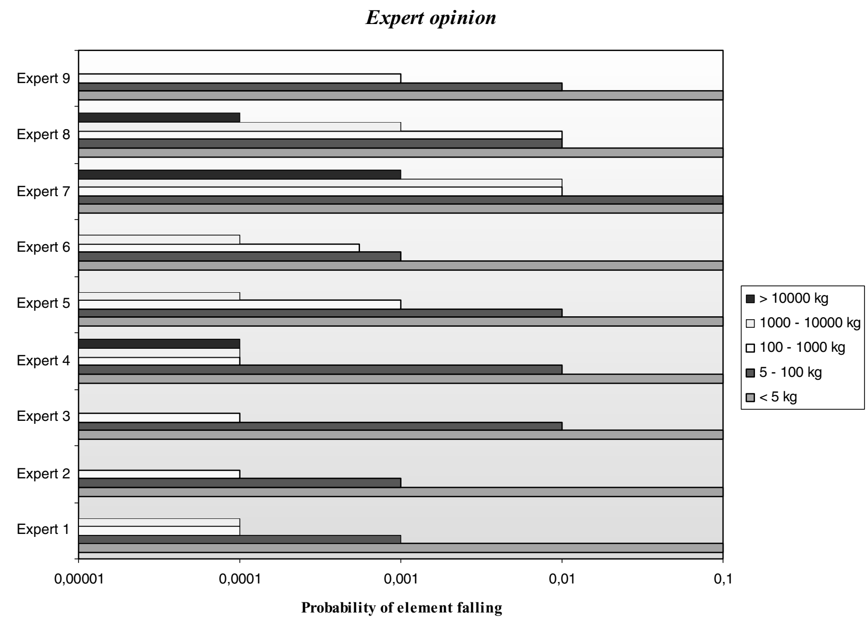

Fig. 6. Results of expert opinion for probability of an element falling.

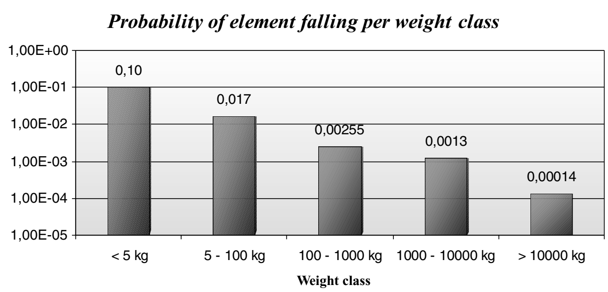

Fig. 7. The average probability of element falling (action^{-1}), according to case study of Fig. 2.(3)

2.3.7. The Collapse of the Main Structure of the Building Caused by Falling Elements

The load-bearing structure of the building will collapse only 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 judgment, laws of mass, and impulse. A logical assumption has been made that the heavier the element (class) and the higher the drop, the higher is the probability that the

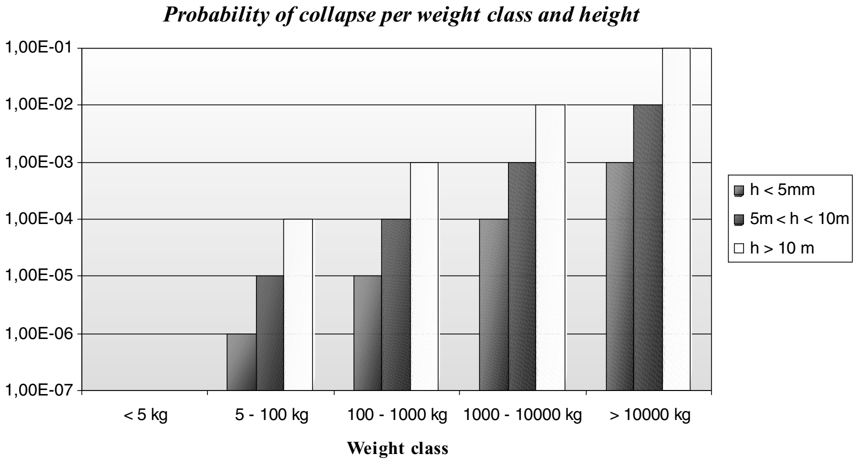

Fig. 8. The assumed probability of collapse of the building due to elements falling inside the building.[1]

building collapses due to the falling of an element inside the building (see Fig. 8).

2.3.8. *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 compared with the height of the building. Three different height levels are proportionally considered: $h < 5$ m; 5 m $< h <$ 10 m; and $h > 10$ m. For the considered case in which the height of the building is 50 m, the proportions are set to be 0.1, 0.1, and 0.8, respectively.

2.3.9. *Fatalities and Economical Risk*

The probabilities of the node "fatalities" are determined by using the conditional probabilities used in Reference 14. The report of the Ministry of Spatial Planning[14] describes the effects on people subjected to the phenomenon of an explosion. One of the subscenarios of an explosion might be the launch of fragments. In this regard, the survey[14] presents the phenomenon blast and whole body displacement; pressure-impulse graphs are given to determine the probability of survivability. It has to be noted that *P*(*person being killed* | *an element falls on a person*) is almost 1 even if an element is less than 5 kg (see Fig. 9). 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.

The probabilities of the node "economical risk" are determined by engineering judgment. The node "fatalities" is divided into injury and loss of life.

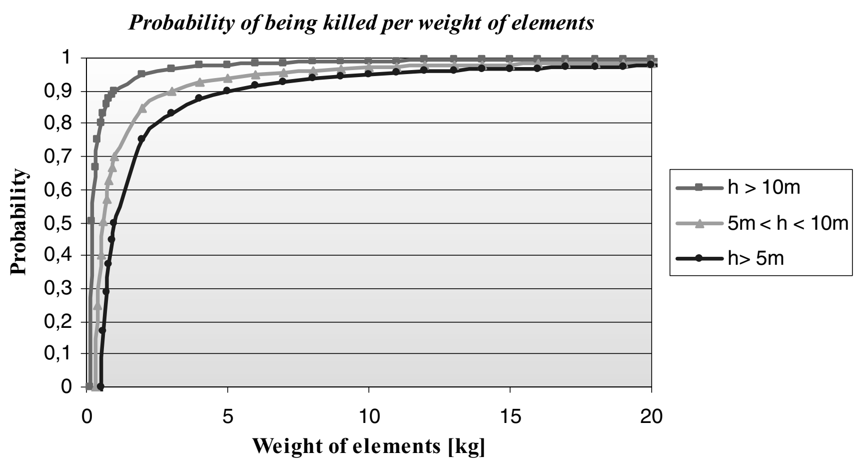

Fig. 9. The probability of being killed due to a falling element.[14]

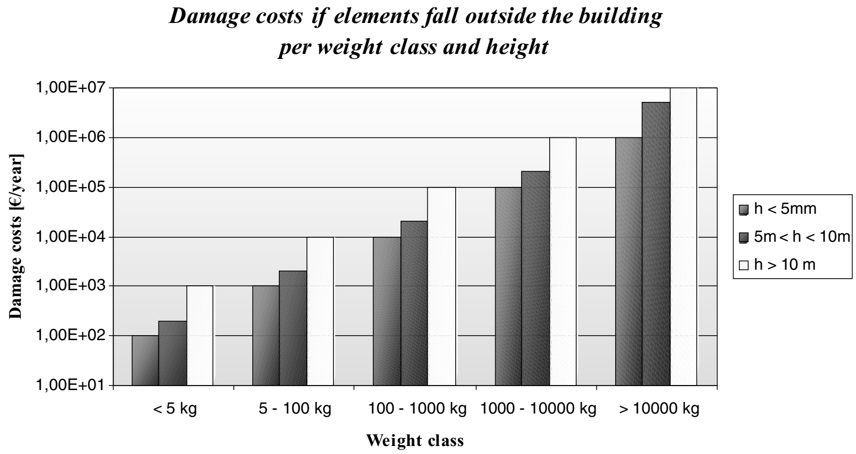

Fig. 10. Damage costs if element falls in the risk-zones of the building.

Table V. 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.

Table VI. The Individual Risk of Third Parties, the Expected Loss of Human Life, and the Expected Injuries Due to the Falling Elements of the Building Above Roads [year^{-1}]

Building Above	Roadway
Individual risk (IR)	$3.0 \cdot 10^{-6}$
Expected loss of human life ($E(N_d)$)	1.65
Expected injuries	5.46

Economic damage mainly depends on, e.g., closing of the road for a long period of weeks due to the collapse of the building above. In this regard five different cost classes (of economic risk) were considered, and the effect of elements falling in the risk zone is determined (Table V). It is assumed that the economic damage increases logarithmically when the weight class is increased. The falling of small elements, such as screws, could hardly cause high costs, while the falling of large concrete beams may cause high costs because of the possible large recovery time of the infrastructure (Fig. 10).

3. RESULTS OF QUANTITATIVE RISK ANALYSIS

3.1. Individual Risk

Three types of risk outcome for the third parties are considered in Table VI: (1) the individual risk per year IR; (2) the expected number of deaths per year $E(N_d)$; and (3) the expected yearly injuries (see Table VI). The risk calculated from the Bayesian network of Fig. 3 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 needed for the construction of the building during its construction period of exactly one year. Subsequently, the individual risk IR is determined by multiplying the computed risk with the total presence time of a considered person per year. The expected loss of human lives $E(N_d)$ is computed by multiplying the individual risk IR with the number of participants per year (555,000). The calculation of the expected yearly injuries is done in the same manner as the individual risk IR. Final risk results of the three early mentioned types of risk are presented in Table VI. It should be noticed that the presented figures in Table VI are more an indication for the virtual and schematic case used in this study. Besides, the results present more the methodology of the quantitative risk analysis, rather than exact results.

Furthermore, the schematic individual risk contours at the construction site can be depicted on a two-dimensional map (Fig. 11). It becomes clear that the individual risk for third parties in the neighborhood of the constructed building is the highest, especially in the so-called risk zones.

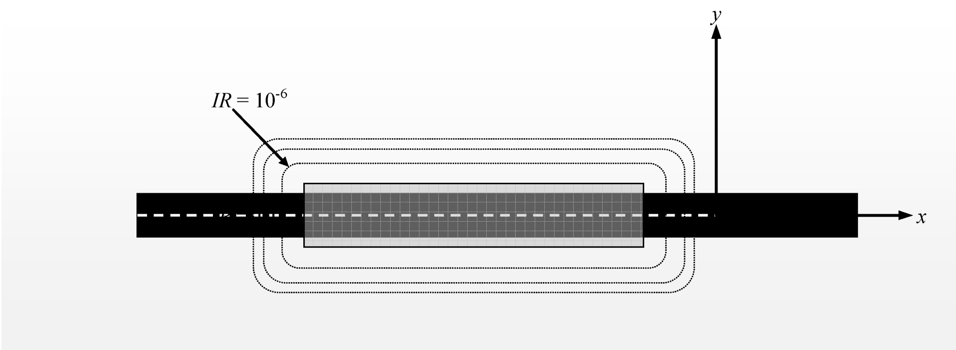

Fig. 11. Schematic risk contours during construction stage for building above road.

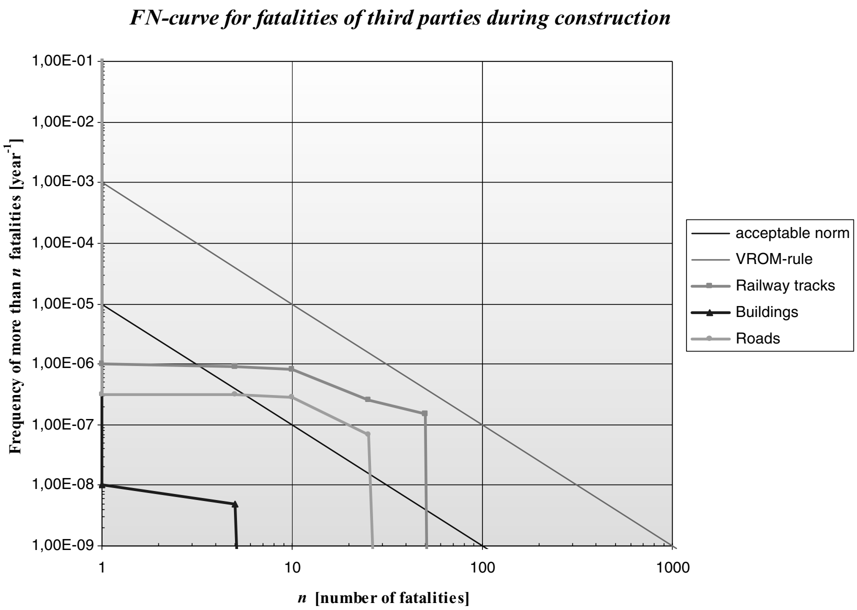

Fig. 12. Group risks of building above transport routes.

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 Fig. 12.[3] This figure shows that the group risk for construction above roads.

3.3. Checking for Compliance with Limits of Risk Acceptance

Until now, explicit norms of risk acceptance for the safety of third parties during construction have not been made.[3] It should be noted that the determination of the exact risk acceptance level is a political issue. The method discussed by Vrijling *et al.*,[15] which is based on voluntariness, is used as an indication for the criteria of individual risk *IR*. The risk acceptance criterion target for individual risk *IR* according to that method is assumed to be 10^{-6} per year. When considering these acceptance limits for risk acceptance, the results of the individual risk *IR* for the case study of Fig. 2 are slightly exceeded. Therefore, safety measures are analyzed and optimized for the virtual case of Fig. 2.

3.4. Economical Losses and Comparison with Human Risk

The comparison with economical risks and human risks is to demonstrate a possible methodology of weighing risks as a supporting tool for rational decision making, rather than considering ethical aspects. The economical losses can also be computed by multiplying the risk per action, obtained from the

Table VII. Comparison of Human Risks and Economical Losses $E(C_j)$ Including a Monetary Value per Fatality

Building Above	Roadway
$E(N_d)$ (fatalities/year)	1.65
$E(N_d) \times \alpha$ (€/year)	1,650,000
$E(C_j)$ (€/year)	945,000

Bayesian network of Fig. 3, with the total number of actions. The results of economic losses are presented in Table VII. In the same table, the human risks are compared with the economic losses, for which the monetary value per fatality α is assumed to be €1,000,000, which, according to Vrouwenvelder,[9] is a reasonable value. It becomes clear that the expected economic costs are less of a concern than the expected loss of life. So, one may assume that when optimizing safety measures, the investment 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 optimization.

4. SENSITIVITY ANALYSIS

In order to investigate the most influencing parameters regarding the result of the risk of the third parties in the QRA, a sensitivity analysis is performed to formulate safety measures and determine their effects. In the sensitivity analysis, the combination of quantified probabilities was varied from a minimum of 0 to a maximum of 1. As a result, some nodes of the Bayesian network of Fig. 3 were hardly influenced and some fluctuated considerably, through which the sensitive parameters could be derived. The sensitivity analysis provides both transparency of relevant scenarios and variance 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; and (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 Fig. 11). 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 judgment. 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 relationship between the height of the building and the individual risk IR is presented in Fig. 13. This figure presents that the higher the building is, the higher is the individual risk of third parties. It also means that the higher the building is, 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 its construction stage. Details of the sensitivity analysis can be found in Reference 3.

5. RISK MANAGEMENT AND OPTIMIZATION OF SAFETY MEASURES

5.1. Formulation of Safety Measures

When considering the cost effectiveness as the basis for ascertaining measure taking and

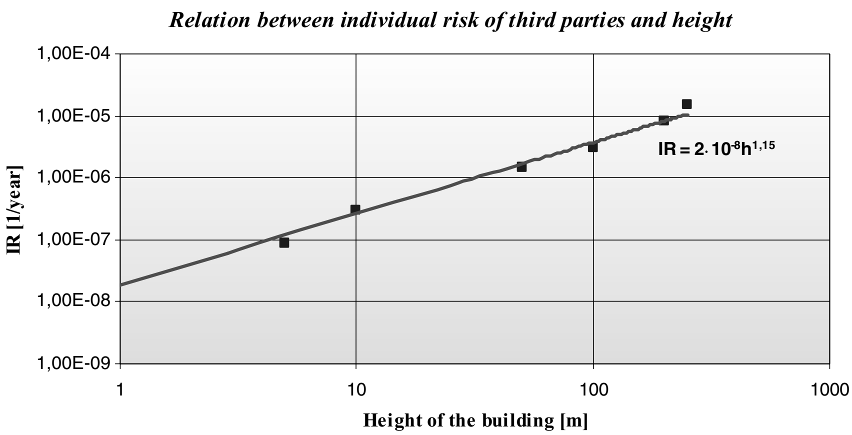

Fig. 13. The relation between height of the building the individual risk of third parties.[3]

decision making, financial aspects should be taken into account besides human risks. As a result, investments C_0 of safety measures must be calculated along with their economic risk C_i and compared with expected loss of human lives $E(N_d)$, monetarized or not, depending on the origin of the decision-maker. In this research we considered seven types of measures, and per measure we determined the total costs $C_{tot,}$, consisting of investments of safety measures C_0 and their economic risk C_i (direct and indirect), combined with the expected loss of human lives $E(N_d)$. In fact, the seven measures presented in Table VIII 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; measures 1, 2, 3, 6) and *logistic measures* (such as closing off the road and rerouting the traffic; measures 4, 5, 7).

The formulated measures are implemented in and verified by the Bayesian network of Fig. 13 by adding a node or changing conditional probabilities between these nodes in the original Bayesian networks of Fig. 3. 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 VIII. An example of implementing such a measure (a shelter/protection canopy) in a Bayesian network is presented in Fig. 14.

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.

Table VIII. 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

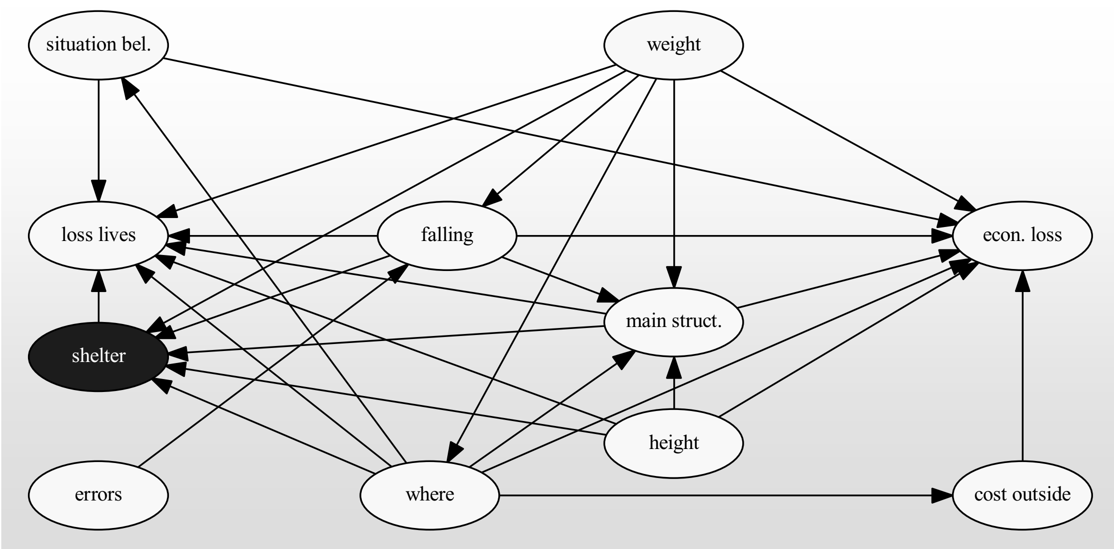

Fig. 14. The safety measure shelter integrated in the original Bayesian network.

However, this methodology brings about an interesting and complex point of controversial decision making from different perspectives, i.e., human based, economical based, or combination of both. To balance and optimize these measures, human risks can even be monetarized by using a monetary value per fatality or injury saved. A reasonable value per fatality saved seems to be €1,000,000.[9]

5.2. Decision Making on Safety Measures

Considering the safety measures of Table VIII, the decisionmaker, 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 minimizes 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 minimizing economical grounds only, 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 VIII—closing off the road and rerouting the traffic—or measure 4—construction during the night—the expected number of lost human lives $E(N_d)$ can be reduced to almost zero; this is because a very small number of people are exposed to the effects of falling elements (small numbers of participants N_{pi}). Unfortunately, the total costs C_{tot} of such measures are relative high because the investments of 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 VIII), through which the number of actions of lifting, moving, and elevating (structural) elements can be minimized. Applying measure 6 means that the human risk in terms of number of loss of human lives $E(N_d)$ can also be reduced compared with the initial situation (case study, measure 0). In the initial situation, it is assumed that no support floor or protection canopy is applied for interrupting falling elements, and a hollow core slab floor is implemented as floor system for the building. Unfortunately, compared 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 (nonstructural) 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 measures 2 and 6 (heavy concrete floor under the building and pumping concrete to the floors).

Another valuable tool to present the difference between the safety measures for the decisionmaker is to plot a scatter diagram, in which the risk-reducing effect of a safety measure is presented along with the costs of that safety measures. The risk-reducing effect is the difference between the $E(N_d)$ value per measure minus the $E(N_d)$ value of the initial situation (1.65). This gives us Fig. 15.

Decision making is even more complex than presented both in Table VIII and Fig. 15. In order to present the complexity of decision making on economical or human risk base, it is interesting to compare human risks and economical risks in one utility or dimension. It depends on the decisionmaker which kind of decision element he or she prefers in the decision-making process. Although the human life and economic impacts are noncommensurate metrics, it is interesting to compare them in one dimension, e.g., varying the human value α from €500,000 to €5,000,000. This phenomenon becomes a multi-objective optimization and is, in this article, done to present the complexity of decision making. In this regard 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 = €500,000 and €5,000,000, respectively, as shown in Table IX. 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.

6. FUNCTIONAL INTEGRATION OF MEASURES

The combination of both the formulated safety measures of Section 5.1 and the hesitation of decisionmakers 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 realize for the contractor.[3] However, one

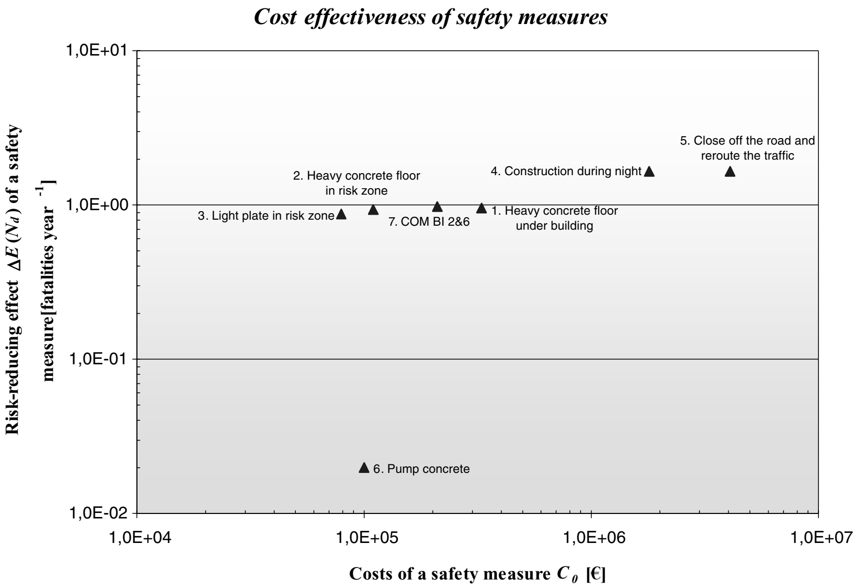

Fig. 15. A scatter diagram in which the risk-reducing effect of a safety measure is compared with costs of a safety measure.

Table IX. Solutions for Safety Measures; Their Investments and Their Risks

Safety Measures	(Sub)Total Costs C_{tot} if$_t$ (€) $\alpha = 0$	$E(N_d)$	Total Costs if$_t$ (€) $\alpha = 500{,}000$	Total Costs if$_t$ (€) $\alpha =$ € 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

should strive to balance these extreme and almost not realizable 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 5.1) 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.

Some examples should be mentioned that allow 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 realize 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 danger to third parties in the construction stage is minimized. 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

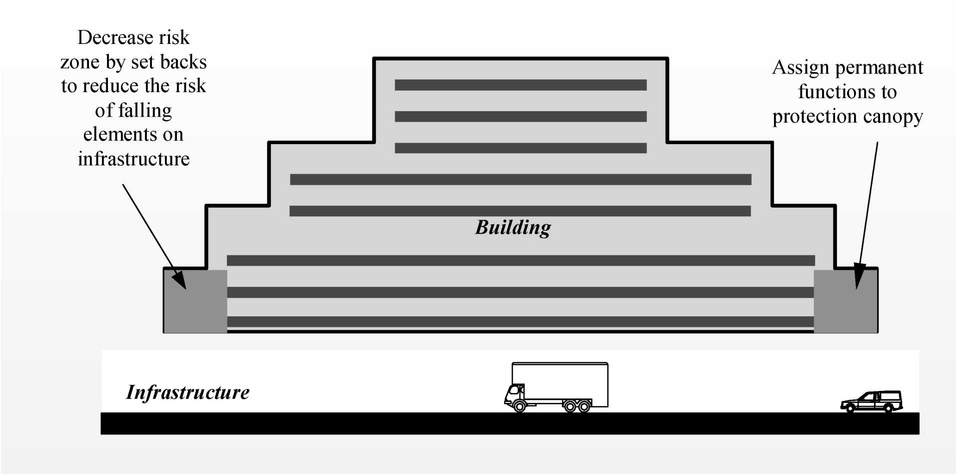

Fig. 16. Improvement of the safety of third parties can be realized by set backs in the shape of the building.[3]

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 Fig. 16). 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 realized.

Another practical measure is to implement several permanent support floors in the risk zones or the lower storys and assign 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 of Section 5.2 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 of removing the protection floor after the construction.

7. CONCLUSIONS AND DISCUSSION

Although the construction stage of multifunctional urban projects is quite short compared with the lifetime of a project, falling objects from the building above the infrastructure due to construction activities are a major hazard for third parties, i.e., car drivers and passengers. In this regard, a systematic approach to conduct quantitative risk assessment (QRA) and risk management of falling elements for third parties during the construction stage of the building above the infrastructure in multifunctional urban locations is outlined in this article. Due to a lack of historical data of conditional probabilities, the QRA is empirically set up in this article. It appeared that quantitative risk analysis by means of Bayesian networks is an outstanding approach to determine and model the risks of falling elements to third parties during construction. For this to happen, data were collected and transformed into conditional probabilities of scenarios and followed by the set up of the risk analysis model in Bayesian network. According to the sensitivity analysis of the Bayesian network, the dominant aspects for risks of third parties were (1) the number of actions per project, (2) the position where the element falls, (3) the situation below the building, and (4) the weight of the falling element.

In order to prevent the consequences of the falling objects from the building to the infrastructure, the implementation of safety measures is inevitable. Safety measures can be implemented from a *structural/functional* point of view (such as applying different types of a protection canopy to prevent falling elements ever reaching the third parties) or *logistic measures* (such as closing off the road and rerouting the traffic). The main question of implementing these measures is: Which is the most cost-effective measure, i.e., less investments and large risk-reducing effect? This means that decision making on safety measures involves different points of views, such as people killed or injured and (in-)direct economical losses. Depending on the nature of the decisionmaker, the decision can be based on human grounds or economical grounds or even the combination of these two, in which the cost-effective safety of safety measures should be considered. Even combining these two entities in one cost-unit, e.g., money, gives different optimized solutions for implementing safety measures. This multi-objective optimization implicitly becomes the issue of what the investment for saving a human life is. The optimized solution of safety measures depends on the origin of the decisionmaker: the higher is the value added for a human life saved, the lower the risk for third parties is. A lower value for a statistically human life saved results in a more economical solution of implementing safety measures. This article shows that minimizing the total costs or the investments in safety measures does not always provide maximum safety for third parties. This means that decision making on safety measures is complex. In this regard, the risk-reducing effect of a safety measure should be weighed with the investments of safety measures.

It is, therefore, strongly recommended from a design point of view that the risk-reducing effect of 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. It should be stated that integrating such measures in the architectural and functional design of the building results in an extra synergetic effect, through which safety is approached from an integral design point of view. This new concept can be called safety integrating design engineering.

Finally, it should be stated that norms for risk acceptance are required for the construction stage for implementing safety measures. Quantitatively based norms are needed for a more objective decision making, through which the decision itself becomes more rational than in case of qualitative base grounds. Quantitatively based arguments may consist of analyzing the risk-reducing effect of safety measures along with its costs. Such norms might be a starting point for, e.g., the applied construction method, which is currently based upon the contractors' experience. Norms may also help the municipality with additional requirements of the contractors in terms of guidelines, such as the construction method and required safety measures. The norms may also suggest that the architect make a safety integrated building design. By this, the level of safety and the cost effectiveness of safety measures can be determined quantitatively, needed for safety protocols during construction of such complex projects.

Last but not at least, it should be noticed that the results presented in this article could vary if the "same" QRA is conducted for another case spanning a by-pass. The result may also differ if more expert opinions were considered, and if their opinions would be different than those presented in this article. However, the main objective was to set up a QRA model rather than to investigate the uncertainties of large number of experts.

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