Quantitative risk analysis as a supporting tool for safety protocols at multi-functional urban locations

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Abstract

Purpose – The aim of this paper is to provide insight into how to deal with safety issues during construction projects at multi-functional urban locations.

Design/methodology/approach – A case study comprising several construction projects for high-rise buildings over a motorway in The Hague provided insight into the complexity of the safety management. A process model was designed of moments of influence of safety measures. This was combined with quantitative risk analyses of some alternative safety measures using failure mode and effect analysis and Bayesian networks.

Findings – It is essential to put safety management on the agenda at a very early stage in the planning process for construction projects at multi-functional urban locations. The erection of heavy structural elements when building activities are being carried out above a motorway is an important risk factor. Structural measures appear to be more cost-effective than closing off the road.

Research limitations/implications – The methods used to develop insight into the cost-effectiveness of different safety measures can also be applied to construction processes at multi-functional urban locations. This might lead to different conclusions on which measures are preferable.

Originality/value – There is very little literature or general knowledge on how to deal with these safety issues. This paper provides a method that can be applied in the development of safety protocols at multi-functional urban locations.

Keywords Construction works, Safety, Buildings, Control, Urban areas, Risk analysis

Paper type Research paper

Introduction

The building projects in most of the major cities in The Netherlands intensify the use of urban space and hence lead to the further integration of urban functions. These projects slot in neatly with the policy of the Dutch Ministry of Housing, Spatial Planning, and the Environment (MVROM) to realise multi-functional urban locations which will bring economic and social vitality to the cities. However, when these projects are being prepared, developed and implemented, complications may arise which are connected with safety guarantees on the one hand and minimum disruption to urban functions on the other. In the Municipality of The Hague major building projects are frequently realised above the main route to the city centre, the Utrechtse Baan motorway. During the construction stage, in which particularly heavy structural elements are erected and assembled, this motorway is often closed to traffic to avoid

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risks to third parties, people who are in the vicinity and users of the infrastructure beneath the building (i.e. motorists), as shown in Figure 1. These motorway closures have met with a barrage of protests from the public. The Municipality of The Hague introduces constructional safety at the earliest possible stage in its decision-making processes on such projects to allow urban activities (such as traffic, everyday life, work and business) to continue and thus avoid extra costs, delays or illegal actions. These problems are addressed in a detailed case study of multifunctional construction sites by Meijer and Visscher (2001), which includes:

- an analysis of the legal means at the municipality's disposal for the management of safety during building projects;
- a detailed evaluation of the development and building processes for five construction projects over the Utrechtse Baan in The Hague and some other projects;
- background profiles of safety issues and building techniques on the basis of literature searches and interviews with experts; and
- an expert session where a protocol was discussed for managing safety in such projects.

An important lesson was learned. The building operations that are carried out in the construction phase of such projects are a hazard for drivers, passengers and other people on road beneath (Meijer and Visscher, 2001; Suddle, 2001). Quantitative-based arguments derived from quantitative risk analysis (QRA) are extensively discussed in the survey by Suddle (2001, 2004), which considers human risks (loss of lives and injuries) and financial risks. This paper discusses some recommendations for integrating safety measures in safety protocols.

Meijer and Visscher (2001) showed that, because of the wide range of influence parameters, there is nowhere near enough knowledge about the actual risks of falling elements. Suddle (2001) integrated these parameters into a QRA models to identify

Figure 1.
Construction of the Malie Tower in The Hague

aspects of physical safety in multifunctional urban locations. There was very little background literature on this problem, i.e. physical safety during construction. Durmisevic (2002) concentrates more on the social aspects of safety in underground space during the exploitation stage. Additionally, most studies (Buur and Lourens, 2000) on construction safety focus on regulation rather than the quantification of the probability of falling elements. So, the literature delivered neither studies nor methodologies to assess physical safety or safety measures for the construction of building combinations above infrastructure – a 3D safety system – in densely populated areas.

Protocol for managing constructional safety and functional disruption

The case studies and the interviews with representatives of the Municipality of The Hague, clients and contractors, and external experts laid the foundations for a protocol that was specifically drawn up for safety-management in building projects at multi-functional locations (Meijer and Visscher, 2001). This protocol sets out the preconditions and the start scenario, the stage of the development and implementation process, and the responsibilities of the various parties. It was used to manage the safety aspects of later projects more effectively.

The start scenario

Meijer and Visscher (2001) assume that no heavy structural elements should be erected above roads which are still in use, as in the case of the Utrechtse Baan. Not enough is known about the risks of large structural elements or about the extent to which certain reduced risks can be made acceptable by safety precautions. As there are no universal cut-and-dried criteria for "acceptable" risks to third parties in construction operations, measures to limit the risks of hoisting and falling cannot be assessed for public acceptability. This creates a situation where people have to resort to "zero" tolerance, i.e. the total elimination of risks, and means that, before (high) building operations can go ahead, the possibilities for cordoning off the site and, if relevant, for diverting the traffic must be explored. If a major traffic artery crosses the site and there is no prospect of a long-term diversion, the client has to be persuaded to adopt a building method that involves the fewest closures.

Regulatory framework

National and local regulations provide the Municipality of The Hague with a broad basis for setting conditions designed to guarantee maximum safety and minimum disruption for local residents and third parties while demolition and construction projects are in progress. There is legislation at national level, (Working Conditions Act – Arbeidsomstandighedenwet, 2005) which addresses health and safety on site (Stichting Bouwresearch, 1996). A Health and Safety Plan is mandatory for projects above a certain size or which carry specific safety risks. This plan must ensure that site workers are adequately protected. The Municipal Building Bylaw (*Gemeentelijke Bouwverordening*) provides the municipality with an instrument for monitoring the safety of third parties during building projects: the municipality may require the client to submit a construction or demolition safety plan. Any road or lane closures and diversions that are considered necessary can then be organised via a roadworks licence (issued by the Police). Besides, the regulatory framework, it is important to settle the question of accountability if – despite the safety precautions – accidents were actually to occur. In many cases, the contractor or the building firm will be held liable for any accidents. However, under the Dutch Civil Code, the municipality may also be called to account, if the situation in question constitutes a direct threat to life.

Site designation and traffic implications

The decision to build at a multi-functional urban location is often the result of an interchange between the municipality, which designates potential construction sites in a master plan, and the interest of a developer to build at a specific location, which is often fraught with constraints. When a master plan is being drawn up and sites are being designated a preliminary analysis of the safety risks could be performed straight away. This would cover, amongst others, the potential for laying foundations and the scope for setting up site cordons and traffic diversions (if applicable). To ascertain the potential for the foundations a detailed inventory needs to be drawn up of the functions at the location (pipelines, tunnels, foundations of adjacent buildings) and of any claims that may be expected in the future (e.g. for tunnels). Finally, if the site crosses a major traffic artery, it is important to pinpoint possible diversionary routes and to decide on an acceptable number and time of closures.

Information to the client

If a client or developer shows an interest in a site, they should be informed of the implications of a development project. This information will provide a clear picture of the space and the scope for design freedom at the site. If the number of road closures needs to be limited, the developer can be informed immediately that he has to deploy specific building methods and bear any extra costs that these may involve. Agreements might also be reached with the developer on the fines that may be incurred if unforeseen circumstances make a deeper impact on the public road than was initially anticipated.

Design

The developer commissions a design. At a preliminary meeting or during the permission procedure the municipality decides whether the plan meets the criteria for site safety and nuisance control. The traditional process of definitive design – permit application – granting the permit – contracting-out – development, in which the contractor plays no part until the permit is granted, has very little to offer such projects. To arrive at a solution which ensures that the building activities cause only minimum disruption, it is essential to create an interaction between design – construction principle – materialisation and building method. Therefore, the best approach is to involve the contractor at an early stage.

Construction principles and building methods

It is the contractor who selects the building method for the design. The building method and the lay-out are determined by the spatial design, the construction principle, the materialisation and the characteristics of the site. The contractor will opt for a method which allows the project to be realized as economically and as quickly as possible. The Municipal Building Control Authority should be abreast of the technical options for realising building projects which seriously affect the underlying traffic routes. A specific analysis of the potential extra costs of alternative construction principles might tip the scales when the disadvantages of closing off a main traffic artery are weighed against the effects on the building costs. If potentially high levels of disruption are involved, the conditions for the size and layout of the site, the construction principle, materialisation and the building method need to be formulated at an early stage. These conditions should take the form of performance targets, so that the builder has sufficient scope to tackle the project as appropriate.

These conditions might include: the ultimate dimensions of the cordoned-off building site; the delivery routes for building materials and equipment (including any restrictions); permanent safety-net constructions to catch relatively small fragments of material and pieces of equipment; the maximum number of road closures that is permitted for building the platform and any later hoisting operations.

Steering, supervision and evaluation

Despite careful preparation and specific criteria, unforeseen circumstances might still crop up at any time. In short, no matter how good the timetable, improvisation is usually needed at some time during the project. This was borne out by experience in the case studies. Afterwards, the projects should be subjected to systematic and extensive evaluation. The results should then be used to refine the departure points for future projects.

Risk analysis and risk results

This section presents the discussion based on the results of the analysis of the risk to third parties of falling elements in multifunctional urban locations. More details of the setup of the risk can be found in the above-mentioned thesis by Suddle (2004), see also URL: http://repository.tudelft.nl/file/354674/203416

Risk analysis

First of all, a qualitative risk analysis for the safety of third parties was performed with failure mode and effect analysis (FMEA) techniques, representing a complete overview of hazards and consequences for the construction of a building above a motorway, as shown in Table I. It may be concluded from the FMEA that major risks to third parties during construction primarily concern falling elements. The chance of falling elements causing human casualties and, in some cases, economic risks as well, was analysed in more detail by a QRA conducted with Bayesian networks.

The possible quantifiable parameters for conducting a QRA were determined on the basis of the FMEA in Table I. The following quantifiable parameters were applied in the risk analysis conducted with Bayesian networks (Figure 2):

- the position where the element lands (inside or outside the building);
- the situation underneath the building;
- (design) errors;
- the weight of the falling element;
- the action of elements in relation to the installation of elements;
- the collapse of the main structure of the building due to falling elements;
- the probability of elements falling;

Table I.
A section of the FMEA for the safety of third parties during construction

Failure mode	Failure cause	Effect of failure
Logistic problems	Planning fault	Time loss
Collapse of concrete element	Design fault	Costs, time loss and fatalities
Fixing concrete elements	Element falls	Costs, time loss, loss of quality and fatalities
Huge deformations of elements	Element collapses and falls	Costs, time loss, loss of quality and fatalities
Wrong composition of concrete	Production fault	Costs, time loss and loss of quality
Fire in building	Gas leak	Costs, time loss, loss of quality and fatalities
Activity: Installing temporary structures/scaffolds; removing temporary structures		
Fixing/removing temporary structures	Construction fault	Costs, time loss AND fatalities
	Collapse of temporary structures	
	Construction falls	
	Construction element falls	

Source: Suddle (2004)

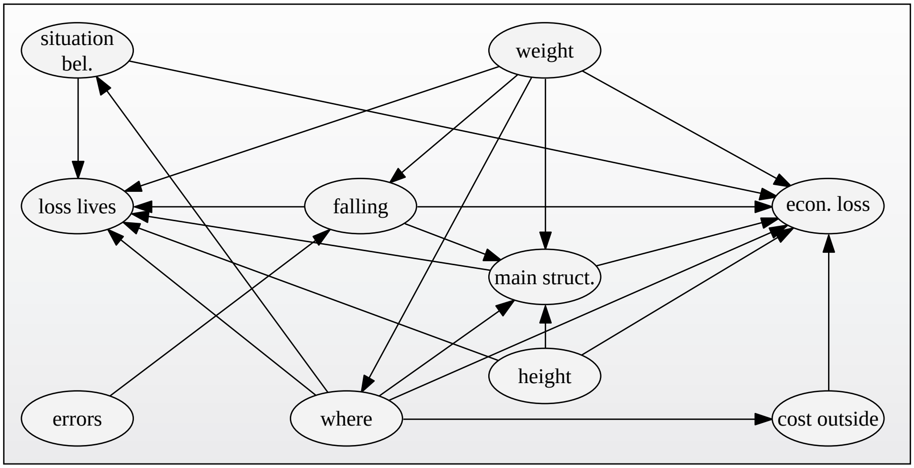

Figure 2.
Bayesian network for building above roads for construction stage

- the height from which the element falls; and
- fatalities and economic risk.

Each of these quantified aspects represents a node in the Bayesian network in Figure 2. Each node is divided into categories corresponding with events which relate to that node. The relationships between the nodes are shown with arrows, which specify the probable influence between them. Figure 2 shows the relationship between falling elements and other (quantified) aspects. The loss of human lives depends on, for example, where the element falls, the height from which it falls, and its weight. The probabilities of each node are determined by historical data, expert opinion, or engineering reports. In some cases, especially those with no historical data – such as the probability of elements falling – an expert opinion, or an (in-house) engineering report was used. The probability of failure was determined on the basis of the likelihood of the occurrence of hazardous events. The determination of the consequences of hazardous events was based upon either calculations or the same order of magnitude severity of events. Full details on the quantification of these probabilities can be found in Suddle (2004).

Results of the risk analysis

The results of the risk analysis presented in this paper are based on a virtual and schematic case study, consisting of the construction of a ten-storey building above a 2 × 2 lane motorway with a duration of exactly one year. Three types of risk outcome for third parties are considered in Table II:

1. the individual risk per year IR;
2. the expected number of deaths per year $E(N_d)$; and
3. the expected number of injuries per year.

The risk calculated with the Bayesian network in Figure 2 shows the risk per action of a considered element per year. In order to calculate the risk per year, the output probabilities were multiplied by the number of actions needed for the construction of the building during the period of exactly one year. Subsequently, the individual risk IR was determined by multiplying the computed risk with the total presence time of a given person per year. The expected loss of human lives $E(N_d)$ was computed by multiplying the individual risk IR by the number of participants per year. The expected number of injuries per year was calculated in the same manner as the individual risk IR. The final results for the three above-mentioned risk categories are presented in Table II.

It should be noted that the figures in Table II are more of an indication for the virtual and schematic case. Moreover, the results present more the methodology of the QRA rather than exact results.

Next, sensitivity analysis was performed to determine the dominant influences in the risks for third parties. These turned out to be the:

- number of actions per project;
- position where the element lands;
- situation beneath the building;
- weight of the falling element; and
- height of the building.

The higher the building, the greater the risk to third parties from falling elements. It also means that the higher the building, the more safety measures are required.

Table II. Individual risk to third parties and human life when building above motorways

Building above	Motorway
Individual risk, IR	3.0×10^{-6}
Expected loss of human life, $E(N_d)$	1.65
Expected injuries	5.46

Source: Results adapted from thesis; Suddle (2001)

In contrast, the covering length of the building has barely any influence on the individual risk to third parties during the construction stage. Furthermore, it should be noted that the individual risk IR to third parties is highest in the vicinity of the constructed building, and especially in the so-called risk zones, i.e. the façades spanning the road. Surprisingly, it turned out that factors such as (design) errors and the collapse of the main structure of the building due to falling elements have scarcely any influence on the overall risk for third parties, since the probability of the collapse of the main bearing structure above the infrastructure is negligible during construction.

An analysis of the cost-effectiveness of safety measures

When cost-effectiveness is considered as a basis for measures and decision making, financial factors need to be considered as well as human risks. As a result, investments C_0 in safety measures must be calculated along with their economic risk C_i and compared with the expected loss of human lives $E(N_d)$, either monetarised or not, depending on the origin of the decision maker. In this research, seven types of measure were considered. The total costs per measure C_{tot}, consisting of investments in safety measures C_0,and their economic risk C_i (direct and indirect) were determined in combination with the expected loss of human lives $E(N_d)$. Basically, the seven types of measure presented in Table III can be divided into two main groups; structural/functional measures (such as applying different types of protective canopy to prevent falling elements from ever reaching third parties; measures 1, 2, 3, 6), and logistic measures (such as closing off the road and rerouting the traffic; measures 4, 5, 7). These measures are implemented in and verified by the Bayesian network in Figure 2 by adding a node or changing the conditional probabilities between the nodes in the original Bayesian network in Figure 2. Logically, changes influence the economic risk as well as the risk to human life. The result and the effect of the formulated safety measures are presented in Table III.

Note that, depending on local circumstances, the cost-effectiveness of safety measures might be inconsistent with the results presented here. Moreover, some measures can only be implemented in combination with others as opposed to individually. This may also lead to different results for cost-effectiveness. This methodology raises the complex and controversial issue of decision making from different perspectives: human-based, economic-based or a combination of the two. To balance and optimise these measures, human risks can even be related to costs by

Table III.
Safety measures: investments and risks

Safety measure	Investments C_0 (in €)	Economic risk C_i (in €)	Total costs C_{tot} (in €)	$E(N_d)$
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 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

Source: Suddle (2004)

applying a monetary value for each avoided fatality or injury. A reasonable value per avoided fatality seems to be €1,000,000 (Vrouwenvelder *et al.*, 2001).

Decision making on and the integration of safety measures

When considering the safety measures in Table III, the decision maker, usually the municipality, finds itself in a dilemma: "which measure should be preferred?", the one that involves minimum investment, C_0, the one that minimises the economic risk, C_i, or the one that reduces the loss of human lives $E(N_\mathrm{d})$. This creates a situation in which the decision should not be based on economic grounds alone, but should also take account of human risk. So, several options can be considered.

Take, for instance, safety measure 5 in Table III – closing off the road and rerouting the traffic – or measure 4 – construction during the night. In both cases the expected loss of human lives $E(N_\mathrm{d})$ can be reduced to almost zero. This is because a very small number of people are exposed to the danger of falling elements (small number of participants N_{pi}). Controversially, the total costs C_tot of such measures are relatively high, because the investments are high as well. However, these costs can be reduced by pumping concrete onto floors of the building (measure 6), whereby the number of actions involving lifting, moving and elevating (structural) elements can be minimised. Applying measure 6 would also allow human risk in terms of loss of lives $E(N_\mathrm{d})$ to be reduced in comparison with the initial situation (case study, measure 0). In the initial situation, it is assumed that there is no support floor or protective canopy to interrupt falling elements and a hollow core slab floor is implemented as the floor system for the building. Unfortunately, compared with the initial situation, there is no substantial improvement in the figure for human risk, the value for $E(N_\mathrm{d})$ was 1.65 and becomes 1.63. The main advantage of a protective canopy or a support floor under the building is that it eliminates the risk primarily caused by small (non-structural) elements. Also, a protective canopy may prevent a psychological (shock) effect on motorists.

Integration of safety measures in safety protocols and design

Together, these safety measures and the hesitation of decision makers can contribute to an instrument – recommendations – that can be generally applied in multi-functional urban projects. Two types of recommendations can be formulated:

(1) recommendations for municipalities to support the safety protocols; and
(2) recommendations for design engineers.

Case studies of projects built above the Utrechtse Baan motorway in The Hague have revealed that the demands made by municipalities at constructions sites have been so diametrically opposed that they were difficult for the contractor to realise (Meijer and Visscher, 2001; Suddle, 2001). One should strive to balance these extremes and almost unrealisable demands or measures with the demands of the contractor. Municipalities should therefore deal with the concept of risk acceptance instead of risk exclusion and should check whether the safety measures are integrated in the design of a project.

The recommendation to designers – the architect or the structural engineer – is to systematically integrate the safety measures (Table III) in the architectural, functional and structural design of the building above the infrastructure. The disadvantage of temporary safety measures is that they are a cost-raising factor in projects. In contrast, if permanent safety measures are implemented, synergy can be achieved; the safety of third parties can be guaranteed and the designer can produce a multifunctional design which saves the extra costs of removing the safety measures (Suddle, 2004). Some examples should be quoted so that the designer can achieve the goal of measures integrated 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 could also use façade elements with a strong deformation capacity or realise a strong, resilient protective canopy. The canopy will catch any falling elements and prevent them from hitting a passing motorist. One could also design the periphery or the shape of the building in such a way that the risk to third parties in the construction stage is minimised. The type of construction may also influence the overall safety.

For instance, when the façade and other structural elements are transported to a floor, they should be erected from inside rather than outside the building. The transport and erection of these elements from outside the building may constitute a considerable risk to third parties due to falling elements. Using and applying "set backs" in the shape of the building can also enhance the safety of third parties (Figure 3). This way, the height of the risk zones can be reduced; in other words, falling elements can only occur once in the risk zone, when the first construction floor is being realised.

Another practical measure is to lay permanent support floors in the risk zones or the lower storeys and assign them specific functions, such as a parking garage. These can intercept falling elements from higher floors. Hence, the elements are not only intercepted at an early stage, but the impact can also be strongly reduced. Configuration with the shape of the building should be used in architectural impressions of buildings above roads and railways. The safety measures (Table III) can also be integrated into the functional design of the building. If the safety measure of "a protective canopy" is considered, a function like a restaurant or a parking garage can be integrated into the lower floors of the building. This will save the costs of removing the protective floor after construction.

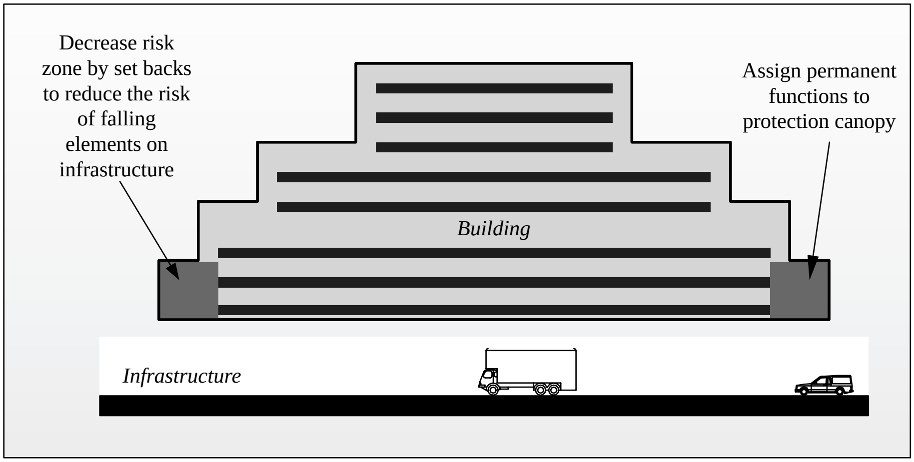

Figure 3.
The safety of third parties can be improved by set backs in the shape of the building

Source: Suddle (2004)

Conclusion

The case study about safety on construction sites on the Utrechtse Baan motorway revealed that very little is known about the risks and cost-effectiveness of safety measures. The evaluation of some construction projects, interviews with experts and an expert discussion session resulted in a protocol, which contains many relevant constraints and decision moments for minimising and controlling safety risks and hindrances for the users of the multi-functional urban area. The erection of heavy structural elements emerged as an important risk factor. Closing the road seemed the only option. However, a more detailed subsequent study of the actual risks and the cost-effectiveness of the available measures increased insight into the problem. It appears that falling elements form a major hazard for third parties, such as the users of the infrastructure (the motorists), because the infrastructure is in use when the building above it is being constructed. Measures to protect against such hazards can easily be taken from a structural point of view –, e.g. apply a protective canopy – or a logistic point of view –, e.g. reroute the traffic when heavy elements are being erected. However, it now appears that closing off the road does not always provide the most cost-effective solution. It is much more cost-effective to implement structural measures against falling elements. These should be integrated into the functional design for the operational stage of the building in order to save costs. Costs are saved because these structures do not have to be removed and can even add to the functional or aesthetic value of the building. The cost-effectiveness of safety measures should be a key starting point for safety protocols. Furthermore, the structural and functional integration of safety measures should be implemented in safety protocols as a basic tool. Municipalities are therefore advised to ensure that such measures are taken into account during the design stage of such projects.

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