Study for a Quantitative Risk Assessment on Accidental Actions

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Illustration front page: The Ronan Point collapse in London 1968 (Alamy)

ABSTRACT

Lately structural safety is an often discussed subject in The Netherlands. Recent collapses have made people question if our buildings are actually safe enough. Research shows that the individual probability of death due to structural failure is below the limit of 10^{-5} per year. However, it is unknown if every single building is safe enough as well.

The main cause of structural failures are human errors (90% of the collapses). However, the Dutch Building Decree does not mention the unidentified accidental actions (the type the human errors belong to) as those an engineer has to take into account when designing the building structure. The Eurocode does mention unidentified accidental actions and states that for consequence class 3 buildings a risk assessment has to be done to check which accidental actions are hazardous and if the total risk to a building is acceptable. However, the Eurocode does not give a maximum value of an acceptable risk in their risk assessment method. So currently when engineers perform a risk assessment, they cannot verify whether the risks of accidental actions on their designed structure are acceptable according to the regulations.

This thesis conducts research for a new method for performing a risk assessment in a quantitative way. First it investigates what the advantages and disadvantages of existing methods for performing a risk assessment are. It appears that the main step missing in existing methods is the verification, based on a quantified limit, whether the risks of accidental actions are acceptable. Based on the known methods, a new protocol for performing a risk assessment is proposed. This protocol includes a determined limit for the probability an accidental action occurs and causes a certain failure mechanism and consequence. This limit is based on the maximum probability the Eurocode gives for failures with a consequence indicated as consequence class 1, 2 and 3 (CC1, CC2 and CC3). By dividing the accidental actions that can occur and their failure mechanisms into the same consequence classes, the estimated probability and the limit of the Eurocode can be compared. In this way the known consequence classes from the Eurocode are used in another way than engineers are used to.

Furthermore research on past structural failures has been investigated to establish whether it can be used to predict the probability a certain accidental action causes a CC1, CC2 or CC3 consequence. Not enough research is done to fully trust on these outcomes; in the protocol proposed in this thesis the engineer will have to estimate a part of the probabilities himself, with the help of a classification table.

The principal advantage of performing a risk assessment on accidental actions in a quantitative way with a prescribed maximum probability per consequence class, is that it is made clear whether a building fulfills the requirements or not. This can be helpful for communication with other involved parties. However, it will never be 100% clear what the limit should be, because estimating the risks is based on the engineer’s estimations and outcomes may differ as they depend on the person performing the risk assessment. This means a hard line, below which the risks are acceptable and above the risks are considered too high, cannot be drawn. An area in between is needed in which it is up to the engineer and client to decide whether or not they find the risks acceptable.

Preface

After nine months of work I present to you my final thesis for obtaining the Master Degree in Civil Engineering: Study for a Quantitative Risk Assessment on Accidental Actions. In those nine months I learned a lot about risk management in the construction industry. It surprised me that at the moment of writing still a lot of uncertainties exist about this subject. The relevance of the research motivated me to work on this thesis.

Although the risk assessment protocol cannot fully be used in practice yet, I think I provided a good first step. With this a basis is created from where new research can be done and actions can be taken. Furthermore, I think it is important that something will be done in the near future about this problem.

I want to thank Van Rossum and in particular Maurice Prumpeler for offering me a place at their office to do my graduation research and for helping me with my everyday questions. Also I would like to thank my supervisors of the TU Delft: Sander Pasterkamp, Raphaël Steenbergen and Rob Nijsse for helping me taking a critical look at my work and the supervision during the whole project. Furthermore thanks to all the people whom I spoke with to gain more knowledge about the subject and the current situation. Also special thanks to Stef and Mark for improving the language and clearance of my report. And of course my family and friends, not only for your support during my graduation but also for all the years before and hopefully after.

I hope you, the reader, can learn something from my work and might get inspired to do more research on this subject.

Sarah Kleijn

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CONTENTS

1. Introduction

1.1 PROBLEM STATEMENT

Structural engineers in The Netherlands face the problem that it is not clear how one should perform a risk assessment on accidental actions and verify if the risks are acceptable. Different methods are prescribed but none give a limit which should not be exceeded to conclude that the risks on accidental actions are acceptable. Moreover, when such a limit would be available, no data engineers can use is available to quantify the risks and test if they fall within the limits. The assumption is that the lack of a clear method to quantitatively perform a risk assessment on accidental actions, including a prescribed limit for the quantified risks, negatively contributes to the number of (partial) building collapses in The Netherlands.

At the moment structural safety is an item often discussed in The Netherlands. With new Eurocodes on the horizon (e.g. EN 1991-1-7) and a new law concerning building safety, this topic not only concerns structural engineers but also politics and normalization institutes in Europe.

The regulations concerning accidental actions in the Dutch Building Decree and the Eurocode differ from each other. The official Dutch Building Decree 2012 states that a building structure shall not collapse during exposure to identified accidental actions if this leads to collapse of another structural element not in the direct proximity of the structural element exposed to the load (Bouwbesluit, 2012). For the definition and examples of identified accidental actions the Building Decree points to the Eurocode. In other words, they say that a building structure should be designed in such a way that an identified accidental action shall not cause a *progressive* collapse. How this should be accomplished is left to the engineer to decide.

The Eurocode (EN 1990) elaborates on this subject and states that a collapse due to accidental actions like explosions, impact or human errors should not be disproportionate to the initial load. The term ‘disproportionate’ is not quantified. In this, the Dutch Building Decree is more explicit than the Eurocode by saying the failure of one structural element cannot cause the failure of another structural element not in the direct proximity of the one exposed to the load. However the Dutch Building Decree only mentions the *identified* accidental action (e.g. impacts and explosions) as a cause, while the Eurocode mentions an explosion, impact or human error as examples of accidental actions to take into account, in which human error is considered an *unidentified* accidental action. In practice it appears that 90% of structural failures are due to human errors (chapter 3), so it is odd that the Dutch Building Decree does not take them into account.

While the Dutch Building Decree does not provide a design strategy to accomplish that no progressive collapse will take place due to an identified accidental action, the Eurocode does provide design strategies to make sure a collapse due to an unidentified or identified accidental action will not be disproportionate to its original cause. It differs per consequence class what strategy is proposed, as for consequence class 1 buildings (CC1) a less comprehensive method is suggested than for consequence class 3 buildings (CC3). For CC3 buildings it is advised to perform a risk assessment to verify if the risks of accidental actions (both identified and unidentified) are acceptable. A guideline on how such a risk assessment could be performed is given in Annex B of EN 1991-1-7. However in this annex no limits for a quantified risk are provided to allow the engineer to verify if his design meets the requirements. The Eurocode suggests that the client and engineer together should determine the maximum allowable risk per project.

In practice it appears that structural engineers do not follow the method suggested in Annex B of EN 1991-1-7 for performing a risk assessment, but use the method prescribed in Stufib report 8. This method is a qualitative way of analyzing the risks. The possible identified and unidentified accidental actions that may occur have to be listed. For each hazard the mechanism it causes and the measures that will be taken to lower the risk have to be described. A list of possible hazards is given and meant as an example, however most engineers use this list as complete and do not think of more possible hazards to add to the list.

Stufib nor the Eurocode provides the engineer with a maximum allowable risk to verify if his design meets the requirements. Strictly spoken the engineer only has to meet the Dutch Building Decree to meet the requirements, so a building structure which will not cause a progressive collapse after being exposed to an identified accidental action is considered safe enough. However in practice engineers tend to follow the method proposed in the Stufib report, since here the unidentified accidental actions are considered as well, while no extra attention is paid to the requirements of the Dutch Building Decree.

The following list gives a numeration of the issues above mentioned.

- According to the Dutch Building Decree only identified accidental actions have to be taken into account, while most of the structural failures in The Netherlands are due to unidentified accidental actions.
- NEN-EN 1990 mentions disproportionate collapse as not acceptable but the term 'disproportionate' is not quantified.
- In practice engineers do not verify if the requirements of the Dutch Building Decree concerning accidental actions are met.
- Stufib nor the Eurocode provides the engineer with a maximum allowable risk to verify if their design meets the requirements.
- The lack of accurate data to estimate the probability an accidental action occurs makes it difficult for an engineer to perform a risk assessment in a quantitative way. This means when an engineer wants to do a quantitative risk assessment, they have to estimate the probability and consequences themselves, which makes it subjective.
- It is not known if the number of structural failures will decline when engineers use a quantitative risk assessment to judge if the risks on against accidental actions are low enough instead of a qualitative method.

1.2 Research Question

A solution for the problem statement could be to develop a protocol for performing a risk assessment with a maximum allowable level of tolerable risk. When the risks of accidental actions on the building are higher than the limit, more measures need to be taken. When the risks are lower or meets the limit, the building structure can be considered safe enough designed on accidental actions. By analyzing the risks in a qualitative way, an engineer's subjective judgment plays a role. To increase objectivity, the risks should be analyzed in a quantitative way. When describing a risk in numbers it can easily be checked if this risk is below a certain limit.

This thesis will investigate how such a risk assessment should be performed, in what manner the risks can be quantified, what the maximum level of tolerable risk should be, what the advantages and disadvantages of such a method are and how it could be helpful in practice.

1.2.1 Main question

The following main question will be investigated in this report:

To what extent can a standard protocol for performing a quantitative risk assessment help a structural engineer by verifying whether the risks of accidental actions on the designed building structure are acceptable?

1.2.2 Key questions

The key questions to help answer the main question are the following:

1. What are accidental actions?
2. What do codes and regulations state about designing against accidental actions?
3. What is a quantitative risk assessment?
4. How do engineering firms currently perform a risk assessment on accidental actions?
5. How can the probabilities that accidental actions occur be quantified?
6. How can the consequences of the accidental actions be quantified?
7. What should the maximum level of tolerable risk be?
8. Which accidental actions need to be taken into account for a risk assessment?
9. Which steps need to be taken to perform a quantitative risk assessment on accidental actions?
10. What should be done before this protocol can be used in practice?
11. What are the advantages and disadvantages of using this protocol?

1.3 Scope

The proposed protocol for the risk assessment in this thesis is used as a reference to answer the main question: *To what extent can a standard protocol for performing a quantitative risk assessment help a structural engineer by verifying whether the risks of accidental actions on the designed building structure are acceptable?.* This is done because at the moment no standard protocol for performing a quantitative risk assessment on accidental actions is available. However, maybe other protocols would lead to another answer to the main question.

In this thesis the focus is laid on the structural safety due to accidental actions. This implies only consequences influencing the structural safety are taken into account. Economic, social or environmental consequences, for example, are not taken into account. Also the consequences of an accidental action which do not influence the structure fall outside the scope.

The protocol for a risk assessment presented in this thesis is meant to be performed by the structural engineer who designed the structure of the analyzed building, or another person who is fully aware of the structural system used in the project. However, it can also be used by a control firm to verify if the risks of accidental actions are low enough.

Because the used research is mainly based on data from past events in The Netherlands, the project for which the risk assessment is performed should take place in The Netherlands. Furthermore the project should be in the design phase when performing the risk assessment, because at this moment still adjustments can be made on the design.

The strategy used for the risk assessment proposed in this thesis is based on identified accidental actions. It is assumed that every accidental action can be quantified on probability and consequence as long as the action is divided clearly enough in the steps of the failure scenario so that every step can be given a probability of occurring. This way every accidental action can be considered an identified accidental action. The only exception is the lack of professional knowledge leading to a collapse. Although this is not predictable, when past events are investigated, the number of times the lack of professional knowledge was the cause of a collapse can be taken as the probability such an error will be the cause of collapses in the future as well.

Furthermore the risk assessment is meant for CC3 buildings, since for those the Eurocode states that a risk assessment on accidental actions has to be performed. However, the method can be used for all consequence classes.

Lastly, combined hazards are not analyzed on their occurrence, since no data of past events is available in this area.

1.4 METHODOLOGY

To answer the main question '*To what extent can a standard protocol for performing a quantitative risk assessment help a structural engineer by verifying whether the risks of accidental actions on the designed building structure are acceptable?',* a standard protocol for performing a quantitative risk assessment has to be made, since this is currently not available. With this protocol an engineer must be able to verify whether the risk on accidental actions are acceptable.

To compose such a protocol, first it is important to know what the Dutch building industry is about. How does a project normally go, which parties are involved and what are the rules an engineer must follow when designing the building structure? More specifically the definition of accidental actions have to become clear, as well as the current codes and regulations concerning accidental actions.

When knowing what accidental actions are and what the current codes and regulations say about how one must take them into account for a structural design, it can be investigated which methods are currently used to perform a risk assessment. Different methods will be compared so the advantages and disadvantages of each method can be taken as a basis for creating a new protocol for a risk assessment.

Furthermore, before a protocol for a quantitative risk assessment can be written, one must know how a risk can be quantified in order to verify if it is acceptable. It will be investigated if analyses of past events can be used to determine the probability of an accidental action causing a collapse. Also the level of tolerable risk has to be determined before the protocol for risk assessment will be written.

All input combined will be the starting point for writing a protocol for performing a risk assessment on accidental actions. A step by step guide will be given so the structural engineer can easily perform the risk assessment and judge if the risks on accidental actions in his design are acceptable.

When the protocol is designed, it can be tested in the field. By letting an engineer perform the proposed method, it can be investigated what the advantages and disadvantages of this specific method are and to what extent it can be useful for the engineer to verify if the risks on accidental actions are acceptable.

2. Dutch building industry

2.1 INTRODUCTION

In The Netherlands the responsibility for the structural safety of a building lies with the different companies working on a project. They are all responsible for their own smaller contribution, but none is responsible for the whole. The 'Onderzoeksraad voor Veiligheid (OVV)' is an institution which (among other things) investigates building collapses. The goal is to learn from these collapses so the same mistake will not happen again. It is not mandatory to investigate all collapses; only when the OVV wants to investigate, they do. The OVV gives the results to the concerned companies but the rest of the building industry does not learn from these mistakes. (Onderzoeksraad voor Veiligheid, 2018)

The OVV pleads for making one party responsible for structural safety. This party has to make a risk file in which differences in execution and design and signals of potential risks for the structural safety will be reported. Another point of attention the OVV states is that contractors with the lowest price usually win the tender. Contractors who pay more attention to structural safety are usually more expensive and thus do not win the tender.

Currently governmental organizations are responsible for checking the design and execution of building projects. The LTB 2012 matrix (Bouwbesluit, 2012) tells the official how precisely a design has to be checked. The indication goes from 1 to 4, in which level 1 in this matrix means that only the assumptions or base for the calculations will be checked and level 4 means everything has to be checked. According to these levels the official knows which calculations need to be checked and how thorough it has to be done. However, the government wants to change this responsibility to private parties (Eerste Kamer, 2017). With a new law, in Dutch the 'Wet kwaliteitsborging voor bouwen' they want to encourage independent companies, instead of governmental organizations, to verify the safety of the design and construction of buildings. Not everybody agrees with this law. In an article Jan Vambersky (Tissink, 2018) states that this law is contrary to what the TU Delft, Kivi and other organizations asked for in a letter to the minister. They say that control on structural safety should not be abolished. With this new law the responsibility of the government will be abolished, while no other party is appointed to take over that role. It is merely suggested is that a private party can take over.

Most mistakes the OVV highlights are accidental actions. Discrepancies between design and execution should not occur. The same goes for a lack of control on structural safety. To see what the rules and regulations are concerning these type of errors, the following key questions will be answered in this chapter,

- What are accidental actions?
- What do codes and regulations say about designing against accidental actions?

First a brief description of the building process in The Netherlands will be explained in this chapter.

2.2 BUILDING PROCESS

Generally spoken, a project starts with an initiative. The client wants a building and starts thinking about requirements. He investigates if it is feasible for himself or his company, and then starts to plan. Different parties can be hired by the client to translate the requirements into a design which meets the national codes and regulations. The detailed design is then given over to different contractors who make an offer with an estimation of the costs of realization of the project. The client chooses a contractor and then the contractor starts building. In most cases the client chooses the cheapest contractor. Depending on what kind of contract the client wants, this process can vary and be more or less extensive.

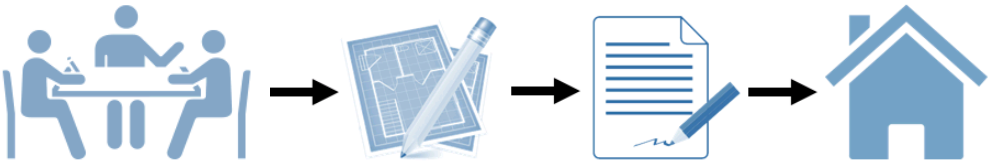

FIGURE 1 BUILDING PROCESS IN THE NETHERLANDS (CONTRACTING, 2019)

Every transaction between the previous and next phase involves a risk on errors in communication. Every arrow in figure 1 is a moment in which more or less parties will get involved and responsibilities can change. When the client do not describe their requirements clear enough, the architect can come up with a design which does not satisfy the client. When the design stage is finished, the contractor can change the design if he finds it more suitable for his construction method. Without control of the parties of the previous phase, these changes can have enormous influences. The more different parties are involved, the greater the possibility that somewhere in the process a communication error will arise. However, when not enough parties are involved, other problems (like insufficient knowledge or incompetent staff) can arise. At this moment there is no party which checks if these risks are under control.

2.2.1 PARTIES INVOLVED

In The Netherlands the following roles are involved in a building project. Each of the roles listed below can consist of multiple parties (Nederland, 2017).

- **Employer**: the party that gives instruction on how a task should be fulfilled
- **Client**: the initiator or party that wants to realize the plan
- **Owner/user**: the one that will use the building
- **Designer**: the parties that make the architectural design. In most cases the architect and/or the engineering firm
- **Structural and installations advisors**: the parties that give specific advice about a certain topic, like the structure or building physics
- **Contractor**: could be divided into main contractor (signs the contract with the client and is responsible for the construction) and subcontractors (work for the main contractor)
- **Installations advisor, producer and installer**: the parties who support the designer and/or contractor in specific elements
- **Maintenance company**: the party who is responsible for maintenance during use

- **Authorized supervision (Bouw- en Woningtoezicht):** the public body who controls the building permit is maintained
-

Not directly involved in the building project itself, but in making the rules and regulations, are the following parties.

- Dutch parliament: The parliament is responsible for making and execution of the law. In the law it states that the Dutch building decree is valid for the rules and regulations for, among other things, buildings.
- Minister for *Wonen en Rijksdienst*: The Dutch minister for living and civil service is responsible for the Dutch Building Decree. The Building Decree is the set of rules and regulations every building (project) in The Netherlands should follow. The Building Decree often refers to the Eurocode (including the national annex).
- CEN European Committee for Standardization: Organization who makes the general part of the Eurocode.
- NEN: The Dutch standardization institute. Organization who makes the Dutch national annex for the Eurocode.

2.2.2 Phases in the building process

Before a project can start, preparation is necessary. The Dutch government has to make sure that when someone wants to construct a building, it should be clear to him which laws and regulations he should follow. The Dutch Building Decree should be comprehensible and comprehensive and it should be clear who is responsible for the building permit. When these boundary conditions are met, it is possible to start a building process, consisting of the initiative, design, construction and use phase. (Nederland, 2017). In this paragraph the phases of a building process will be explained, including which parties are involved in which phase.

<u>Initiative phase</u>

The **client** or initiator makes a plan for what he wants to be build and how it should be done. He makes a list of wishes and requirements, which need to adhere to the laws and regulations. The client decides in this phase what the process will look like and which parties will be involved and get which responsibilities.

<u>Design phase</u>

In the design phase the complete design will be made by all the **designers** and **advisors**, according to the wishes and requirements the **client** has set in the initiative phase and the laws and regulations. When the design is ready, the **contractor** will set a price for the client for how much he can build it. While setting this price he also checks if he finds the design safe and good enough to actually build, use and maintain it. When the contractor has doubts, he has to inform the client about it.

<u>Construction phase</u>

The **client** starts by applying for a building permit from the **municipality**, so the **contractor** can start building. During construction often still changes to the design (of the part which has not been built yet) are implemented. The **client** is responsible for communicating these changes to the designers and advisors of the design phase. However the client is not always a person or party with specific knowledge about construction or the details about the design, so communication can be difficult. Furthermore it is important that the contractor and subcontractors have a good and clear distribution of functions and responsibilities.

Use phase

In the use phase the **user** or **owner** is responsible for the **maintenance** of the building. He has to make sure the building is properly maintained and the right parties are involved in the execution of the maintenance. The user or owner is also responsible for the correct use of the building.

2.3 Structural Safety

Structural safety is related to accidents happening due to structural failure. Since the number of accidents is difficult to count (what is considered an accident?), most research is done by counting average fatalities per year due to structural failure. This can be subdivided in different populations, for example the workers in the building sector, workers in other sectors and residential end-users. In his thesis Terwel used the research of Storybuilder and Cobouw, who used past research to count the fatalities per population type (Terwel, 2014).

Cobouw counted 43 fatalities in a period of 17 years, of which 38 (2,2 per year) were during construction, 2 (0,12 per year) during work in other sectors and 3 (0,18 per year) during residential end-use. Storybuilder, who set up a database for job-related accidents, has data from 1998-2009. Of the 23.000 Dutch cases, 5.600 were related to the building industry. Of those the ones that are related to structural failure are used for their data. Storybuilder reports 5,3 fatalities on average each year due to structural failure, of which 3,7 in the building industry and 1,6 in other sectors, even though nearly 16 times as many people work in other industries than in the building industry. Figure 2 gives the probability of dying per year for each population group due to structural failures. (Terwel, 2014)

	Population (average for period 1998-2009 (CBS)	Storybuilder (per year)	Cobouw (per year)	Probability of dying (per year)
Workers in building sector	493000	3.7	2.2	$3.7/493000= 7.5*10^{-6}$
Workers in other sectors	8.3 million	1.6	0.12	$1.6/8.3$ million= $1.9*10^{-7}$
Residential end-users	16.1 million	-	0.18	$0.18/16.1$ million= $1.1*10^{-8}$

FIGURE 2 PROBABILITY OF DYING PER POPULATION GROUP DUE TO STRUCTURAL FAILURES (TERWEL, 2014)

For residential end-users the Eurocode gives a maximum allowable probability of 10^{-5} per year on dying due to structural failure. The 1,1 x 10^{-8} given in figure 2 is lower than this limit and thus acceptable. However this 1,1 x 10^{-8} is based on a total number of 3 fatalities in 17 years. When only one accident happens with a low probability but high consequence, the outcome can vary significantly. Also the total probability of dying due to structural failure might be small enough, a single building however might not fulfill safety restrictions. Madsen et al (2006, p. 7) concludes from research by CIRIA that the individual risk of dying due to structural failure is 10^{-7} per year. (Terwel, 2014)

Other research has been done by Ellingwood in his paper *Strategies for mitigating risk to buildings from abnormal load events.* The probability for an individual on dying because of a building collapse is compared to probabilities on dying due to for example diseases and natural disasters in the USA, see table 1. According to Reid (2000), individuals consider a risk as great as the risk for a disease (around 10^{-3} for people between 30 and 40 years) as high, while they consider a risk the same as a natural hazard (around 10^{-6}) as low. Since building collapses are also around the 10^{-6} per year, people tend to find it acceptable. (Ellingwood B. , Strategies for mitigating risk to buildings from abnormal load events, 2007)

Source	**Fatality/year**
Cardo vascular disease	$3,5 \times 10^{-3}$
Cancer (all)	$2,0 \times 10^{-3}$
All accidents	$3,4 \times 10^{-4}$
Motor vehicle	
Per vehicle-km	*$6,4 \times 10^{-9}$*
Per year (25.000 km)	*$1,6 \times 10^{-4}$*
Accidents in the home	$1,1 \times 10^{-4}$
Fires	$1,2 \times 10^{-5}$
Homicide and legal intervention	$6,4 \times 10^{-5}$
Electrocution	$5,3 \times 10^{-6}$
Air travel	
Per round trip	*$1,6 \times 10^{-7}$*
Per year (25 trips)	*$4,0 \times 10^{-6}$*
Hurricanes, tornados and floods	$7,2 \times 10^{-7}$
Lightning strike	$3,3 \times 10^{-7}$
Dam failures	$1,0 \times 10^{-4}$
Bridge collapse	$1,0 \times 10^{-4}$
Building collapse	$1,0 \times 10^{-6}$

TABLE 1 ANNUAL INDIVIDUAL FATALITY RISKS (ELLINGWOOD B. , STRATEGIES FOR MITIGATING RISK TO BUILDINGS FROM ABNORMAL LOAD EVENTS, 2007)

2.4 ACCIDENTAL ACTIONS

In this section the following key questions will be answered:

- What are accidental actions?
- What do codes and regulations say about designing against accidental actions?

The key question w*hat are accidental actions* will be answered in section 2.4.1 by using a definition used in the background document to EN 1991-1-7. The key question w*hat do codes and regulations say about designing against accidental actions* will be answered in section 2.4.2, in which the methods used in the Dutch building regulations and the Eurocode will be explained.

2.4.1 Definition

The background document to EN 1991-1-7 gives the following description of an accidental action (A. Vrouwenvelder, 2005):

"Accidental actions in the Eurocode system are defined as actions with low probability, severe consequences of failure and usually of short duration. Typical examples are fire, explosion, earthquake, impact, floods, avalanches, landslides, and so on.
Next to these identified accidental actions, structural members may got damaged for a variety of less identifiable reasons like human errors in design and construction, improper use, exposure to aggressive agencies, failure of equipment, terrorist attacks and so on."

A difference is made in identified and unidentified reasons. However, as the term 'less identifiable' implies, the line between the identified and unidentified accidental actions is not that clear. The reason the difference is made, is that for unidentified accidental actions other design strategies are suggested than for identified accidental actions. In this thesis no difference will be made between identified and unidentified; the same risk assessment has to be performed for both types of accidental actions.

The reason not to differentiate is that when hazards and their following hazard scenario are described in a systematic and clear way, the consequence can be estimated as well. A terrorist attack is mentioned by the EN 1991-1-7 as an unidentified accidental action. But when the hazard is divided in different scenarios, like 'a terrorist shooting' or 'a van with a bomb inside drives into the building', the probability and consequence can just as easily be estimated as the probability and consequence of an identified accidental action (like an explosion).

The only really unknown hazard is a lack of professional knowledge. The Tacoma Narrows Bridge clearly exemplifies this; at the time of designing, the designers of the bridge did not know about the oscillations due to the wind that could occur (Harish, 2019). Or more recently the floor system used in the Eindhoven garage; the designers did not know the bubble deck floor panels used were less strong than anticipated.

Taking into account that this document will not differentiate between identified and unidentified accidental actions, and that the lack of professional knowledge has to be considered as an accidental action as well, the following definition of accidental actions will be used:

Accidental actions are defined as actions with low probability, severe consequences of failure and usually of short duration. Typical examples are fire, explosion, earthquake, impact, natural hazards, human errors in design and construction, improper use, terrorist attacks, the lack of professional knowledge and so on.

2.4.2 Codes and regulations

To ensure building structures are calculated with equal principles and an overall safety is guaranteed, structural engineers need to design according to the national building regulations. The Dutch Building Decree dates from 2012 and in most cases it refers to the Eurocode; the European standards. Both in the Eurocode and the Dutch Building Decree attention is paid to accidental actions.

2.4.2.1 DUTCH BUILDING DECREE

In The Netherlands the most recent regulations date from 2012. In article 2.3 of the 'Bouwbesluit 2012' the following is written about accidental actions (Bouwbesluit, 2012):

1. A building structure does not collapse during its intended life, as prescribed in NEN-EN 1990, during exposure to accidental load combinations, as prescribed in NEN-EN 1990, if this leads to collapse of another structure* not in the direct proximity of this structure. Hereby the identified accidental actions, as prescribed in NEN-EN 1991, are assumed.
2. A roof or floor does not collapse during the design life, as prescribed in NEN-EN 1990, during exposure to accidental load combinations, as prescribed in NEN-EN 1990. Hereby impacts as described in NEN-EN 1991 are assumed.

**With structure, a structural member is meant. Not a complete building structure.*

By only mentioning *identified* accidental actions (quantifiable abnormal events such as gas explosions or impact of vehicles) and leaving *unidentified* accidental actions (hard to identify, such as human errors) out in point 1, the structural calculations do not have to take, for example, human errors, bomb explosions or malicious impacts into account.

The Dutch Building Decree often refers to the Eurocode. Sometimes with extra rules to follow, but in general the Dutch engineers follow the Eurocode to make the structural design of a building. For accidental actions the Dutch Building Decree is slightly more specific than the Eurocode. Not only are only the identified accidental actions mentioned, but also the term 'disproportionate' used in the Eurocode (see next paragraph), is explained more specifically by mentioning *"… if this leads to collapse of another structural member not in the direct proximity of this structural member".*

2.4.2.2 EUROCODE

The Eurocode was written by the European Committee for Standardization. When a new Eurocode is established, the countries have a certain period to adapt the standard with their own national annex. When this national annex is made, the standard can be made official in this specific country. But until the time the national building regulations or some other law refers to the standard, it is solely an advise. In The Netherlands the Building Decree refers to the Eurocode often. Concerning accidental actions, as mentioned in the previous paragraph, NEN-EN 1991 and the general NEN-EN 1990 are referred to.

NEN-EN 1990

This standard, also known as Eurocode 0, is about the basis of structural design. It states the following about designing on accidental actions:

A structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause.

By mentioning human errors as a possible cause, the Eurocode does, in contrast to the Dutch Building Regulations, assume *unidentified* accidental actions. Furthermore the term *disproportionate* is being introduced. No explanation is given on what is considered disproportionate.

NEN-EN 1991-1-7

Eurocode 1 is about actions on structures. More specifically, NEN-EN 1991-1-7 is about accidental actions.

<u>Accidental design situations</u>

Chapter 3 of the standard is about strategies for accidental design situations. To avoid disproportionate collapse, table 2 can be used in a specific situation. The table is based on a distinction between identified and unidentified accidental actions. Since it is not known which actions can occur and what their consequences are for the actions categorized as unidentified, these strategies are based on limiting the extent of localized failure. Since the Dutch Building Decree only mentions identified accidental actions, only the left part of table 2 is mentioned.

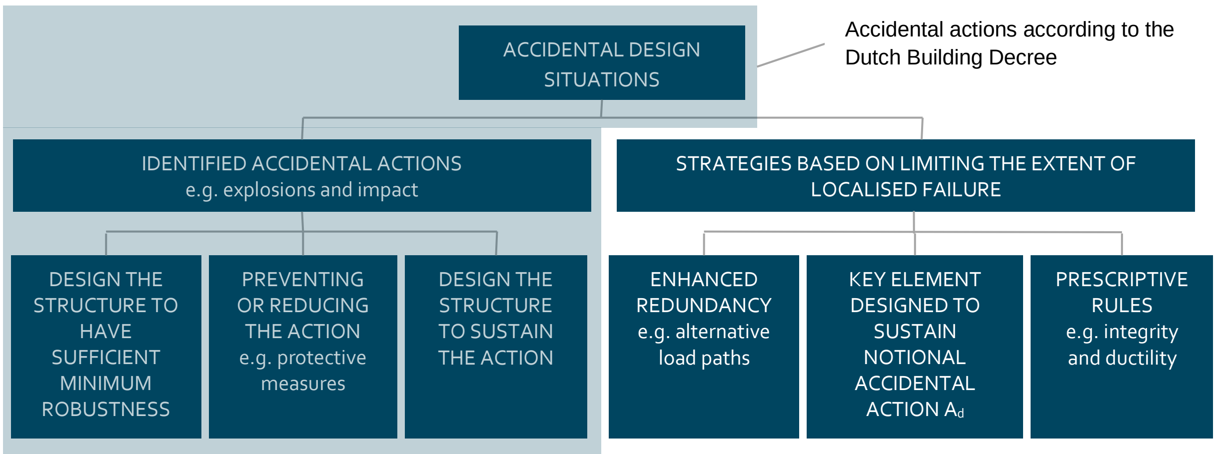

TABLE 2 STRATEGIES FOR ACCIDENTAL DESIGN SITUATIONS (CEN, 2006)

Notable is that the strategy 'based on limiting the extent of localized failure' is a strategy for *unidentified* actions, but the value A_d is based on the force a gas explosion in London in 1968 caused (Ronan Point), while a gas explosion should be considered as an *identified* accidental action.

<u>Identified accidental actions</u>

The Eurocode gives five criteria to judge if an identified action has to be taken into account. The criteria are the following:

- Taken measures to prevent the accidental action from happening or to reduce the consequences;
- Probability that the accidental action takes place;
- Consequences after occurring;
- Public perception;

- Acceptable risk level.

For examples of identified accidental actions that can occur, the National Annex gives a list of possible hazards. These have to be evaluated with the above-mentioned criteria. After this, a (probably shortened) list of hazards is obtained for which measures have to be taken. These measures can consist of one of the three methods mentioned in table 2. Depending on the consequences class of the project the calculations have to be done more or less precise.

Unidentified accidental actions

For unidentified accidental actions a method based on localized failure is prescribed. There are three main measures that can be taken against unidentified accidental actions (CEN, 2006):

- designing key elements, on which the stability of the structure depends, to sustain the effects of a model of accidental action A_d;
- designing the structure so that in the event of a localized failure (e.g. failure of a single member) the stability of the whole structure or of a significant part of it would not be endangered;
- applying prescriptive design/detailing rules that provide acceptable robustness for the structure (e.g. three-dimensional tying for additional integrity, or a minimum level of ductility of structural members subject to impact).

Annex A: Designing for the consequences of localized failure (unidentified accidental actions)

For these design strategies in Annex A of NEN-EN 1991-1-7 (should be read as informative) a distinction is made in the different consequence classes.

1. For buildings in consequences class 1 no further consideration is necessary with regard to accidental action from unidentified causes.
2. For consequences class 2a (lower group), horizontal ties or anchorage of suspended floors to walls should be provided.
3. In consequences class 2b buildings (upper group) both horizontal and vertical ties should be installed or as alternative, it should be checked that by removal of a load bearing structural element the damage should not exceed a certain limit. The Dutch Annex gives 15% of the attached floors area or 100 m^2 as proposed limit.
4. For consequences class 3 buildings a risk assessment on both foreseeable and unforeseeable hazards should be done. Guidance on the risk assessment is provided in Annex B.

Annex B: Risk assessment for consequences class 3

Annex B of EN 1991-1-7 (CEN, 2006), which should be read as informative, describes how an engineer can perform a risk assessment on accidental actions for buildings categorized as consequence class 3. It has a general descriptive (qualitative) and a numerical (quantitative) part. The risk assessment of NEN-EN 1991-1-7 annex B will be elaborated more in section 3.3.

2.5 CONCLUSION

Even though the responsibilities are not always clearly allocated in the building process, the annual probability of fatalities because of structural failure is lower than the limits. For residential end-users the Eurocode gives a maximum allowable probability of 10^{-5} per year of death due to structural failure. The research by Storybuilder showed a probability of death for residential end-users of 1,1 x 10^{-8} per year. However, this research was based on only 3 fatalities in 17 years. One more incident alone would have had a great influence on the predicted probability. Research of CIRIA gives an annual probability of 10^{-7} per year of dying due to structural failure, which is also below the limit of 10^{-5} per year. However, although the total probability of death due to structural failure might be small enough, a single building might not fulfill safety restrictions.

When fatalities due to building collapses are compared to other deadly incidents (diseases, natural hazards, etc.), it seems that people tend to find the probability of dying as a result of a building collapse within acceptable limits, according to Ellingwood and Reid. People 'feel' like a probability of 10^{-6} per year is low enough, contrary to the probability of getting, for example, a deadly disease (10^{-3} per year).

So although the Onderzoeksraad voor Veiligheid states that a lot can be improved in the building industry, the results are actually not that bad. Yet surely it should be mentioned that the less accidents happen, the better. Also the results can differ a lot when another time frame or location for example is taken into consideration. These arguments combined argue for improvement on the matters where improvement is possible.

The definition of EN 1991-1-7 is used as a basis for the definition of accidental actions used in this thesis. No difference is made between identified and unidentified accidental actions. The following definition is used in this thesis:

Accidental actions are defined as actions with low probability, severe consequences of failure and usually of short duration. Typical examples are fire, explosion, earthquake, impact, natural hazards, human errors in design and construction, improper use, terrorist attacks, the lack of professional knowledge and so on.

The Dutch Building Decree refers to the Eurocodes 0 and 1 for designing against accidental actions, but adds an explanation to the term 'disproportionate' used in the Eurocode. The Dutch Building Decree states that due to an identified accidental action a collapse of a structural member may not cause the collapse of a structural member not in direct proximity of that member, and that a floor or roof does not collapse due to impacts.

By stating *A structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause,* the Eurocode 0 does include, in contrary to the Dutch Building Decree, the unidentified accidental actions by mentioning human errors. However, the term disproportionate is not explained.

Eurocode 1 gives separate design strategies for identified and unidentified accidental actions. For identified accidental actions a list with examples is available. For unidentified accidental actions, a design should be based on general rules like the provision of horizontal or vertical ties. Which design strategy should be used depends on the consequence class of the building. For CC3 buildings a risk assessment should be made for both identified and unidentified accidental actions. An example of how one should perform such a risk assessment is explained in Annex B of EN 1991-1-7 and will be explained more in chapter 3.

3. METHODS FOR RISK ASSESSMENT

3.1 INTRODUCTION

This chapter will present the basis for the protocol for the quantitative risk assessment on accidental actions presented in chapter 4. First a definition of a quantitative risk assessment will be given, after which examples of current used methods for risk assessments will be compared. The last section will present the method for quantifying the risks of accidental actions. The following key questions will be answered in this chapter.

- What is a quantitative risk assessment?
- How do engineering firms currently perform a risk assessment on accidental actions?
- How can the probabilities that accidental actions occur be quantified?
- How can the consequences of accidental actions be quantified?
- What should the maximum level of tolerable risk be?

3.2 DEFINITION RISK ASSESSMENT

According to Marvin Rausand in his book Risk Assessment (Rausand, 2011), a r**isk assessment** is an "*overall process of risk analysis and risk evaluation"* in which the risk analysis and risk evaluation are explained as follows.

- *"**Risk analysis**: Systematic use of available information to identify hazards and to estimate the risk to individuals, property and the environment.*
    a. ***Qualitative risk analysis**: A risk analysis where probabilities and consequences are determined purely qualitatively.*
    b. ***Quantitative risk analysis**: A risk analysis that provides numerical estimates for probabilities and/or consequences-sometimes along with associated uncertainties.*
- ***Risk evaluation**: Process in which judgments are made on the tolerability of the risk on the basis of a risk analysis and taking into account factors such as socioeconomic and environmental aspects."*

This definition will be used in this report. For simplification reasons, where a 'quantitative risk assessment' is mentioned in this report, a risk assessment with a quantitative risk analysis is meant.

3.3 RISK ASSESSMENT: EXISTING METHODS

To determine the steps needed to be taken in a risk assessment, different existing methods will be used as references. The RISMAN method, the risk assessment advised in the 'Manual for the systematic risk assessment of high-rise structures against disproportionate collapse', the risk assessment advised in the Eurocode and the method proposed in the Stufib 8 report will be compared in this section.

3.3.1 RISMAN

The RISMAN method is a method for risk management (CROW). It consists of five steps in which the risks are described, implemented, evaluated and updated, see figure 3.

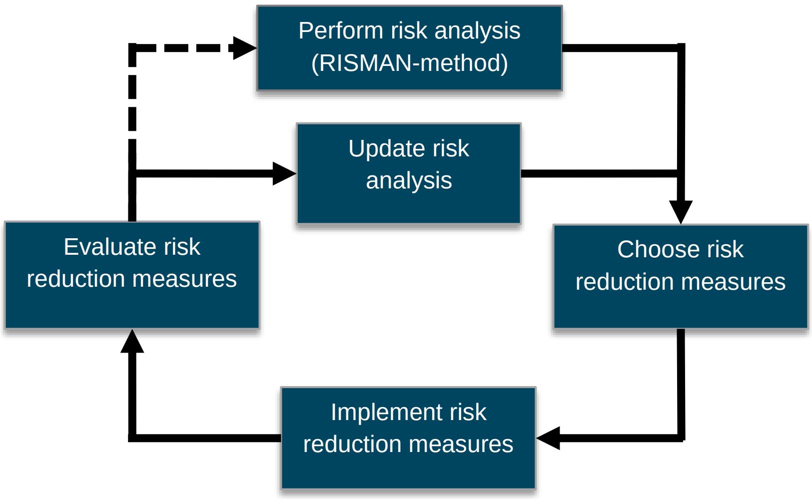

FIGURE 3 RISMAN METHOD FOR A RISK ASSESSMENT

Step 1: Perform integral risk analysis

First the goal for the risk analysis will be determined. With a goal it becomes clear what an unwanted situation for the project will be. After determining the goal, a list of possible risks is made. This is done by looking at the project from the following points of view. In *Italic* examples are given on how the aspects can be interpreted for a building project.

1. Organizational

When a building collapses, organizational consequences could for example be that people do not trust the responsible company anymore. The company might lose work and could go bankrupt.

2. Financial/economical

A clear and quantifiable consequence is financial. It can be estimated how much the damage of a collapse will cost to repair.

3. Managerial/political

In The Netherlands at the moment new laws are being made to ensure structural safety. A new collapse could for example influence the outcome of this law.

4. Technical

A technical consequence is what exactly goes wrong to cause the building to partly collapse. For example the amount of square meters that will be damaged or destroyed. In addition to the structural elements, non-structural elements can be taken into account as well.

5. Legal

When a collapse can be attributed to a person or company, legal consequences can follow.

6. Geographical/spatial

A building collapse usually creates a lot of chaos. The debris falls down on the street, for example. This could mean the road becomes blocked and cannot be used for a while. Moreover neighboring buildings can suffer consequences from the collapse, for example, becoming inaccessible for a certain period because of the remaining danger.

7. Social

Injuries and fatalities can be listed as social consequences. This can be quantified by an estimation on how many people will be harmed by the collapse.

The hazards will be either qualitatively or quantitatively graded on the probability and consequence. A list is made with the higher risks at the top of the list and the lowest at the bottom.

<u>Step 2: Determine measures</u>

In this step the measures that will be executed are chosen. This is done according to the expected effect on the risk and the costs to execute it. The outcome of this step will be a list with the risk, the measure(s) that will be taken to reduce the risk and the responsible person for this risk and measure.

<u>Step 3: Implement measures</u>

The chosen measures are implemented. This should be done by the person who has been made responsible for the specific measure.

<u>Step 4: Evaluation of measures</u>

At certain intervals the measures will be evaluated. It will be checked if the measures are taken and if they perform according to the expectations.

<u>Step 5: Update the risk analysis</u>

After the evaluation the list of risks has to be updated. Risks that are no longer a threat will be removed and possible extra risks will be added. Measures against the extra risks will be determined in this step as well.

3.3.2 MANUAL FOR THE SYSTEMATIC RISK ASSESSMENT OF HIGH-RISE STRUCTURES AGAINST DISPROPORTIONATE COLLAPSE

In *Manual for the systematic risk assessment of high-risk structures against disproportionate collapse* (Cormie, 2013), a step by step guide (see figure 5) is given on how to do a risk assessment on high-risk structures against disproportionate collapse.

In contrast to the RISMAN method, in the manual for systematic risk assessment the engineer should not start with determining the goal of the risk assessment. Here the first step is to identify the hazards, after which the first easy hazards must already be eliminated where feasible to do so. Furthermore the level of tolerable risk has to be determined before the risks are evaluated.

In step 4 the probability, consequence and risks are determined in a semi-quantitative way (estimated in categories, not numerical, see figure 4). For each of the hazards, risk reduction measures must be identified. To choose which of these measures is to be implemented, a cost-benefit assessment is done. After the choice has been made which measures will be implemented, the residual risk will be reviewed.

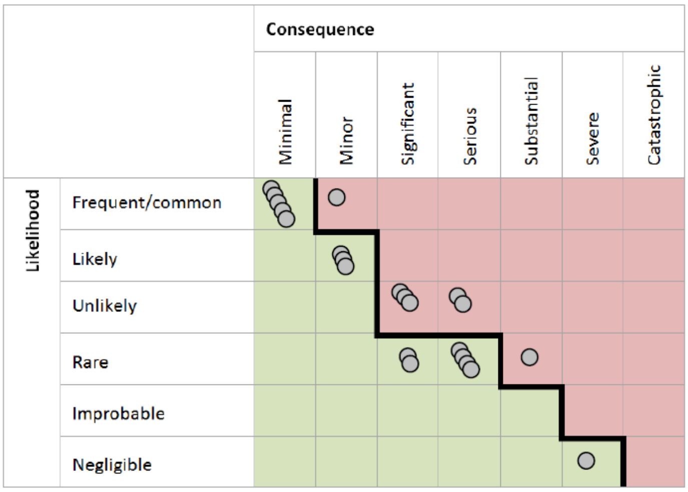

FIGURE 4 CATEGORIZATION OF EXAMPLE RISKS (CORMIE, 2013)

Step 9 of the risk assessment is to check the sensitivity of the risk assessment: whether there are cliff edge effects (hazard for which a small change in assumption would mean a huge change in the consequences), low probability /high consequence hazards (hazards for which the probability is estimated as small and the consequence as high) or combined hazards that need to be taken into account.

The final steps are to review the overall level of risk and effectively communicate about the remaining risks. A more comprehensive explanation of this method is presented in appendix A.

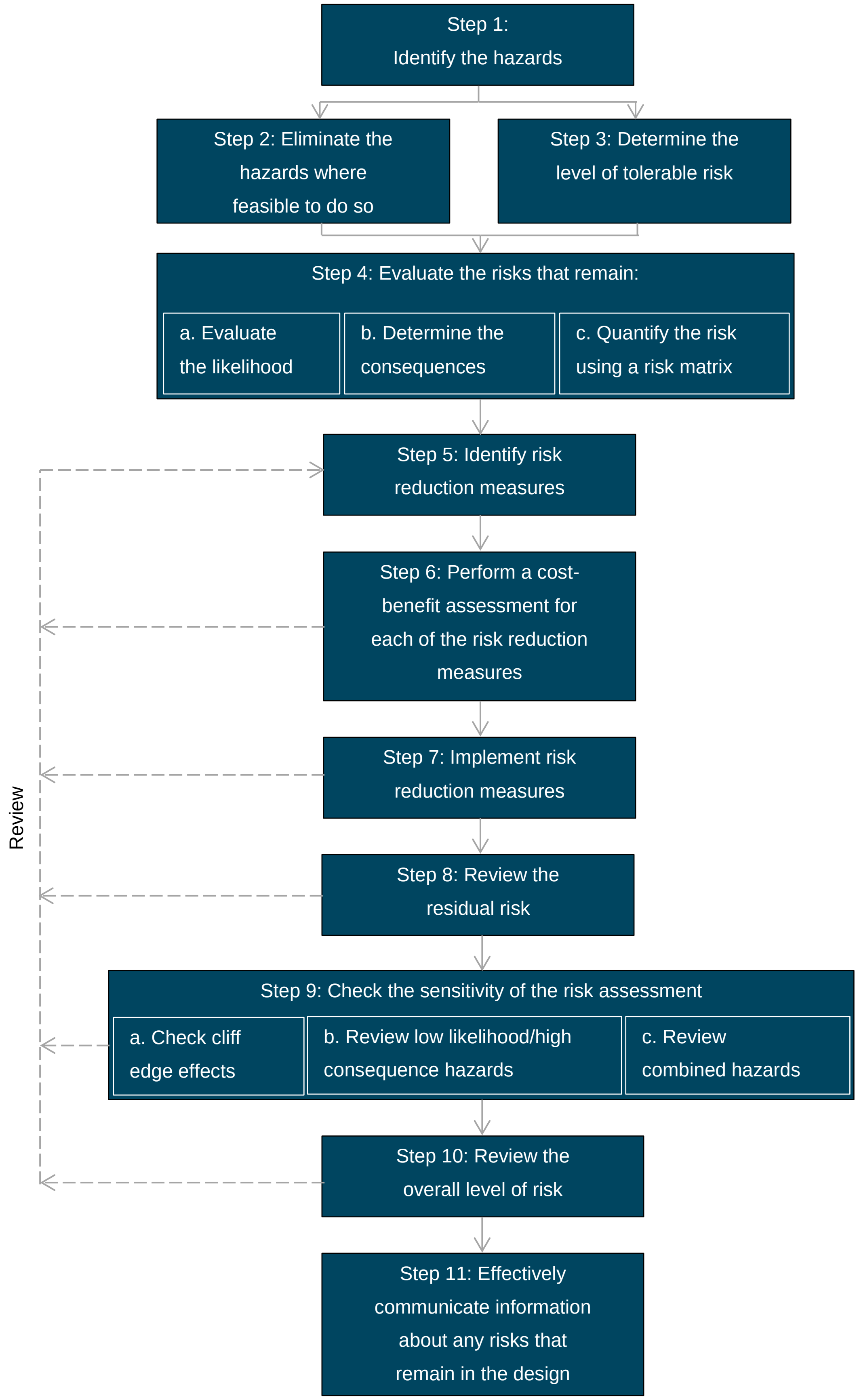

FIGURE 5 GUIDELINE FOR PERFORMING RISK ASSESSMENT (CORMIE, 2013)

3.3.3 EUROCODE

Annex B of EN 1991-1-7 (CEN, 2006), which should be read as informative, describes how an engineer can perform a risk assessment on accidental actions for building categorized as CC3. It has a general, descriptive (qualitative) and a numerical (quantitative) part, see figure 6.

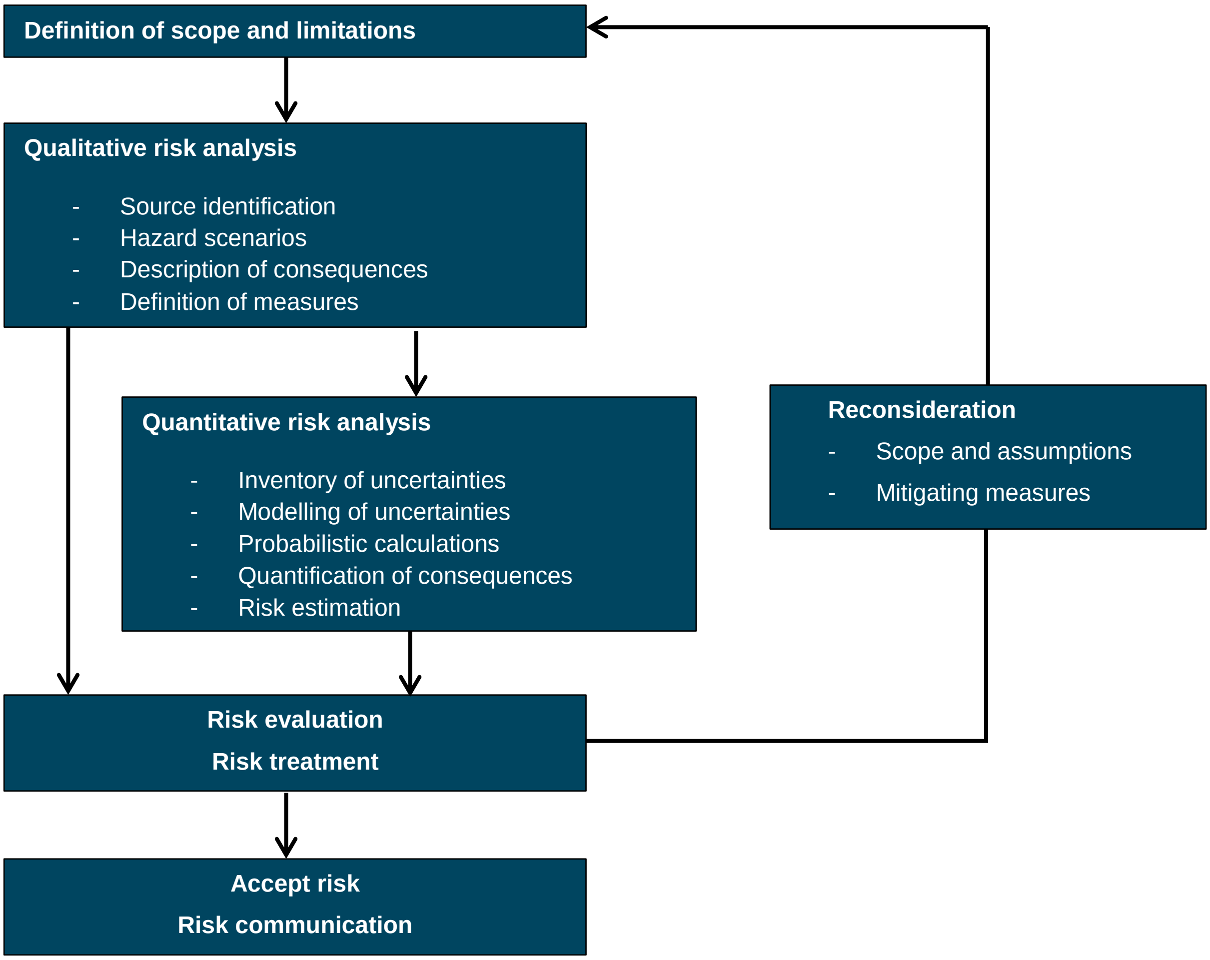

FIGURE 6 EUROCODE RISK ASSESSMENT METHOD

Qualitative risk analysis

In this part the possible hazards should be identified and described, including the failure scenarios and consequences that may follow. When defining the hazard scenarios, the following should be taken into account (CEN, 2006).

- The anticipated or known variable actions on the structure
- The environment surrounding the structure
- The proposed or known inspection regime of the structure
- The concept of the structure, its detailed design, materials of construction and possible points of vulnerability to damage or deterioration
- The consequences of type and degree of damage due to the identified hazard scenario

After describing the different hazard scenarios, a list should be created with possible measures that can be taken to reduce the risks.

<u>Quantitative risk analysis</u>

In the quantitative part the probability and consequences must be estimated. There are multiple ways in which this can be done. The engineer can for example estimate the probability of a specific hazard occurring, or they can use data to predict the probability. When the structural failure can also be expressed numerically, the risk can be calculated by multiplying the probability and consequence. A matrix can show the results, either when done fully numerically or only half.

For determining the level of tolerable risk mostly an upper bound and lower bound are given. When a risk lies below the lower bound (light blue indicated in the figure 7), no measures need to be taken. When it lies above the upper bound (dark blue), mitigation measures should definitively be taken. When it is between the lower and upper bound (medium blue), the ALARP (as low as reasonably practicable) principle is being used: lower the risks as much as is reasonably doable for an acceptable price.

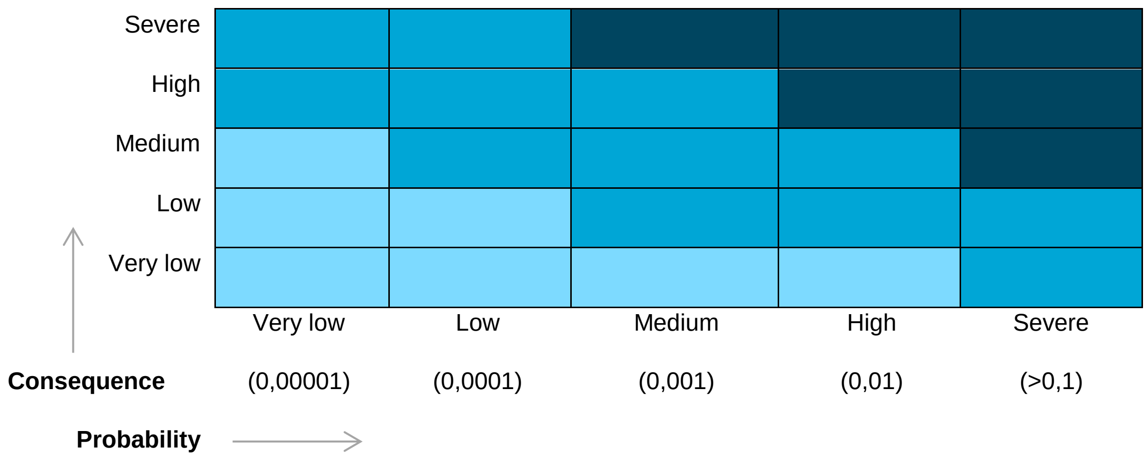

FIGURE 7 CATEGORIZATION OF RISKS EXAMPLE ACCORDING TO EUROCODE

The following two aspects will mostly be taken into account when determining the level of tolerable risk (CEN, 2006).

- The individual acceptable level of risk: individual risks are usually expressed as fatal accident rates. They can be expressed as an annual fatality probability or as the probability per time unit of a single fatality when actually being involved in a specific activity.
- The socially acceptable level of risk: the social acceptance of risk to human life, which may vary with time, is often presented as an F-N curve, indicating a maximum yearly probability F of having an accident with more than N casualties.

The scope and assumptions and the mitigating measures should be reconsidered until the risks can be accepted by and communicated with all stakeholders.

3.3.4 STUFIB

Stufib is a Dutch organization which focusses on the development of structural concrete. As it seemed to be unclear for structural engineers what to do with the risk assessment, Stufib wrote report 8 in 2006. In this report recommendations are given to create enough redundancy in the design to withstand damage caused by accidental actions. (Ing. R. Sagel, 2006). Table 3 shows a roadmap on what to do on which occasion, according to Stufib.

CC	Structural system:	What should be done extra when considering accidental actions:
CC1	Anything	Nothing
CC2-low	Columns	Construct horizontal ties around the floors and internally for every column in two directions.
	Load bearing walls	Nothing
CC2-high	Columns	Choose one of the following: - Effective horizontal and vertical ties; - Virtual removal of a structural element should not cause more than 15% collapse of one of the attached floor areas; - Design elements which cause more than 15% collapse of the floor area as key elements.
	Load bearing walls	Two types of ties: internal ties in two orthogonal directions in the whole floor, and around the floor a tie in the first 1,2 meter.
CC3	Anything	Perform a risk analysis. In this analysis firstly a description of the object is given, which includes the following points: - Strategic role of the building for the society; - The probability on a high number of victims; - The innovative character of the structure and the used materials; - The possibilities on extraordinary risks caused by industrial activities; - The probability of terroristic or other attacks. The possible risk scenarios including the cause, mechanism and measure per risk have to be described. The following examples are given: - Unforeseen high values of variable actions; - Different circumstances in the soil and other environmental conditions - Identified accidental actions like fire, explosions and impacts - Unidentified accidental actions - Low resistance of the structure

TABLE 3 STUFIB: DESIGN STRATEGIES ACCORDING TO CONSEQUENCE CLASS

For CC1 nothing has to be done to reduce the risks of accidental actions to an acceptable level. For CC2 (low and high), a strategy based on localized failure (unidentified cause) is advised. No specific identified actions have to be taken into account. For CC3 it is advised to list possible risks. For each risk the cause, mechanism and measures have to be written down, so the structural engineer is encouraged to think about the risks in a structured way.

Although Stufib offers the most concrete guidance for performing a risk analysis for CC3 buildings, even in this report it is not made clear how to quantify risks and judge if, in the end, the building is designed safe enough. The risk assessment method of Stufib is purely qualitative. The report helps the engineer to think of risks by giving examples, although the Eurocode does the same. Stufib helps, by letting the engineer think of the cause, mechanism and measures, to think about how to deal with a risk. Mostly it helps by giving a better overview about what to do in which situation. It is something an engineer can follow and execute, while the Eurocode is unclear in the deliverables.

3.3.5 Risk assessments in the field

To see how engineering firms currently use the regulations in their design, five risk assessments of five different companies are compared: Van Rossum Raadgevende Ingenieurs B.V., Pieters Bouwtechniek and Bartels Ingenieurs voor Bouw & Infra as structural engineering companies, BouwQ as a quality control company and Expertisecentrum Regelgeving Bouw who advised on the judgment of hollow core slabs under fire conditions. The structural engineering firms all follow the Stufib method: describe the possible threats, given by Stufib, in a qualitative way and explain the mechanism and measures taken per threat. BouwQ and Expertisecentrum Regelgeving Bouw have their own method for performing a risk assessment.

BouwQ is a firm that checks the technical quality of a building. Most insurance companies ask for a certificate of such a firm to make sure the building is of sufficient quality. The buyer or investor can hire for example BouwQ to do a check and deliver the certificate to the insurance company to get their insurance. One of the reports BouwQ delivers is a risk assessment on the structural safety. They check all the calculations of the engineering firm and highlight risk factors. The important risks are described and written in a report, which is sent to the engineering firm. The engineer has to either prove that the described risks are of less importance, since they did perform the right calculation, or they have to change it. Changing can cause a lot of trouble, since the check is sometimes (for example for Pontsteiger) only performed at moment the construction has already started or is about to start. Making adjustments at that time can be costly. BouwQ's risk analysis makes is unlike that of other firms. BouwQ organizes a session with multiple employees to think of possible risks, and as such they do not follow the Stufib (or Eurocode) method.

Expertisecentrum Regelgeving Bouw investigated the behavior of hollow core slab under fire conditions. They advise on how one can judge if the hollow core slabs of an existing or a new building will be sufficiently fire resistant, and what can be considered *sufficient*. Scholten, Vrouwenvelder and Van de Leur used the consequence class classification system of the Eurocode as a basis for their method of performing a risk assessment. They classify each structural member as consequence class 1, 2 or 3 according to the Eurocode. For each member the probability it collapses due to a fire is investigated. They sum up the probabilities of all the members classified as CC3 and verify if it is below the limit set in the Eurocode. For the CC2 members they sum up the probabilities of all the CC2 and CC3 members, since a CC3 consequence is at least a CC2 consequence as well. For the verification of the CC1 members, the probabilities of CC1, CC2 and CC3 are summed up and it is verified if they are below a certain limit. The limits they use are based on the structural safety β value given in the Eurocode. Depending on the design life of a building and the consequence class, this value will vary. From this β value a maximum allowable probability of failure can be determined. These values are used to verify if all the structural members fulfill the requirements. When this is not the case, measures have to be taken. (Dr. Ir. N.P.M. Scholten, 2015)

From both BouwQ and one of the structural engineering firms, an example is given below on how they describe a threat. The complete risk assessments can be found in appendix B.

3.3.5.1 VAN ROSSUM RAADGEVENDE INGENIEURS B.V.

For the Cooltoren project a risk analysis is made the way Stufib describes. First an explanation about the building and its environment is given, following the points Stufib addresses (strategic role of the building for society; the probability of a high number of victims; the innovative character of the structure and the used materials; the possibilities of extraordinary risks caused by industrial activities; the probability of terrorist or other attacks). An example is described in the following segment.

<u>The possibilities of extraordinary risks caused by industrial activities, traffic, water, etc.</u>

- *Industrial activities: no industrial activities take place in the surroundings so this is not a threat.*
- *Water: no water is in the direct surroundings of the building so this is no threat.*
- *Traffic: the probability that traffic under and next to the building will cause a collision with a structural element is high. This means these elements have to be designed on these loads according to Eurocode 1-7.*

After the description of the project, the different accidental actions (unforeseen high values of variable actions; different circumstances in the soil and other environmental conditions, identified accidental actions like fire, explosions and impacts, unidentified accidental actions, low resistance of the structure) are described and explained by mentioning the threat, mechanism and measures. An example is the following:

<u>Unforeseen high values of variable actions</u>

- *Threat: The variable actions as stated in Eurocode 1, consider distributed loads for which the probability of exceedance is very low. Although the probability is low, it is still possible the loads can either locally or globally be higher than the value of the calculations.*
- *Mechanism: Collapse of the structure because of overloading.*
- *Measures: The main supporting structure of the tower will be designed with an over capacity and alternative load path according to Eurocode 1-7.*

3.3.5.2 BouwQ

BouwQ addresses specific risks per project and indicates the risk level as low, medium high or very high. The following is an example.

The basement lies 5 to 7 meters under the highest groundwater level. This means the walls have to be watertight. Besides the water pressure, the walls also have to be calculated for shrinkage tension. If not handled carefully, it can cause cracks which make the basement not watertight.

- *Risk level: medium.*

Creation of an alternative load path is described as 'where possible' instead of an obligation. Not executing an alternative load path could have major consequences for the structural safety.

- *Risk level: high.*

The report BouwQ makes goes to the client and back to the engineer. No suggestion is given which indication (medium, high, very high) is considered too high and should be dealt with. The idea is that the client is responsible so he has to check with the engineering firm which risks they must eliminate.

3.4 QUANTIFICATION OF RISKS

To quantify risks, the probability and consequence have to be quantified. In this section first attention is paid to the probability and then to the consequences. The last part will be about how the risk can be quantified using the probability and consequences discussed.

3.4.1 PROBABILITY

The probability can be described as the probability an event happens and it causes the consequence of interest. For making a risk assessment for checking the safety of a building on structural failure due to accidental actions, the probability can be quantified in two ways:

1. The engineer estimates the probability of a failure scenario causing the consequence of interest.
2. Data of past collapses are used to estimate the probability of a failure scenario happening causing the consequence of interest.

Up until now when a risk assessment was made in a quantitative way, mostly number 1 (the engineer estimating the probability) has been used to quantify the probability. However, using number 2 (the use of data) is less vulnerable to subjectivity. When enough data is available this can be used to predict the probability of certain hazards causing a collapse in the future. This chapter will investigate if enough data is available.

In addition to the different ways of estimating what the probability is, it is also important to understand which probability is exactly of interest. When a certain accidental action happens, it does not necessarily result in the building *collapsing* due to that accidental action. Different failure scenarios can follow an accidental action, which can all either cause a collapse or not, and if it causes a collapse, the magnitude can differ. So not only the probability of an incident happening caused by an accidental action, but also the probabilities of that specific accidental action causing a certain failure scenario, and the probability of that scenario causing the consequence are of interest. These four probabilities have to be multiplied by each other to obtain the total probability (figure 8).

In this section different sources which investigated probabilities of accidental actions will be compared. Not all research uses the same sub probability which can immediately be used to calculate the usable probability. Each section first explains which probability is meant by that research. Three different studies are used to see if it is possible to quantify, by using data, the probabilities of an accidental action happening and causing the consequence of interest. These studies are based on past events both in The Netherlands and in other countries. The data from the Netherlands come from the report of Terwel (Terwel, 2014), which collected it from Cobouw, ABC registration and Dutch arbitration awards. The other data come from other countries and are older (~1970-1990).

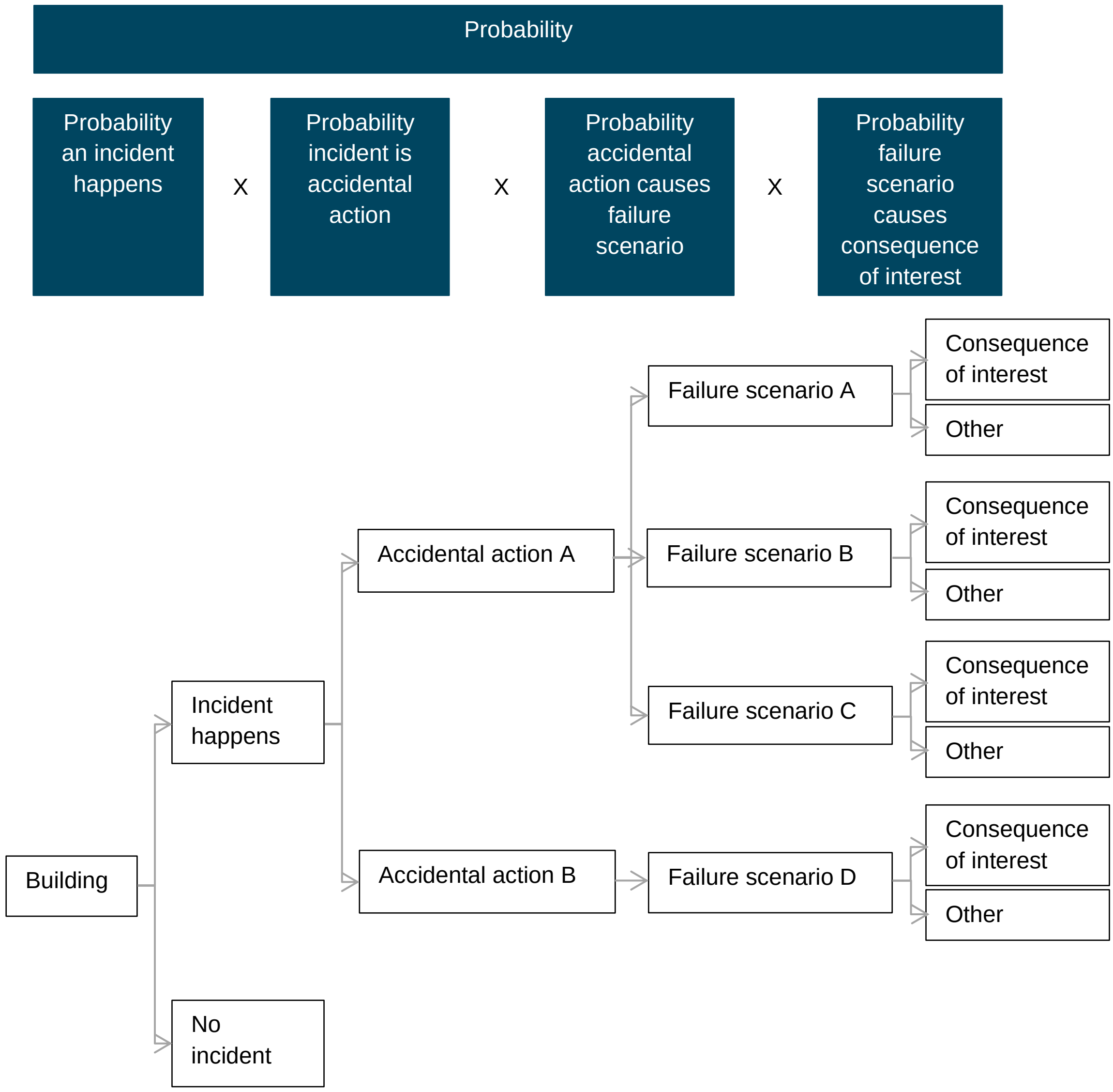

FIGURE 8 VISUALIZATION OF SUBDIVISION OF PROBABILITIES

3.4.1.1 SOURCE ONE: DESIGN AND CONSTRUCTION ERROR EFFECTS ON STRUCTURAL RELIABILITY

Bruce Ellingwood in his report researched the probabilities of the occurrence of human errors in general (Ellingwood B. , 1987). He does not specify what failure scenario followed those human errors, nor does he specify how many incidents were investigated in total. The following figure 9 gives a visual impression of which probability was investigated in this research compared to what is needed to calculate the total probability for quantification in a risk assessment.

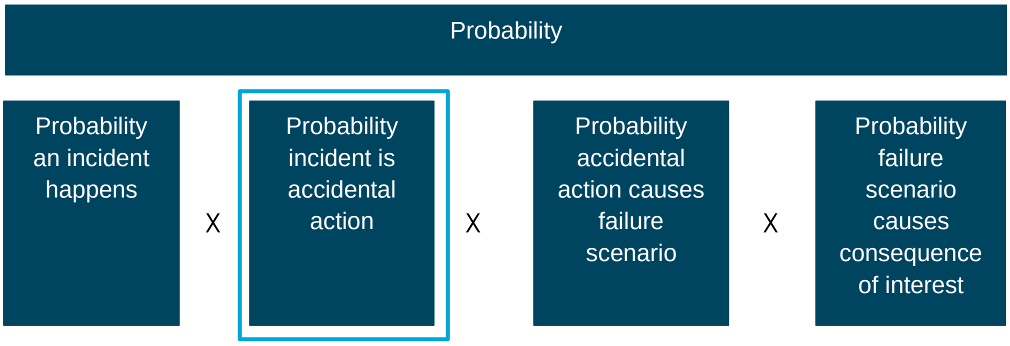

FIGURE 9 PROBABILITIES FROM 'DESIGN AND CONSTRUCTION ERROR EFFECTS ON STRUCTURAL RELIABILITY'

Ellingwood divides three categories of errors, namely (1) the errors of concept (stupidity, ignorance), (2) errors of execution (carelessness, forgetfulness, negligence) and (3) errors of intention (venality, irresponsibility). He used research by Matousek (Matousek, 1981) and Melchers et al. (R. E. Melchers, 1983) to quantify the probabilities of occurrence of those errors. Results can be seen in table 4.

Reference	Ignorance, negligence, carelessness	Insufficient knowledge	Forgetfulness, mistakes	Reliance on others	Other sources
Matousek (1982)	35%	38% [a]	9%	6%	12% [b]
Melchers, et al. (1983)	24%	52%	8%	2%	13%

[a] Breaks down as insufficient knowledge 25%; underestimation of influences 13%.
[b] Breaks down as unknown situations 4%; other sources 8%.

TABLE 4 ERRORS DIVIDED IN THREE CATEGORIES

It can be seen that most errors are due to ignorance, negligence, carelessness or insufficient knowledge. Forgetfulness, mistakes and reliance on others are minor sources of errors. Notable is the difference in the two studies on the ignorance, negligence, carelessness on one side and insufficient knowledge as the source of an error on the other side. Where Matousek has 35% and 38% respectively, Melchers et al. gives 24% and 52%. An explanation could be that the authors either interpreted the results differently or they made the survey they used for the results in such a way that the participants in the survey interpreted some questions differently.

The same report offers a table that describes at which stage of the building process errors are made according to twelve studies. See table 5. Most errors are made during planning and design and the construction phase.

Reference	Planning and design	Construction	Utilization including maintenance	Other[a]
CEB 157 (1983)	50%[b]	40%[c]	8%	-
Matousek (1982)	45%[d]	49%	6%	-
Taylor (1975)	36%[e]	12%[f]	-	-
Yamamoto and Ang (1982)	36%	43%	21%	-
Rackwitz and Hillemeier (1983)	46%	30%	23%	-
AEPIC	67%	33%	-	-
Melchers, et al. (1983)	55%	24%	21%	-
Fraczek (1979)	55%	53%	-	-
Allen (1979)	55%	49%	-	-
Hadipriono (1985)	19%	27%	33%	20%
Hauser (1979)	37%	35%	5%	23%
Gonzales (1985)	29%	59%	-	13%

[a] Includes cases where failure cannot be attributed clearly to any one factor and may be due to several of them.
[b] Broken down as planning 25%; design 25%.
[c] Broken down as materials 15%; execution 25%.
[d] Broken down as planning 11%; design 34%.
[e] Identified as design, not planning
[f] Does not differentiate between construction and utilization.

TABLE 5 ERRORS DIVIDED IN PHASE THEY OCCUR

From table 5 the average of the different studies can be calculated:

- Planning and design 44%
- Construction 38%
- Utilization including maintenance 10%
- Other 5%

3.4.1.2 Source two: Structural safety

The thesis of Terwel (Terwel, 2014) concludes that 90% of the structural failures are due to human error. Of those human errors, most are made in the design and construction phase (80-85%). The probabilities '*probability incident is accidental action'* and *'probability accidental action causes failure scenario'* are not separated in this research. Furthermore the '*probability failure scenario causes consequence of interest'* is given, while the '*probability an incident happens'* is missing (figure 10).

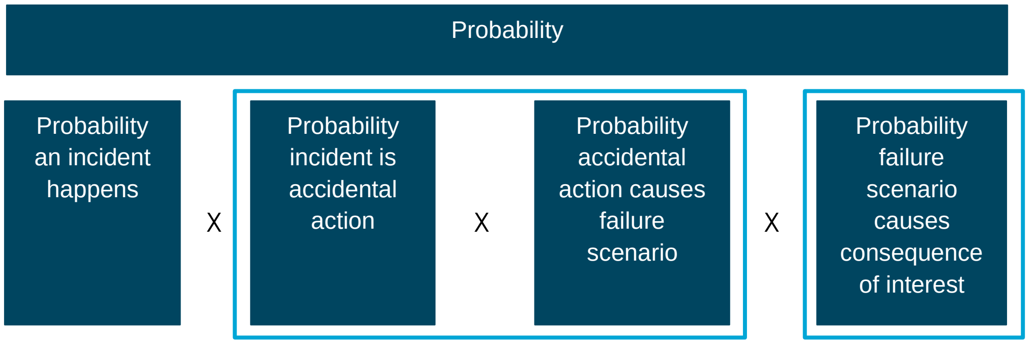

FIGURE 10 PROBABILITIES INVESTIGATED IN 'STRUCTURAL SAFETY'

Terwel did research on the structural failures registered by Cobouw (401 incidents), ABC registration (189 incidents) and Dutch arbitration awards (151 incidents). Terwel compared the results. The most relevant conclusions are the following.

- The type of building is important for how vulnerable it is to structural failure. Houses are less vulnerable than other buildings. This can be due to the large repetition factor (houses are often produced in series) and the larger dimensions in floors and walls than needed for structural safety due to sound and heat insulation regulations.
- The type of material used is not of much importance for the probability of failure.
- Horizontal elements are more vulnerable to failure than vertical elements. Roofs, balconies, beams and floors were damaged in 38% of the cases (average of Cobouw, ABC registration and Dutch arbitration). The total average of facades, walls and columns is 24%.
- Foundation failures are common (on average 17%), which is to be expected because of soft soils and erratic soil profiles in the Netherlands.
- In over 80% of the cases of ABC registration there was no damage because the errors were detected in time.
- A small portion of the failures is due to force majeure. Force majeure is when a failure is due to something that was not known at that time.

Cobouw elaborated more on what the cause of failure was in the specific phases. From the 401 incidents Cobouw registered, 135 had an undetermined cause. The rest could be accounted to the design, construction or use phase. The average percentages per phase of reference one (44% in the design phase, 38% during construction, 10% during use and 5% for other) are added in the list below. When the numbers of the previous and this reference are multiplied with each other, see below under ‘total’, the probability of a specific event being the cause of a given collapse is obtained.

	Design phase (44%)	Cobouw	Total
-	incorrect modeling or calculation error:	57%	57% * 44% = **25%**
-	conflicting drawing and calculation:	2%	2% * 44% = **1%**
-	absence of drawing and/or calculation:	19%	19% * 44% = **8%**
-	other:	21%	21% * 44% = **9%**

Construction phase (38%)

-	incorrect quality of materials applied:	27%	27% * 38% = **10%**

-	insufficient amount of material used:	14%	14% * 38% = **5%**
-	incorrect assembling of elements on the building site:	27%	27% * 38% = **10%**
-	erroneous measurements on the building site:	2%	2% * 38% = **1%**
-	other:	30%	30% * 38% = **11%**

Use phase (10%):

-	larger load than expected (also related to force majeure)	66%	66% * 10% = **7%**
-	insufficient inspection	2%	2% * 10% = **0,2%**
-	insufficient maintenance:	23%	23% * 10% = **2%**
-	other:	10%	10% * 10% = **1%**

Other phase: 5%

When these errors occur, the following outcomes are possible (including the percentages according to Cobouw and the average).

- (Partial) collapse (Cobouw 51%, average 27%)
- Structural damage (Cobouw 29%, average 24%)
- Material deterioration (Cobouw 8%, average 5%)
- Insufficient functionality (Cobouw 4%, average 13%)
- No actual damage (Cobouw 9%, average 31%)

Incorrect modeling/calculation error is the most likely cause of an incident. With an estimated probability of 25% of being the cause of a structural failure, it is more than twice as likely to being the cause than any other error given in the list above. The least likely causes are a conflicting drawing and calculation, erroneous measurements on the building site and insufficient inspection. Furthermore most errors have a probability between 1% and 11% of being the cause of a failure. Just one is 25%.

3.4.1.3 Source three: Progressive collapse, abnormal loads, and building codes

In the paper of D.E. Allen and W.R. Schriever (D.E. Allen, 1972) data is collected of progressive collapses and collapses with heavy damage in the USA and Canada. The data represent the probability an accidental action leads to a specific consequence (figure 11).

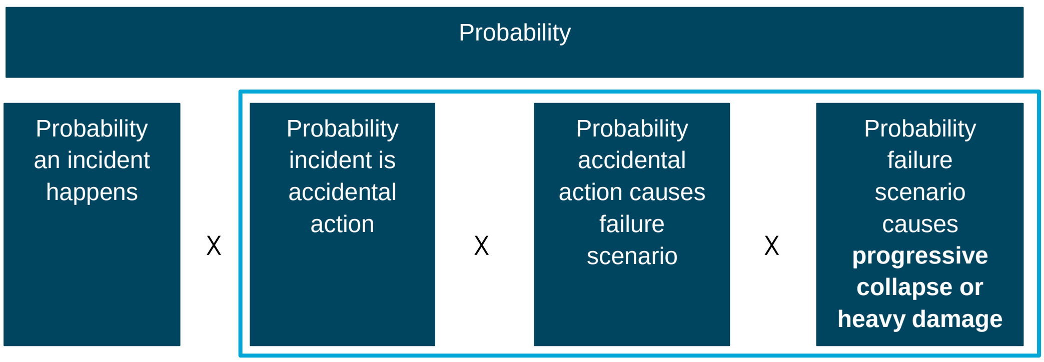

Figure 11 Probabilities investigated in 'Progressive collapse, abnormal loads, and buliding codes'

The USA data comes from Engineering News-Record from 1968 to 1972. The Canada data comes from newspaper clipping from 1962 to1972. The following table 6 with news incidents involving progressive collapse is presented in the report of Allen and Schriever.

Collapse designation	Engineering News Record (4 years)	Canada (10 years)
During construction		
- Due to impact, explosion	2 (2%)	1 (0%)
- Formwork, bracing or erection error	10 (9%)	35 (7%)
- Design error	1 (1%)	0 (0%)
During Service Life		
- Due to explosion	1 (1%)	0 (0%)
- Due to impact	4 (4%)	8 (2%)
- Design, manufacture or construction error	3 (3%)	22 (4%)
During demolition, adjacent excavation	1 (1%)	6 (1%)
TOTAL	**22 (20%)**	**75 (15%)**
Total news incidents involving all types of collapse	110	495

TABLE 6 NEWS INCIDENTS WITH PROGRESSIVE COLLAPSES IN THE USA AND CANADA

Between brackets the percentage of the specific type of error in comparison to the total news incidents is given. An important difference with the data from Terwel (Terwel, 2014) is that in table 6 ‘during construction’ means that the collapse happened during construction, while Terwel mentions the phase in which the error is made. Notable is that almost half of the collapses which are progressive, occur during construction due to formwork, bracing or an erection error.

Furthermore, in the paper of Allen and Schriever table 7 is presented. It contains incidents that caused heavy damage. The same sources are used for the data. It can be seen that of the news incidents in the USA and Canada during the years of research, most incidents with heavy damage come from impacts due to large falling or flying objects. However, it should be mentioned that for example fire or low strengths due to faulty design or workmanship is not mentioned in this research. Even though these could be significant causes of heavy damage as well. Also the vehicle impact by trucks and trains and the gas leak are accidental actions that are relatively common of being the cause of damage.

Type of loading	Engineering News Record (4 years)	Canada (10 years)
Explosions		
- Gas leak	5 (4,5%)	7 (1,4%)
- Dust or other chemical	0 (0%)	2 (0,4%)
- Bomb	1 (1%)	0 (0%)
- Excavation blast	0 (0%)	1 (0,2%)
Vehicle impact		
- Trucks, trains, cars	5 (4,5%)	10 (2%)
- Ships	1 (1%)	0 (0%)
- Airplane	1 (1%)	0 (0%)
Impact due to large falling or flying objects		
- During construction (falling elements etc.)	6 (5,5%)	14 (2,8%)
- During use (collapsing structures)	3 (2,7%)	8 (1,6%)
- Wind-blown objects (flying roofs etc.)	0* (0%)	12 (2,4%)
Excavation, sinkholes, slides, etc.	1 (1%)	20 (4%)
Miscellaneous	2 (2%)	6 (1,2%)
TOTAL	**25 (of 110)**	**80 (of 495)**
*Hurricanes , tornado and earthquake damages are not included		

TABLE 7 NEWS INCIDENTS OF ABNORMAL LOADS CAUSING HEAVY DAMAGE IN THE USA AND CANADA

The types of abnormal load events differ from the ones given in *Source two: Structural Safety* (Terwel) so they cannot directly be compared with each other. However what can be compared is the range of the probabilities. When it is assumed that the description of Terwel of '(partial) collapse' is the same as 'progressive collapse or heavy damage' by Allen and Schriever, the ranges of the presented numbers can be compared. The study of Terwel combined with the study of *Design and construction error effects on structural reliability*, most events had a probability between 0% and 11% of being the cause of a failure.

The percentages given by Allen and Schriever include the sub probability of '*probability scenario causes consequence of interest'*, where the percentages of Terwel do not. To compare the two studies, the numbers from Allen and Schriever will be divided by the probability of a failure being a (partial) collapse, given by Cobouw as 51% and with an average of Cobouw, ABC registration and Dutch arbitration award of 27%. The percentages presented in table 6 and 7 are mostly between 0% and 4%, with one exception of 8%. Using 27% as the probability of a failure being a (partial) collapse, the 0% to 4% corresponds to percentages between 0% and 15%, with one exception of 30%. Using Cobouw's 51%, gives percentages between 0% and 8% with one exception of 16%. Terwel's study gave 0% to 11% with one exception of 25%.

3.4.1.4 Source four: Design methods for reducing the risk of progressive collapse in buildings

The U.S. Department of commerce (E. V. Leyendecker, 1977) made a report for design methods for reducing the risk of progressive collapse in buildings. They studied previous cases of collapses. In this study all the sub probabilities (figure 12) are taken together.

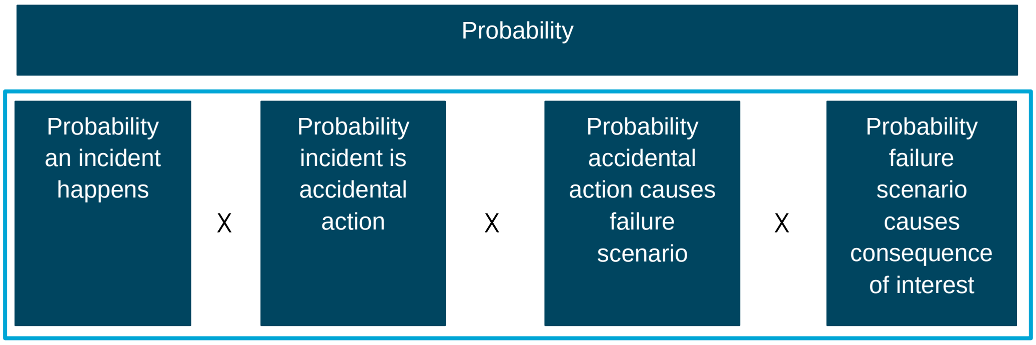

FIGURE 12 PROBABILITIES INVESTIGATED IN 'DESIGN METHODS FOR REDUCING THE RISK OF PROGRESSIVE COLLAPSE IN BUILDINGS'

Leyendecker's report mentions that gas explosions, bomb explosions and vehicular collision are the most contributing abnormal load events for buildings. Human errors were not considered as abnormal load events. In the year 1970 the total number of incidents due to abnormal load events in the U.S. were counted as well as how many of those caused intermediate damage and severe damage. The following description is given on intermediate and severe damage.

"Intermediate damage: Damage between $1.000 (with an average inflation rate of 3.89% per year this would be worth around $6.500 in 2019) and $10.000 (around $65.000) for gas explosion; $1.000 and $5.000 (around $32.000) for vehicular collision, or described as intermediate for bomb explosions. This level implies fairly extensive damage such as walls blown down.

Severe damage: Damage in excess of $10.000 for gas explosions; $5.000 for vehicular collision; or described as severe for bomb explosions. This level implies extensive structural damage, such as dwelling units destroyed." (E. V. Leyendecker, 1977)

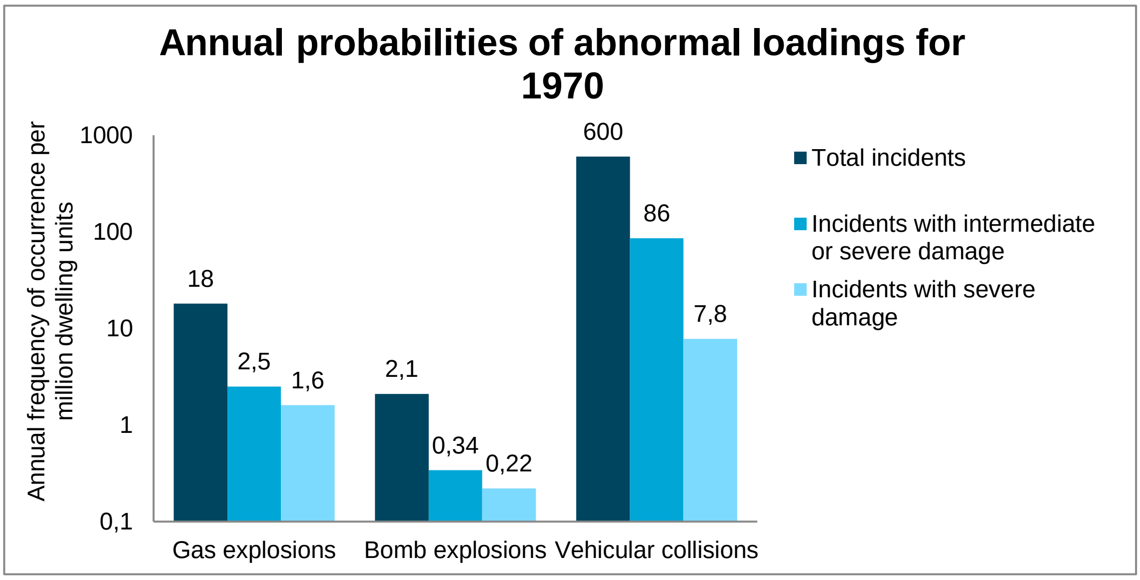

FIGURE 13 ANNUAL PROBABILITIES OF ABNORMAL LOADINGS FOR 1970

The following annual probabilities per abnormal load event causing intermediate or severe damage to a single building can be taken from figure 13.

		Annual probability per type of damage per building	
		Intermediate damage	Severe damage
Abnormal load (*AB*)	Gas explosion	2,5 x 10^{-6}	1,6 x 10^{-6}
	Bomb explosion	0,34 x 10^{-6}	0,34 x 10^{-6}
	Vehicle collision	86 x 10^{-6}	7,8 x 10^{-6}

These annual probabilities per type of damage per building cannot be compared to the other sources, since the others did not include the sub probability '*probability an incident happens'* (figure 12). However, what can be compared is the ratio between the gas, bomb and vehicle collision probabilities, since the '*probability an incident happens'* should be the same for other sources, the ratio between the probabilities should be roughly the same as well. Only source three (Allen and Schriever) took the gas explosions, bomb explosions and vehicular explosions into account as well. However, where source four (Leyendecker) gives all the incidents caused by one of those loads, source three makes a distinction in when the failure occurred and what type of damage was caused.

Furthermore, source three mentions 'explosion' during construction and does not specify what kind of explosion (gas, bomb or other). The same holds for the impact during construction; it is not divided into truck, train, car, ship and airplane impacts. However, in table 7 (causes of heavy damage) the explosions and vehicle impact are subdivided into truck, train, car, ship and airplane impacts. When the same ratio of the division in ‘heavy damage’ is used in ‘progressive collapse’, the following numbers are the ones to compare with the numbers given in this reference.

Gas explosions: (3,8 / 8) * (3 / 3,8) * 1% + (3 / 3,8) * 1% + 3% = 4,2%
Bomb explosions: (3,8 / 8) * (0,5 / 3,8) * 1% + (0,5 / 3,8) * 1% + 0,5% = 0,7%
Vehicular collisions: (4,2 / 8) * 1% + 3% + 4,2% = 7,7%

The ratio of the 4,2%, 0,7% and 7,7% should be the same as the ratio of 1,6 x 10^{-6}, 0,34 x 10^{-6} and 7,8 x 10^{-6} for respectively gas explosions, bomb explosions and vehicular collisions:

0,042 / (1,6 x 10^{-6}) =? 0,007 / (0,34 x 10^{-6}) =? 0,077 / (7,8 x 10^{-6})
26.250 ≠ 20.588 ≠ 9.872

It can be seen that the ratios are not the same, so the references would not give the same probabilities on a specific event being the cause of a failure. More specifically the ratios between the gas explosion probabilities and the bomb explosion probabilities is roughly similar, but the ratio between the vehicular collisions is around half of the other ratios. This could mean that the probabilities of the gas and bomb explosions are roughly the same in the two studies, but the probability of a vehicular collision being the cause of a failure is twice as high in the study of Leyendecker than of Allen and Schriever.

3.4.1.5 Comparison

From the four sources given in section 3.4.1 it can be concluded that not enough research is done to fully trust on data to quantify the probability needed for a risk assessment. The studies did not investigate the same type of probabilities and they looked at different load events as being the cause of a collapse. Even the collapses are differently described in the different studies.

However, when the percentages are compared as far as possible, the ranges found are roughly the same. The events of Allen and Schriever give a probability of between 0% and 15% with one exception of 30% of a specific event being the cause of the collapse, where Terwel found percentages between 0% and 11% with one exception of 25%. Leyendecker roughly agrees with the probabilities of the bomb and gas explosions of Allen and Schriever, but gives twice as high values for vehicular collisions. These numbers represent the ‘*probability incident is accidental action* x *probability accidental action causes failure scenario’* (figure 14).

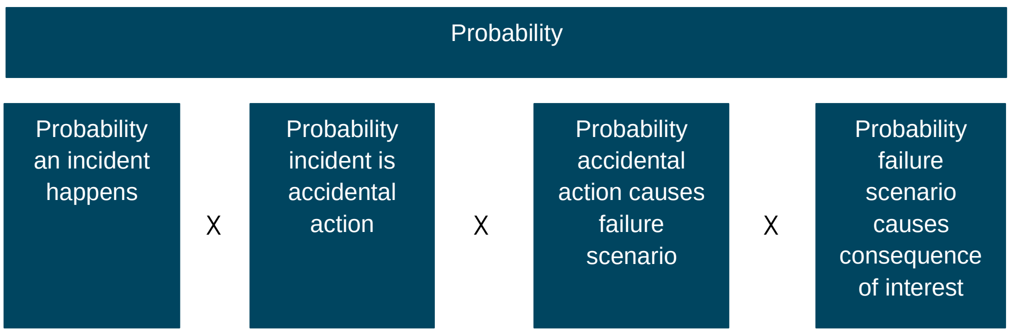

FIGURE 14 DIFFERENT TYPES OF PROBABILITIES GIVEN IN REFERENCES

When only '*probability incident is accidental action* x *probability accidental action causes failure scenario'* (or easier put as: the probability a given incident was caused by a specific failure scenario $P(F_{i,j,k}|I)$ with i representing all failure scenarios with a consequence of class 1, j the failure scenarios with a CC2 consequence and k all the failure scenarios with a consequence of CC3) are taken from the sources, Allen and Schriever give between 0% to15% with one exception of 30% and Terwel from 0% to 11% with one exception of 25%. Concluding that the sources cannot be used to precisely estimate the probability per event, the indications can be used to make a classification, both described in words as in percentages, for an engineer to estimate the probability.

	$\boldsymbol{P(F_{i,j,k}|I)}$
Severe	50%
Very high	25%
High	15%
Medium	5%
Low	1%
Very low	0,1%
Negligible	0,01%

However, to get the total probability a failure occurs and causes the consequence of interest $P_{CC1,2,3}(F_{i,j,k})$, the percentages of the above given indications have to be multiplied with the '*probability an incident happens',* or $P(I)$ and '*probability hazard scenario causes consequence of interest*, or $P(C|F_{i,j,k})$:

$$P_{CC1,2,3}(F_{i,j,k}) = P(I) * P(F_{i,j,k}|I) * P(C|F_{i,j,k})$$

For $P(I)$, the results of the Cobouw research can be used. When the 401 incidents Cobouw recorded in 16 years, of which only half had a consequence of (partial) collapse, are taken as a reference and assuming the total number of buildings in The Netherlands was around 10 million (Steeph, 2003), the probability a (partial) collapse occurs for a single building is around $6 * 10^{-5}$ per 50 years. Because this probability is only based on a reference period of 16 years, in which not all types of hazards occurred that could theoretically occur, a factor a must be added to the 6 x 10^{-5}. This $P(I) = a * 6 * 10^{-5}$ should represent the actual probability an incident happening in The Netherlands which causes structural failure per building per 50 years. It is assumed that this factor a must be greater than 1, because in the 16 years of Cobouw's research no big hazards such as a heavy storm occurred.

The $P(C|F_{i,j,k})$ is set as 1 because the failure scenarios following the accidental actions will be divided in the consequences they will cause (section 3.4.2). This means a failure scenario with consequence class 1 has a probability of 1 of causing a consequence of class 1. The same holds for CC2 and CC3.

3.4.1.6 EUROCODE

The Eurocode works with a so called reliability index β, which is used to, for example, determine the safety factors in the Eurocode. This β factor relates to the probability of failure by the following function:

$$P_f = \phi(-\beta)$$

Where ϕ is the cumulative distribution function of the standardized Normal distribution (NEN, 2002). Furthermore the Eurocode gives minimum β values for a design life of 50 years for CC1, CC2 and CC3 as 3,3, 3,8 and 4,3 respectively. These values can be transformed to the maximum probability of failure in 50 years, which results in 4×10^{-4} for CC1, 7×10^{-5} for CC2 and 8×10^{-6} for CC3.

3.4.2 Consequences

In the protocol for the risk assessment proposed in this thesis, the consequence classes of the Eurocode will be used to classify each accidental actions causing a specific failure scenario on their expected consequence. When dividing all failure scenarios in the CC1, CC2 and CC3 classes of the Eurocode, the maximum allowable probability per consequence class, also suggested by the Eurocode, can be used.

Table 8 gives a description of the consequences per consequence class (NEN, 2002), combined with an indication of the square meters floor area that will collapse per consequence class, added by the author. Note that the square meters floor area that will collapse is an indication and that it has to be reconsidered for every project.

Consequence class	Description consequence	Indication of square meters floor area that will collapse
CC1	Minor consequences with regard to the loss of human life, and/or small or negligible economic or social consequences or environmental consequences	< 10
CC2	Mediocre consequences with regard to the loss of human life, and/or significant economic or social consequences or environmental consequences	10-100
CC3	Major consequences with regard to the loss of human life, and/or very large economic, social or environmental consequences	> 100

TABLE 8 DESCRIPTION CONSEQUENCE CLASSES

Each failure scenario caused by accidental actions, has to be classified according to these descriptions and the view of the structural engineer. It is important to realize that the classification of the building itself, although employing the same terminology, is something different. A CC3 building does not automatically have all failure scenarios classified as CC3. Each failure scenario has to be reviewed individually to check which consequences will occur when the failure scenario happens. The following factors are important to take into account for classifying the consequences (V. Janssens).

- Nature of the hazard scenario
- Properties of the structure
- Location of the building
- Use of the building
- Meteorological conditions
- Time frame over which the consequences are assessed

Another method could be to estimate the square meters floor area that will collapse and use that number as consequence. This would be more precise but when doing so, the maximum probability per consequence class of the Eurocode cannot be used as a given limit. When this method is preferred, first an authority has to determine a maximum level of tolerable risk in the units of the maximum allowable expected collapsed floor area in 50 years.

3.4.3 RISKS

Generally spoken, if both the probability and the consequence are quantified, the risk is the probability times the consequence. If the consequences are estimated in square meters floor area that will collapse, and the probability in a percentage, both the probability and consequence are clearly quantified and can be multiplied with each other to obtain the risk. This risk can be compared to a maximum allowable risk and so the engineer can calculate if the risks are low enough or not. The total risk should then be calculated as follows (according to B.9.2 in EN 1991-1-7):

$$\mathrm{R} = \sum_{i=1}^{N_H} P(H_i) \sum_{j}^{N_D} \sum_{k=1}^{N_S} P\left(D_j \middle| H_i\right) P\left(S_k \middle| D_j\right) C(S_k)$$

Where it is assumed that there are N_H different hazards and N_D different hazard scenarios per hazard. N_S is how many damage states the structure can take when the hazard scenario has occurred with consequence type S_k. The probability of occurrence within a reference time interval of the i^{th} hazard is called $P(H_i)$ and the consequence is quantified as $C(S_k)$. The conditional probability of the j^{th} damage state of the structure given the i^{th} hazard is the $P\left(D_j \middle| H_i\right)$. The $P\left(S_k \middle| D_j\right)$ is the conditional probability of the k^{th} adverse overall structural performance (S) given the i^{th} damage state. (CEN, 2006)

However, in this thesis the quantified risk as probability times consequence is not of interest. Not the maximum risk is given as a limit, but the maximum probability a certain consequence occurs is given as a limit. To be able to verify whether the probability a certain consequence occurs on a specific building is lower than the limit, this probability has to be estimated by the engineer. Per consequence class a maximum probability is given in the Eurocode, so per consequence class an estimation on the probability such a consequence occurs has to be made by the engineer. All accidental actions and their failure scenarios are divided according to the consequence they cause; CC1, CC2 or CC3. In this way the sum of the probabilities of the failure scenarios occurring per consequence class can be taken and compared to the given limits of 4×10^{-4} per 50 years for CC1 events, 7×10^{-5} per 50 years for CC2 events and 8×10^{-6}

per 50 years for CC3 events. To fulfill these requirements, the following three equations should be true for each building.

Note: The consequence class a complete buildings is categorized in, has no influence on this verification. For each building it should be checked if the criteria of all CC1, CC2 and CC3 are met.

$$\mathrm{P_{CC1}} = \sum_{i=1}^{p} P_{CC1}(\mathrm{F_i}) + \sum_{j=1}^{q} P_{CC2}(\mathrm{F_j}) + \sum_{k=1}^{r} P_{CC3}(\mathrm{F_k}) \leq \mathrm{P_{CC1,max}}$$
$$\mathrm{P_{CC2}} = \sum_{j=1}^{q} P_{CC2}(\mathrm{F_j}) + \sum_{k=1}^{r} P_{CC3}(\mathrm{F_K}) \leq \mathrm{P_{CC2,max}}$$
$$\mathrm{P_{CC3}} = \sum_{k=1}^{r} P_{\mathrm{CC3}}(F_k) \leq \mathrm{P_{CC3,max}}$$

Where P_{CC1} is the probability a failure occurs with at least* a consequence classified as CC1, P_{CC2} is the probability a failure occurs of at least CC2 and P_{CC3} is the probability a failure occurs of (at least) CC3. $P_{CC1,2,3}(F_{i,j,k})$ represents the probability a specific failure scenario F_i, F_j or F_k occurs with a consequence of respectively CC1, CC2 or CC3. They can be calculated using the following formulas (section 3.4.1.5):

$$P_{CC1}(F_i) = P(I) * P_{CC1}(F_i|I)$$
$$P_{CC2}(F_j) = P(I) * P_{CC2}(F_j|I)$$
$$P_{CC3}(F_k) = P(I) * P_{CC3}(F_k|I)$$

Where $P(I)$ is the probability an incident happens in The Netherlands with structural failure as a consequence, and $P(F_{i,j,k}|I)$ is the conditional probability that failure scenario i, j or k is the cause of a given incident with consequence CC1, CC2 or CC3. The sum of the conditional probabilities $P(F_{i,j,k}|I)$ cannot be larger than 1:

$$\sum_{i=1}^{p} P_{CC1}(\mathrm{F_i}|I) + \sum_{j=1}^{q} P_{CC2}(\mathrm{F_j}|I) + \sum_{k=1}^{r} P_{CC3}(\mathrm{F_k}|I) \leq 1$$

The maximum allowable probabilities per 50 years per consequence class are given as:

$$\mathrm{P_{CC1,max}} = b * 4 * 10^{-4}$$
$$\mathrm{P_{CC2,max}} = b * 7 * 10^{-5}$$
$$\mathrm{P_{CC3,max}} = b * 8 * 10^{-6}$$

Where the factor b, which is smaller than or equal to 1,0, can be added as extra safety margin.

**A consequence of class 2 can be considered as at least of magnitude CC1 as well. For example when a failure occurs due to which 50m^2 floor area collapses, at least 10m^2 is collapsed as well. The same holds for a CC3 failure which has a magnitude of at least CC1 and CC2 as well.*

3.5 CONCLUSION

According to Marvin Rausand a risk assessment can be described as follows: a risk assessment is an overall process of risk analysis and risk evaluation. A risk analysis is hereby described as a systematic use of information to identify hazards and to estimate the risks, with a distinction in a quantitative and qualitative risk analysis. A qualitative analysis is an analysis where probabilities and consequences are determined purely qualitatively (descriptive), while a quantitative risk analysis is one that provides numerical estimates for probabilities and/or consequences. The risk evaluation part of the risk assessment is the process in which judgments are made on the tolerability.

Existing methods for performing a risk assessment are analyzed in this chapter. RISMAN, Manual for the systematic risk assessment, Eurocode, Stufib and risk assessments performed by engineering firms are compared.

The RISMAN method is the basis for all the risk assessments compared in this chapter. It starts with identification of the risks, after which the measures have to be thought of and implemented. Then the measures have to be evaluated and updated. The basis of this idea can be found in the other methods as well.

The Manual for the systematic risk assessment is a method specifically for designing high-risk structures against disproportionate collapse. Positive points of this method are the following:

+ The level of tolerable risk has to be determined before the risks are quantified. This is positive because in this way the outcome of the quantification will have no influence on the level of tolerable risk.
+ A cost benefit assessment has to be made. This is positive because with this method it will be easier for the engineer to choose which measures will be implemented.
+ A sensitivity check has to be done. In this way the engineer will not only look if the level of tolerable risk is met, but he will also review all the risks again to see if there are any unnoticed elements.
+ It is a clear manual which an engineer can follow and execute

However there are also some points that can be improved:

- The measures have to be determined after the level of tolerability is set and the risks are quantified. This means in practice an engineer might think of measures to just meet the level of tolerable risk. No further research will be done if there might be solutions which are so cheap that even when the tolerable risk level is already met, it is still worth it to implement those solutions.
- The level of tolerable risk is set per individual risk. Each risk should be below a certain level, instead of that all the quantified risks together should be below a certain level.
- The risk assessment is being done semi quantitatively, which makes judgment subjective.

The Eurocode gives an example on how one could perform a risk assessment in the Annex B of EN 1991-1-7. The positive points of this method are the following:

+ The scope and limitations have to be defined in the first step. This gives a clear overview of the project and so also other engineers than the one who made the risk assessment can easily check it. Also it attributes to the systematic way of thinking of the engineer.

+ Not only the hazards have to be identified but also the complete hazard scenario that will follow a certain hazard. This contributes to the systematic approach of dividing a problem in smaller sub problems, which can be dealt with more easy.
+ The risk assessment consists of a qualitative and a quantitative part. In this way it is made sure that first all the hazards, scenarios and measures are systematically described before the probability and consequence will be quantified. Also it makes it easier for CC2 buildings (where doing a risk assessment is not required) from which the engineer is not sure yet if he wants to do a complete quantitative risk assessment or not. After the qualitative part he can decide if he wants to do the quantitative part as well or not.
+ It is advised to take the total risk into account instead of only the individual risks to compare to a level of tolerable risk.

The points of the Eurocode risk assessment that can be improved:

- Making the assessment in a quantitative way is not necessary, one can go from the qualitative analysis to the risk evaluation and treatment immediately.
- No level of tolerable risk has to be set in the qualitative part.
- Only an example is given on how the analysis can be performed quantitatively, no clear guidance on how an engineer can apply it in practice is given.
- No cost benefit assessment has to be done to determine which measures are most cost effective.

The risk assessment of Stufib is the one which is performed by structural engineers in practice. The positive points of the Stufib method:

+ Apparently, since most engineers use it, it is the most clear and practicable method to perform a risk assessment.
+ By letting the engineer describe the cause and mechanism, he is helped to think in a systematic way about the risks.

The negative aspects of the method of Stufib, and thus the method used in practice:

- No level of tolerable risk is set, it is up to the engineer to decide if the risks are low enough.
- It is solely a qualitative way of making the risk assessment, which makes it harder for the engineer to decide if a risk is too high or not.
- The engineers in practice are not encouraged to think of more hazards than given as examples in the Stufib report.

The advantage of the method the Expertisecentrum Regelgeving Bouw is that they use a determined limit, based on the Eurocode, to verify if the risks are low enough. The positive and negative points of all the risk assessments combined will be used to create the protocol for the quantitative risk assessment given in this report, see chapter 4 for this protocol.

Engineering firms mostly use the Stufib method to perform the risk assessment in a qualitative way. From the four analyzed firms, only BouwQ, who is specialized in doing risk assessments, has its own method. They check structural calculations and organize a workshop with people working at the firm to identify the risks. They indicate the risks as being low, medium, high or very high and make a report of it. This report is sent to both the client and the responsible structural engineer.

Furthermore in this chapter different researches on past collapses are compared. From the four sources given in section 3.4.1 it can be concluded that not enough research is done to fully trust on these numbers when using it for exact quantification of the probability for a risk assessment. The studies did not investigate the same type of probabilities and they looked at different load events as being the cause of a collapse. And even the collapse is differently described in the different references.

However, it can be used to make a classification with which an engineer can estimate the probability of a specific event being the cause of a given collapse. The probability $P\left(F_{i,j,k}|I\right)$ is estimated by using the following categorization: negligible (0,01%), very low (0,1%), low (1%), medium (5%), high (15%), very high (25%) and severe (50%).

From research by Cobouw it can be found that the probability an incident happens in The Netherlands is around 6 x 10^{-5} per 50 years per building. However, since Cobouw used a reference period of 16 years, which is not that long, a factor (larger than 1) has to be added to get $P(I) = a * 6 * 10^{-5}$ per 50 years per building.

The consequence of each failure scenario can be classified as CC1, CC2 or CC3 according to the Eurocode description of the consequences per consequence class. Verification if the risks are below the limit can be done by adding all probabilities of the failure scenarios categorized in one specific consequence class, and making sure this summation is lower than the given limits:

$$\sum_{i=1}^{p} P_{CC1}(\mathrm{F_i}) + \sum_{j=1}^{q} P_{CC2}\left(\mathrm{F_j}\right) + \sum_{k=1}^{r} P_{CC3}(\mathrm{F_k}) \leq \mathrm{b} * 4 * 10^{-4}$$

$$\sum_{j=1}^{q} P_{CC2}\left(\mathrm{F_j}\right) + \sum_{k=1}^{r} P_{CC3}(\mathrm{F_K}) \leq \mathrm{b} * 7 * 10^{-5}$$

$$\sum_{k=1}^{r} P_{\mathrm{CC3}}(F_k) \leq \mathrm{b} * 8 * 10^{-6}$$

In which b is a factor to be included to add an extra safety margin to compensate for non-accurate estimations of the engineer.

4. Protocol

INTRODUCTION

By combining the methods explained in the previous chapter with original input, the proposed protocol for performing a risk assessment against accidental actions is explained in this chapter. First an overview is given, after which each step is explained more in the following paragraphs. The following key questions are answered in this chapter.

- Which accidental actions need to be taken into account for a risk assessment?
- Which steps need to be taken to perform a quantitative risk assessment on accidental actions?

The first thing to do when making a risk assessment is defining the scope of application, see figure 15. In this thesis only accidental actions which can cause structural failure to buildings are taken into account. After defining the scope, first the qualitative part of the risk assessment is done. In this part the first step is to list the accidental actions that need to be taken into account. The failure mechanisms of these actions and the possible consequences are described in steps 2 and 3. The last step of the qualitative part discusses possible measures that can lower the risks.

When the risk assessment is done in a quantitative way (at least for CC3 buildings, according to the Eurocode), after determining which risk reduction measures are possible, first the maximum allowable probability that a structural failure is of the magnitude of a specific consequence class has to be determined. Then, in steps 7 and 8 the consequences and probabilities must be quantified. This can be done by either the structural engineer’s estimation or by using statistical data from past collapses (if this is available).

When the probabilities and consequences are quantified, it can be checked if they fall within the limits determined in step 9. If this is the case, it is still advised to perform a cost-benefit assessment for the risk reduction measures. When it appears that certain measures costs are relatively low and the benefits high, even when the level of tolerable risk has already been met, it is still advisable to implement the measure. When the level of tolerable risk has not yet been met, the cost-benefit assessment can be used to rank the measures so the highest scoring measures can be implemented to reduce the risks to the tolerable level.

After determining which measures are to be implemented, an evaluation and sensitivity check will take place. This step will be evaluate if the assumptions made at the beginning of the assessment still hold and if, for example, implemented risk reduction measures cause extra accidental actions that need to be taken into account. When this is the case, a reconsideration of the risk assessment is done. Furthermore all risks will be individually reviewed on sensitivity. The last step is accepting the remaining risks and communicating them to the relevant parties. The acknowledgement of the remaining risks will be done by the engineer and client together.

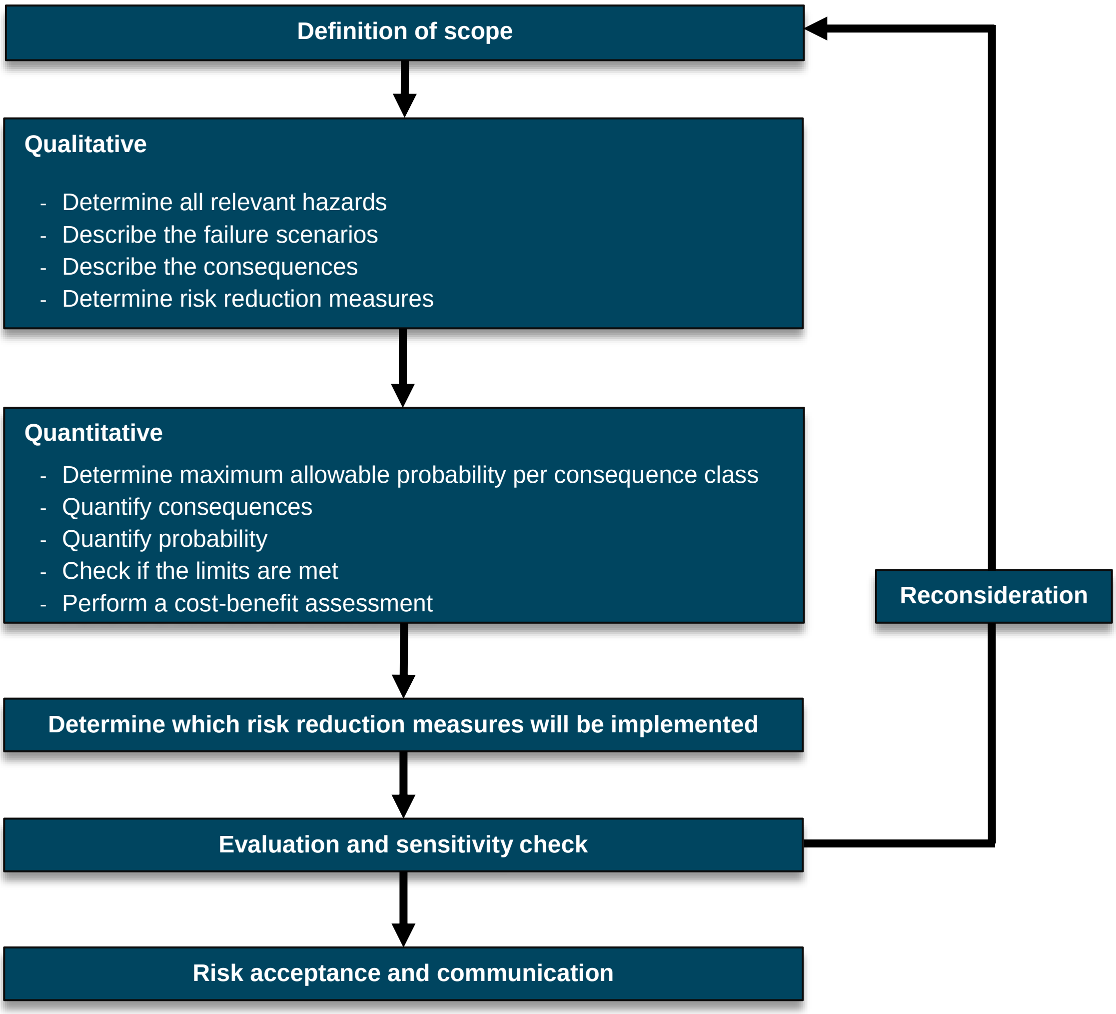

FIGURE 15 PROTOCOL FOR A QUANTITATIVE RISK ASSESSMENT

STEP 1: DEFINITION OF SCOPE

The first step is to defining the scope of the project. The goal and objectives of the risk assessment should be clearly described, as well as the background and specific circumstances of the project. After reading the scope, it should be clear to anyone what the project is about, what assumptions are made and why the risk assessment is being performed. At least the following points need to be described,

- The strategic role of the building for society. Think about power plants, drinking water supply, transport, economic life, governmental activities, health care, food supply.
- The probability of a high number of victims. Think about theaters, shopping malls, stations, stadiums.
- The innovative character of the structure and the materials used. Think about forms, heights, spans.
- The possibilities on extraordinary risks caused by industrial activities, traffic, water, etc.
- The probability of terroristic or other attacks. Think about monuments, embassy's, government buildings, banks.

STEP 2: DETERMINE ALL RELEVANT HAZARDS

Many different lists of possible accidental actions to buildings exist. All mention different hazards, one more explicit the other more general. In this section different studies are used to compare and create a list of important hazards to take into account for the risk assessment. The list of hazards of the sources can be found in appendix C.

When the sources are compared, it can be seen that different research finds different ways of listing possible hazards. The Eurocode (CEN, 2006), COST TU0601 (Ellingwood B. , Safety Checking Formats for Limit States design, 1982) and The Manual for the systematic risk assessment of high-risk structures against disproportionate collapse (Cormie, 2013) list hazards to inspire the engineer to think of all possible risks when making a risk assessment. KiK has the same type of list but to fulfill the KiK requirements, it is enough to check the boxes, which indicates the hazard has been taken into account. The engineer himself does not need to think of any additional risks. Terwel's thesis, Structural Safety (Terwel, 2014), focusses on human errors. He states that human errors are influenced by factors of their surroundings. It is thus important to take these factors into account. Furthermore, he lists the errors that caused damage to buildings in The Netherlands, divided into errors made during the design and the execution phase. Again, only human errors are taken into account.

Combining the lists of these sources, in that it would take the organizational factors into account as well as divides the remaining hazards in the phase they occur, a new, more comprehensive list, is obtained. The following list will be the basis for the engineer to identify hazards in the risk assessment. Besides this given list, the engineer is required to think of risks himself as well. He can add those to the list for the risk assessment.

<u>Organizational factors</u>

- Not (enough) attention paid to organizational factors
    - Communication and collaboration
    - Control mechanisms
    - Allocation of responsibilities
    - Structural risk management
    - Safety culture
    - Knowledge infrastructure

<u>Design phase</u>

- Incorrect modeling by the structural engineer
- Erroneous use of rules and regulations or calculation error
- Incorrect dimensioning on drawings or conflicting/missing drawings or calculations
- Not taking environmental factors into account
- Not taking loads during construction into account
- Designing with (new) methods or techniques which turnout not to behave as predicted

<u>Execution phase</u>

- Not taking accurate measures against weather conditions

- Insufficient quality or amount of materials applied
- Incorrect assembling of elements on the building site
- Erroneous measurements on the building site
- Falling elements
- Deviation from the design in execution or circumstances taken into account
- Formwork, bracing or erection error

<u>During use</u>

- Insufficient maintenance
- Insufficient inspection
- Deviate from the use for which it was designed
    - Natural hazards (earthquake, landslide, hurricane, tornado, avalanche, rock fall, high groundwater, flood, volcano eruption)
- Manmade hazards
    - Fire
    - Explosion (gas leak, dust or chemical, bomb, excavation blast)
    - Impact by vehicle (car/train/truck, ship, airplane
    - Mining subsidence
    - Environmental attack
    - Soil pollution
    - Excavation, sink holes, slides etc. in the neighborhood
- Deliberate misuse (vandalism, demonstrations, terrorist attack)
- Exceedance of loads not taken into account (self-weight, imposed loads, car park loads, traffic, snow, wind, hydraulic)
- Falling objects, like collapsing structures
- Windblown objects

The hazards of which it has been estimated that the probability they occur and cause the consequence of interest is negligible (see section 3.4.1.5 for the quantification of 'negligible'), can already be taken off the list of possible hazards.

STEP 3: DESCRIBE FAILURE SCENARIOS

To gain more insight in the mechanism that can develop because a hazard occurs, the failure scenarios are described in this step. Systematically per hazard the threat and possible failure mechanism is described in a way that further on in the risk assessment the probability of a certain scenario happening can be estimated.

STEP 4: DESCRIBE THE CONSEQUENCES

In this report only structural failure will be relevant as consequence. Hazards with other consequences do not have to be taken into consideration for this risk assessment. However when one wants to perform a risk assessment taking different consequences into account, this step allows for a description of the kind of consequence that will follow a failure scenario. The consequences do not have to be quantified yet in this step; only what kind of consequence the failure scenario will cause (for example: collapse).

STEP 5: DETERMINE RISK REDUCTION MEASURES

To reduce risks, measures can be taken. Such measures can lower the probability of occurrence or reduce the consequences. Each of the failure scenarios can have multiple measures, and one measure can have influence on multiple failure scenarios. Measures are compared according to the existing theories and can be found in appendix D. The sources differ a lot. Where KiK describes very detailed measures like "*Check if in earthquake area shock-absorbers are used between the piles and foundation"*, the Eurocode mentions "*Preventing or reducing the action (e.g. protective measures)"* as a general method.
No general, complete list of measures is available that can be taken against accidental actions. Such a list should consist of every possible measure that can be taken to lower a risk caused by accidental actions. Since new building methods and insights become available over time, if such a list is wanted, it should be kept up to date to ensure its comprehensiveness. In addition to the changes in time, it is a challenge to create the list in the first place. Since every building project is different, although the same hazards can threaten, measures will have a different effect per project. This means it will be difficult to quantify the effect of the measure in general terms.

For the risk assessment protocol the general principle of Ellingwood (Ellingwood B. , 1987) is used. Each risk can be:

- eliminated (e.g. design a building without gas pipes to make the probability a gas leak occurs zero);
- reduced (e.g. use one integrated software program for the drawings);
- compensated for in the design (e.g. design vehicle barriers around the building to reduce the risk of impact by a vehicle);
- contained by control and monitoring (e.g. let a third party check the drawings and calculations to lower the probability a mistake is made);
- accepted as a known risk (e.g. vandalism).

This concept is based on implementing measures per hazard. However, besides the measures for a specific hazard, general measures can also be taken. Examples for measures that reduce multiple risks at once are:

- Design key elements that can take more load (e.g. 34 kN/m^2) than initially needed.
- Add an alternative load path (e.g. horizontal and vertical ties).
- Do not use new techniques or materials that have not proven their credibility (yet).
- Make sure the correct (number of) people work on the correct project.

In this step all measures from which the engineer thinks they might be effective, must be listed. It would be efficient to pay extra attention to measures which reduce multiple risks at once.

STEP 6: DETERMINE MAXIMUM ALLOWABLE PROBABILITY PER CONSEQUENCE CLASS

This is the first step of the quantitative part of the risk assessment. With the information of the previous (qualitative) steps, it should be clear what the goal of making this risk assessment is. For this thesis it is to verify if the risks of accidental actions on a building structure are low enough. To determine if it is low enough, a certain quantified limit should be available.

Instead of only looking at the risk of one failure scenario and set a limit of a maximum risk per failure scenario, like most existing risk assessments do (see paragraph 3.3), in this report the sum of the probabilities per consequence type will be evaluated. For a user it does not matter if the building collapses because the engineer made a modelling error or because the contractor used a different material, when the consequences are the same. For a user's safety it is more important that the probability a collapse with a certain consequence occurs is below a certain level than that every individual possible cause has a probability lower than a certain level.

From the β value given in the Eurocode, the maximum probabilities of the failure scenarios causing a consequence of class 1, 2 or 3 can be determined as respectively 4 x 10^{-4}, 7 x 10^{-5} and 8 x 10^{-6} per 50 years (section 3.4.1). To add an extra safety margin, the factor b, which is smaller than or equal to 1, can be added:

$$P_{CC1,max} = b * 4 * 10^{-4}$$
$$P_{CC2,max} = b * 7 * 10^{-5}$$
$$P_{CC3,max} = b * 8 * 10^{-6}$$

STEP 7: QUANTIFY CONSEQUENCES

In this step the engineer has to classify each consequence that will follow a certain failure scenario caused by a specific hazard. This classification is made by using the Eurocode description of CC1, CC2 and CC3, see table 9 (NEN, 2002). Note that the square meters of floor area that will collapse are added by the author in this table and are solely an indication; this has to be reconsidered for every project.

It is important to realize that the classification of the building itself, although employing the same terminology, is something different. A CC3 building does not automatically have all failure scenarios classified as CC3. Each failure scenario has to be reviewed individually to check which consequences will occur when the failure scenario happens. The following factors are important to take into account for classifying the consequences (V. Janssens).

- Nature of the hazard and failure scenario
- Properties of the structure
- Location of the building
- Use of the building
- Meteorological conditions
- Time frame over which the consequences are assessed

With these factors in mind, the engineer can estimate which consequence class each failure scenario will get.

Consequence class	Description consequence	Indication of square meters floor area that will collapse
CC1	Minor consequences with regard to the loss of human life, *and/or small or negligible economic or social consequences or environmental consequences*	< 10
CC2	Mediocre consequences with regard to the loss of human life, *and/or significant economic or social consequences or environmental consequences*	10-100
CC3	Major consequences with regard to the loss of human life, *and/or very large economic, social or environmental consequences*	> 100

TABLE 9 CONSEQUENCE CLASSES AND THEIR DESCRIPTION

STEP 8: QUANTIFY PROBABILITY

Step 8 is meant to quantify the probability the accidental actions and their failure scenarios happen and cause the consequence of interest. As explained in section 3.4.1 the probability of an accidental action causing the consequence of interest can be subdivided in the probability an incident happens $P(I)$, the conditional probability $P_{CC1,2,3}(F_{i,j,k}|I)$ a specific failure scenario caused by an accidental action is the cause of the given incident and the conditional probability $P_{CC1,2,3}(C|F_{i,j,k})$ a specific consequence follows when the failure scenario happens, in which $P_{CC1,2,3}(C|F_{i,j,k}) = 1$ and is left out of the equation. The probability a structural failure of CC1, CC2 or CC3 occurs per 50 years, due to an accidental actions, can be described as:

$$P_{CC1}(F) = P(I) * \sum_{i=1}^{p} P_{CC1}(F_i|I)$$

$$P_{CC2}(F) = P(I) * \sum_{j=1}^{q} P_{CC2}(F_j|I)$$

$$P_{CC3}(F) = P(I) * \sum_{k=1}^{r} P_{CC3}(F_k|I)$$

For $P(I)$ the results of Cobouw are used: $P(I) = a * 6 * 10^{-5}$, in which a is a factor larger than 1 to compensate for the fact that in the 16 years of the Cobouw research, no real big hazards (such as a heavy storm) occured. The engineer has to estimate the conditional probability $P(F_{i,j,k}|I)$ per failure scenario, in which the sum of these probabilities of all failure scenarios cannot be larger than 1.

$$\sum_{i=1}^{p} P_{CC1}(F_i|I) + \sum_{j=1}^{q} P_{CC2}(F_j|I) + \sum_{k=1}^{r} P_{CC3}(F_k|I) \leq 1$$

Here $P_{CC1,2,3}(\mathrm{F_{i,j,k}}|I)$ represent the conditional probability a given incident is caused by a specific failure scenario i, j or k. With the failure scenarios F_i representing the ones with a consequence of class 1, F_j with a consequence of class 2 and F_k with a consequence of class 3.

To help the engineer by estimating the $P(F_{i,j,k}|I)$, the following classification table can be used.

	Probability a given failure was caused by a specific hazard scenario $\boldsymbol{P(F_{i,j,k}|I)}$
Severe	50%
Very high	25%
High	15%
Medium	5%
Low	1%
Very low	0,1%
Negligible	0,01%

Step 9: Check if the limits are met

In this step the calculated probabilities of step 8 have to be compared with the limits of step 6. The total probability per consequence class must be lower than the boundary set in step 6. When these boundary conditions are fulfilled, no further actions *have to* be taken, although it might be useful to check if there are risk reduction measures which can be implemented against low costs.

$$P_{CC1}(F) + P_{CC2}(F) + P_{CC3}(F) \leq \mathrm{b} * 4 * 10^{-4}$$

$$P_{CC2}(F) + P_{CC3}(F) \leq \mathrm{b} * 7 * 10^{-5}$$

$$P_{CC3}(F) \leq \mathrm{b} * 8 * 10^{-6}$$

Note: To check if the limit is met for CC1, the sum of the probabilities of CC1, CC2 and CC3 is taken, since strictly speaking a risk of CC3 causes at least the consequences classified as CC1 and CC2 as well. The same goes for CC2, where CC2 and CC3 are summed.

Step 10: Perform a cost-benefit assessment

To make a considered choice of which risk reduction measures from step 5 will be implemented, a cost-benefit analysis can be used to rank the measures. For each measure the costs have to be estimated as well as the effect.

To be able to compare the measures and grade them on how effective they are, the costs per measure have to estimated and the effect has to be quantified. The ranking can then be made according to the lowest cost/benefit ratio as most positive measure and the highest cost/benefit ratio as the least positive measure.

The costs can be estimated by the engineer. The effect can be quantified by comparing the initial risk with the rest risk. Since the risks can only be compared when they are quantified, the quantified risk as probability times consequence has to be used here. The initial probability has already been quantified in the previous steps. The rest probabilities have to be estimated by taking the effect of the measures into account. For the consequence the estimation of square meter floor area that will collapse due to the event is used. The engineer can use the classification of CC1, CC2 and CC3 combined with $10m^2$, $50m^2$ and $100m^2$ or use a more precise personal estimation (for example $500m^2$).

The original risk minus the rest risk will give the risk reduction. The costs of the measure (in €) can then be divided by the risk reduction (in m^2) to obtain the cost/benefit ratio and rank the measures on cost effectiveness.

STEP 11: DETERMINE WHICH RISK REDUCTION MEASURES WILL BE IMPLEMENTED

The cost-benefit assessment from the previous step can be used to determine which measures will be implemented. At least the measures necessary to fulfill the limits of step 6 need to be implemented, the rest is optional.

STEP 12: EVALUATION AND SENSITIVITY CHECK

In this step first the probabilities and consequences are quantified again, taking the implemented risks into account. It is evaluated if the probabilities per consequence class are now acceptable. If this is not the case, the engineer must go back to step 5 to think of new risk reduction measures.

Furthermore the risk assessment has to be evaluated on whether the assumptions made at the beginning still hold. Also the risk reduction measures can create problems on other levels. It has to be checked if new hazards might arise from measures that are taken. In this case the engineer must go back to step 1 of the risk assessment and adjust it to the new insights.

A sensitivity check is done based on the risk assessment explained in section 3.3.2. This check consists of the following points:

1. When small changes in assumptions can have a large influence on the risk verification, the worse assumptions have to be taken into account for the design (chapter 3).
2. An analysis if the risks meet the rules set in the Dutch Building Decree (chapter 2):
   - A building structure does not collapse during its intended life, as prescribed in NEN-EN 1990, during exposure to accidental load combinations, as prescribed in NEN-EN 1990, if this leads to collapse of another structure* not in the direct proximity of this structure. Hereby the identified accidental actions, as prescribed in NEN-EN 1991, are assumed.
   - A roof or floor does not collapse during the design life, as prescribed in NEN-EN 1990, during exposure to accidental load combinations, as prescribed in NEN-EN 1990. In this, impacts as described in NEN-EN 1991 are assumed.

Step 13: Risk acceptance and communication

If there are remaining risks and they are accepted as a known risk, they have to be communicated to the client and other relevant parties for the construction, use and maintenance of the building.

Conclusion

In this chapter the positive and negative points of the existing methods for risk assessment are combined and a new protocol for making a risk assessment on accidental actions is presented. In this method the risk assessment is done quantitatively, ideally by basing probabilities of accidental actions occurring on past events. However, since this data is not (sufficiently) available, an alternative is provided by letting the engineer estimate the probabilities and consequences.

The first part of the proposed risk assessment is qualitative: the project has to be described as well as the possible hazards and, more specifically, the different failure scenarios and measures that can be taken against them. By doing this the engineer is encouraged to systematically organize his thoughts about risks and the behavior of the structure when an accidental action occurs. An example list with possible hazards is provided.

The quantitative part of the risk assessment starts with determining the maximum allowable probability per consequence class. In this report the following maximum allowable probabilities per 50 years per building are used: $P_{cc1,\max}(F) = b * 4 * 10^{-4}$, $P_{cc2,\max}(F) = b * 7 * 10^{-5}$, $P_{cc3,\max}(F) = b * 8 * 10^{-6}$, in which b, lower than or equal to 1, represents a factor that can be added for an extra safety margin. These probabilities are based on the β values given in the Eurocode per consequence class. However in the Eurocode the given values are not specifically meant for a risk assessment, which means they have to be reviewed by an official party (NEN or the government for example) before they can be used in the field. After determining the maximum allowable probability, the actual probabilities and consequences for the project have to be quantified. The probability will be quantified by estimating the probability of each failure scenario. The consequence will be quantified by categorizing each hazard scenario into a CC1, CC2 or CC3 consequence class. All the probabilities of the hazard scenarios of one consequence class summed cannot exceed the given limits.

After this, a cost-benefit assessment has to be made to rank the measures according to their ratio on cost and benefit. Even when the total risks already fall within limits, it is advised to perform this cost-benefit assessment, since there might be measures which are so cheap and so effective that it would be a shame not to implement them. With this ranked order in mind, the engineer can choose which measures will be implemented. An evaluation will follow in which every single risk has to be reviewed again if there are circumstances which might make the risk greater than originally thought. Moreover, in the evaluation it is checked if the total risk falls within limits now. When this is not the case, the engineer goes back to step 1 of the risk assessment. This iterative process goes on until the level of tolerable risk is met. The final step is to communicating and accepting the remaining risks.

5. Case study

5.1 INTRODUCTION

In this chapter the risk assessment as proposed in chapter 4 is tested. The project of the Cooltoren in Rotterdam is the subject. Engineering firm Van Rossum already did a risk assessment for this project (see chapter 3) so this existing one can be compared with the new one, which is performed by the same engineer as the one presented in chapter 3.

The goal of comparing the two methods for performing the risk assessment is seeing how the one proposed in this report performs in the field. Not primarily to check if the used probabilities and estimations are correct, since the factors a and b to increase the probability an incident happens and to decrease the maximum allowable probability an incident happens and causes a consequence of class 1, 2 or 3 (chapter 3) are not given in this report. For the case study assumptions are made for these factors.

The advantages and disadvantages of performing a risk assessment in a quantitative way (instead of qualitative) will become clear when an engineer tests the protocol for an existing project. The risk assessment itself can be found in Appendix E. The feedback of the engineer and the conclusion are given in this chapter.

The following key questions will be answered in this chapter:

- What should be done before this protocol can be used in practice?
- What are the advantages and disadvantages of using this protocol?

5.2 FEEDBACK ENGINEER

The engineer who had already performed the qualitative risk assessment for the Cooltoren, also did this quantitative risk assessment of chapter 4 for the Cooltoren. He finds it useful that a clear verification can be done to check if the risks are acceptable. Not only for himself but also for communication with other involved parties. It is easier to show the municipality or client that the risks are below the limit than to describe the risks in a qualitative way and form an opinion whether the risks are acceptable or not.

The engineer found it difficult to estimate the conditional probability a specific hazard is the cause of a given incident. When the indication of very low, low, medium, high and very high is used it is easier than when the percentage has to be estimated from blank, but it is still guessing. Furthermore the hazards *organizational factors* were difficult to quantify. Even describing a failure scenario per organizational hazard is difficult, since almost anything can follow from 'communication error' for example. In this risk assessment all organizational factors were put at consequence class 2 and have a medium conditional probability (5%).

The consequence class per hazard scenario was easy to estimate for the engineer, as well as the costs per measure for the cost-benefit assessment. Also step 1, the description of the project, was easy, since this is the same as has already been used for the qualitative risk assessment.

The given list of possible hazards looked complete for this project. Some of the hazards were taken off the list but no additional hazards were added.

Although it took a bit longer to perform the risk assessment in a quantitative way, the engineer thinks it is worth it because of the easy verification method. And that it took longer is not surprising, since this was the first time the engineer had to work with this method. He thinks when he is used to this method it might take a little bit longer than making a qualitative risk assessment, but not that much longer. The step by step guidance on how to execute this risk assessment is clear so it is easy to perform.

5.3 CONCLUSION

It was useful to test the risk assessment in a case study. In this way the method can be tested and positive and negative aspects can be pointed out. However, one case study is not enough to see how it would work in different situations and with different users.

It can be concluded that it would be useful for engineers to have a standard protocol for performing a risk assessment in a quantitative way and be able to verify whether the risks on accidental actions are acceptable. This would make communication with other parties of the building project easier, since it can easily be shown whether the risks are acceptable or not, and if certain measures are really needed or just a ‘nice extra’.

Moreover, the outcome of the risk assessment performed for the Cooltoren fulfills the expectations of the engineer concerning the verification. Without measures it should indeed indicate that the risks are too high and with the measures taken the outcome should be that the risks are under the limit. Although it should be kept in mind that for this case study assumptions are made for the factors $a = 2$ and $b = 0{,}8$.

However, it is important to realize that it is hard for an engineer to estimate the probabilities. More research should be done about past failures to investigate if the used indication of low, medium and high is correct. When this indication is not correct and an engineer follows this, the verification and conclusion can be wrong and thus not reliable. It is important that the values gotten from the verification are reliable, since the most important reason an engineer would perform a risk assessment in a quantitative way instead of a qualitative way, is that the verification of whether or not the risks are low enough, is easier. When this outcome might be flawed, an engineer cannot use the results.

When engineers feel confident that they can actually estimate the probabilities and consequences accurately, the method proposed in thesis would be a clear one to use.

The following points need to be performed before this protocol for performing a quantitative risk assessment can really be the official way to check whether the risks on accidental actions are acceptable. This does not mean an individual engineering firm cannot use it for an extra check, for example, before the following points are executed,

- Make it easier for an engineer to estimate the probability accurately.

- Check if the assumed value of the probability a structural failure happens in The Netherlands of $6 * 10^{-5}$ per 50 years per building is accurate and determine the factor a (see chapter 3).
- Test the method in different situations and by different users.
- Check if the indications in percentages of very low, low, medium, high and very high are accurate by doing more research on past failures.
- Check if an indication as very low, low, medium, high and very high is the best way to predict the probability, or if another method would be better (for example use the exact percentages of the research).
- Check if the classification of consequences in the consequence classes of the Eurocode is the best way to estimate the consequence.
- Determine the factor b to lower the maximum allowable probability a failure of a specific consequence occurs per 50 years.
- The accidental action of the lack of professional knowledge should be investigated if that has to be taken into account or not.
- An official party of The Netherlands should control everything and make it official before it can be implemented.

Advantages and disadvantages of the proposed method for performing a quantitative risk assessment are the following:

Advantages
- It is clear which steps need to be taken and how the risk assessment should be executed.
- It is easy to verify if the risks on accidental actions are low enough.
- Communication with the client, municipality, quality control or other involved party about if the risks on accidental actions are low enough becomes easier.

Disadvantages
- It is difficult to estimate the probabilities.
- Risk estimation will never be exact so even when the risk assessment is done quantitatively, a grey area in which it is not clear whether the risks are low enough or not will always consist.
- More research needs to be done before this method can be used in the field.

6. Conclusions and recommendations

6.1 INTRODUCTION

In this chapter the outcomes of the research are presented, as well as how they can be interpreted and what one can do with the results. The main research question

To what extent can a standard protocol for performing a quantitative risk assessment help a structural engineer by verifying whether the risks of accidental actions on the designed building structure are acceptable?

is answered in section 6.2. In section 6.3 recommendations are given for future research. The final section contains the discussion.

6.2 CONCLUSIONS

Although research shows the individual probability of death due to structural failure is below the limit of 10^{-5} per year, it is not known whether the probability of structural failure per building is acceptable as well. This is because in current regulations no limits are given for the risks of accidental actions on building structures.

For the Dutch building industry it would be helpful if limits for the risks of accidental actions on building structures are given, as well as a way to estimate these risks quantitatively when the building structure is being designed. This way the estimated risks and the limits can be compared and it can be verified whether the requirements are fulfilled.

The maximum probability a failure occurs per 50 years with a consequence of magnitude CC1, CC2 or CC3 as stated in the Eurocode, can be used as a limit which should be fulfilled for every building structure. In order to be able to compare the maximum probability per consequence class of the Eurocode with the actual (estimated) probability, the hazardous events should be divided into the same consequence classes as the limits are given in. For all hazardous events of at least a CC1 consequence the sum of the probabilities they occur and cause this consequence per 50 years, should not exceed the given CC1 limit, as well as the sum of the probabilities of the hazardous events of at least CC2 and CC3 should not exceed the limit of the CC2 and CC3.

Not a lot of research has been done on the probability an accidental action causes a structural failure. Although some research is done, the different results cannot be compared to each other and the timeframe in which the research took place is short. This means not all accidental actions that could relatively likely occur during the design life of a building, are taken into account in the results. As such, the results cannot directly be used when the probability an accidental action causes a structural failure has to be estimated in a risk assessment. When a risk assessment is performed, the user has to estimate the probabilities himself.

Although a protocol for performing a risk assessment on accidental actions in a quantitative way is given in this thesis, it cannot be used in the field yet. Assumptions made in this thesis and undetermined factors need to be verified and determined first.

In conclusion, a standard protocol for a quantitative risk assessment can actually help a structural engineer in verifying whether the risks on accidental actions are acceptable or not. The main advantage of performing the risk assessment in a quantitative way is that it will be clear for everyone whether the risks are acceptable or not. This makes communication between the engineer and other involved parties clearer. However, since it is not easy to determine the exact limit and to estimate the actual risks or probabilities for a building project (with the information presented in this thesis), current advantages are limited. Nonetheless, when more of the assumptions and non-determined factors of this report are clarified, a standard protocol for performing a quantitative risk assessment on accidental actions will be useful.

6.3 RECOMMENDATIONS

It appears that performing a risk assessment on accidental actions is currently an unclear task for structural engineers. Different methods are prescribed but none of them give clear requirements considering the maximum allowable risk level. It is recommended that the government ensures the regulations for designing on accidental actions are clarified and a maximum allowable risk level will be determined.

Furthermore it is advised to do more research on structural failures and their causes. It is important that we know what the most common causes are and how large the probabilities are that certain accidental actions occur and cause a structural failure.

Because of a lack of time (and information), this thesis does not investigate everything that could be investigated for this topic. The following topics can be used for future research to continue on this subject:

- Estimation of probabilities; investigate how an engineer can most accurately estimate the probability a specific accidental action is the cause of a given structural failure.
- Determination of the maximum level of tolerable risk; the maximum probabilities a failure occurs with a consequence of class 1, 2 or 3 including the factor b should be checked and determined.
- Determination of the probability a structural failure incident occurs in a building in 50 years; the assumed $P(I) = a * 6 * 10^{-5}$ should be checked and the factor a needs to be determined.
- It should be investigated if performing the risk assessment in a quantitative way instead of a qualitative way would cause less disproportionate collapses. When it turns out this is too difficult to investigate or test, a conclusion could also be drawn from the opinion of professionals.
- It should be investigated whether estimating probabilities is too little of an exact science to be able to verify if the risks are low enough with a quantitative method.
- It should be investigated if the lack of professional knowledge must be taken into account as accidental action and if so, how it can be quantified.

- It can be investigated whether using probability functions instead of exact percentages for the probability would be preferable in the risk assessment.

6.4 DISCUSSION

From this thesis it cannot be concluded that when a risk assessment is done in a quantitative way, less disproportionate structural failures will occur in The Netherlands. It can thus be questioned if performing a risk assessment in a quantitative way is actually better than doing it qualitatively.

Furthermore it can be questioned whether or not estimated risks or probabilities can or should be compared to a determined limit. When risks or probabilities are estimated by a person, it could be that another person performing the same risk assessment obtains different results. This can partly be avoided by introducing a factor to lower the acceptable limit, but the question is how easy it will be to determine such a factor and how accurate it will be even with that factor included.

The probability of an incident with a structural failure as a consequence is set as $P(I) = a * 6 * 10^{-5}$ per 50 years in this thesis. A factor a, which is larger than 1, is added to compensate for the short timeframe this research was performed in. However, this factor has not yet been determined. It can be questioned how accurately this factor can be estimated, since some accidental actions do not occur that often and as such it will be hard to determine what the probability is of that accidental action causing a structural failure.

Another point of attention is the categorization table presented in this thesis for an engineer to estimate the conditional probability a structural failure is due to a specific failure scenario. Since most engineers will find it hard to estimate this conditional probability themselves, most will probably use the indications given in this table. For most failure scenarios they will estimate the conditional probability as 'medium', some as 'low' and some as 'high'. It is thus very important that this table gives an accurate estimation. However, it depends on how many failure scenarios the engineer has thought of to determine and how specifically one describes them, how large these probabilities should actually be. The more specific an engineer describes the failure scenarios, each scenario will have a smaller probability of being the cause of the failure. Another aspect that needs to be studied better, is that the conditional probabilities a specific event is the cause of a given incident, should sum up to 1 to be complete. Probably the engineer cannot think of all possible scenarios, so in most cases the sum will not exactly be 1, but lower. It should be investigated if it would be good to add an event 'others' and give this a probability of 1 minus the sum of the rest.

Furthermore, to be able to judge to what extent a standard protocol for performing a quantitative risk assessment would be helpful for an engineer to verify whether the risks on accidental actions are acceptable, it could be useful to have multiple methods for performing such a risk assessment. In this thesis only one method is presented and according to this method, conclusions are drawn. However, when another method is used, maybe other conclusions would arise.

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APPENDIX

A. RISK ASSESSMENT METHOD OF 'MANUAL FOR THE SYSTEMATIC RISK ASSESSMENT OF HIGH-RISE STRUCTURES AGAINST DISPROPORTIONATE COLLAPSE'

Step 1: identify the hazards

In this step the hazards will be identified by organizing a workshop with all relevant team members who can identify hazards. A list is given to inspire the team members, but the list is incomplete. The structural engineer is responsible that all reasonably possible hazards that can cause harm are taken into account. The only hazard that is unforeseeable is the lack of professional knowledge. All other hazards, like a human error (which is considered a unforeseeable hazard in the Eurocode), are foreseeable. Designing against unforeseeable hazards is only possible with making a scenario-independent design approach, based on localized failure. The foreseeable hazards can be taken into account with making a risk analysis.

Step 2: Eliminate the hazards where feasible to do so

The elimination of hazards can best be done in the earliest phase of design.

Step 3: Determine the level of tolerable risk

Important is that the level of tolerable risk is decided before the risks are calculated. This determination should be done by the structural engineer and client together. Also when fatalities are concerned, a review by the building control authority could be worthwhile.

Extra attention needs to be paid to risks with a very low probability but very high consequences. These might not immediately seem to be of great danger, since the probability is so small, but *when* the hazard occurs, the consequences could be destructive.

Step 4: Evaluate the risk

First the probability and consequence have to be estimated. This is done by dividing the probability in categories such as negligible, improbable, rare, unlikely, likely and frequent and the consequence in minimal, minor, significant, serious, substantial, severe and catastrophic. Each risk is placed in the risk matrix to see if it lies above or under the in step 3 determined level of tolerable risk (figure 16).

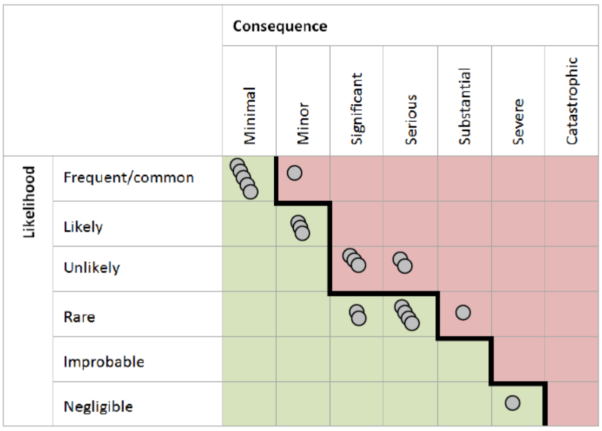

FIGURE 16 RISK MATRIX

Step 5: Identify risk reduction measures

For all identified hazards, risk reduction measures must be considered. Even for the risks that are already in the green (tolerable) area of the risk matrix. All risks in the red part must be reduced to at least the green part. Several measures could be possible per risk and must all be considered. The ALARP principle (as low as reasonably practicable) will be used to determine which measure(s) will be taken. The structural engineer must take side effects of measures into account. For example when risk 1 will be reduced by measure 1 but risk 2 will increase by measure 1, it could be that the end situation is even worse.

A difference can be made between scenario-dependent and scenario-independent measures. Where thickening a column withstands an impact of a small car, it does not reduce the risk of a large car. A scenario-independent measure, such as an alternative load path for when the column loses its function, withstands both the small and the large vehicle. Scenario-independent approaches will thus always be preferable to scenario-dependent approaches.

Step 6: Cost-benefit assessment

For the measures of step 5 a cost-benefit assessment is made. The costs and effectiveness per measure are estimated so they can be compared. The costs do not have to be expressed in currency, it could also be expressed in delay of the project, aesthetics or functionality of the project.

Every measure determined in the previous step will be considered. The effectiveness of a risk reduction measure is the sum of the influences on different hazards. For example when measure 1 influences both hazard 1 and 2, the sum of the two is the total effect. The effect can be measured by for example taking the length of the arrow in the risk matrix which describes from which box to which box a hazard goes when a certain risk reduction measure is performed.

When the reduction in risk is similar, a choice can be made by comparing the following aspects:

- If the measure is scenario-dependent or scenario-independent, where the scenario-independent measure will be prioritized above the scenario-dependent measure.
- The measure which has effect on the larger risk will be prioritized over the measure with the same effect but on a lower risk.
- Mostly the measure which effects more risks (but has the same total reduction) will be prioritized over the measure with less risks.

Step 7: Implement the risk reduction measures

In this step the structural engineer has to implement the measures in the design or the process. Measures that have a great positive cost-benefit ratio, that takes risks from the red to the green part in the matrix and measures that show contemporary good practice should be always implemented.

Step 8: Review the residual risk

The risk owner (the one who is responsible for the risk and its measures), client and other risk stakeholders must agree upon the residual risk.

Step 9: Check the sensitivity of the risk assessment

Check the following aspects on sensitivity:

- Cliff edge effects: when small changes in assumptions can have a big influence on the consequence. If this is the case, the small changes in assumptions must be the governing to take into account for the design.
- Low probability /high consequence hazards: check if with slightly higher probability, the consequence can be much larger so that the risk is much greater than before. If this is the case, it should be considered if more mitigation is needed.
- Combined hazards: to take combined hazards into account, it is good to both look at the probability of the hazards separately, and the probability of one hazard happening given the other has happened. When these two approaches give significant other outcomes, it should be considered again.

Step 10: Review the overall level of risk

When all the risks are in the green part but close to the border of the red part in the risk matrix, it should be investigated where those mitigated risks came from. When they were first all a big risk but the risk reduction measures lowered them significantly, the total risk is sensitive to the implementation of the risk reduction measures. On the contrary when the unmitigated risks were close to the mitigated risks in the matrix, it means that the total risk is sensitive to the quality of the risk assessment. See figure 17 for a) the great influence of the measures and b) the sensitivity to the quality of the risk assessment. In both situations another party (either in the same company or from another company) has to check the risk assessment and measures to see if different interpretations or executions can cause an unacceptable overall level of risk.

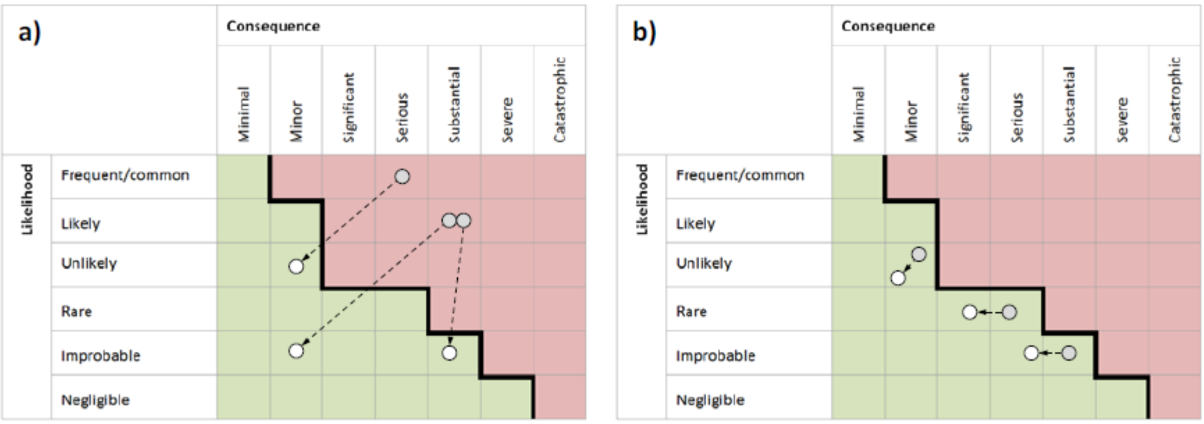

FIGURE 17 A) GREAT INFLUENCE OF MEASURES ON RISKS AND B) SENSITIVITY TO THE QUALITY OF THE RISK ASSESSMENT

Step 11: Provide adequate information about any risks that remain

From the past it appeared that human errors are the most important factor for mistakes. Miscommunication is an example of a human error. It is therefore important that, to make sure all the work of making the risk assessment will not be for nothing, the information about the remaining risks are well communicated to the involved parties (client, other designers, contractor). This information can include the following aspects:

- The remaining probability and consequence per hazard
- An overview on where the risk is quantified in the risk matrix with level of tolerable risk indicated.
- Recommendations about control procedures such as maintenance and inspection.

B. Risk assessment examples

Examples of how Pieters Bouwtechniek, Bartels Ingenieurs voor Bouw & Infra and BouwQ do a risk assessment is given in this appendix.

B1. Van Rossum Raadgevende Ingenieurs B.V.

Cooltoren Rotterdam (CC3)

First of all a technical and organizational description of the project is given. Drawings and explanations are given about the structural design of the Cooltoren. Furthermore the themes about the environment (given in Stufib 8) are discussed. Answers of this firm are italic written:

1. The strategic role of the building for the society. Think about power plants, drinking water supply, transport, economic life, governmental activities, health care, food supply.
    - *The Cooltoren is mainly meant for housing. Only the first and second floor are occupied by retail stores.*
2. The probability on a high number of victims. Think about theaters, shopping malls, stations, stadiums.
    - *This building belongs to the group for which a high number of victims is surely possible. The Cooltoren is indicated as consequences class 3 from Eurocode 1-7.*
3. The innovative character of the structure and the used materials. Think about forms, heights, spans.
    - *The building is designed in a, in The Netherlands, well-known structural method. The structure consists of cast-in-situ concrete in combination with steel, in a stackable construction.*
4. The possibilities on extraordinary risks caused by industrial activities, traffic, water, etc.
    - *Industrial activities: no industrial activities take place in the surroundings so this is not a threat.*
    - *Water: no water is in the direct surroundings of the building so this is no threat.*
    - *Traffic: the chance the traffic under and next to the building will cause collision with a structural element is high. This means these elements have to be designed on these loads according to Eurocode 1-7.*
5. The probability of terroristic or other attacks. Think about monuments, embassy's, government buildings, banks.
    - *Given the function of the building, it is not necessary to dimension the structure on terroristic attacks. No special attention is paid to this matter in the design. In the building an alternative load path is designed so in the rare case an attack does happen, the building is still robust enough.*

The engineering firm adds another chapter about the risk scenarios. Per scenario, inspired by the Stufib report 8, the threat, mechanism and measures (if needed) are discussed.

a. Unforeseen high values of variable actions
    - *Threat: The variable actions as stated in Eurocode 1, consider distributed loads for which the probability of exceedance is very low. Although the probability is low, it is still possible the loads can either locally or globally be higher than the value of the calculations.*
    - *Mechanism: Collapse of the structure because of overloading.*

- *Measures: The main supporting structure of the tower will be designed with an over capacity and alternative load path according to Eurocode 1-7.*

b. Different circumstances in the soil and other environmental conditions

- *Threat 1: Geotechnical soil studies only give details about the exact location where the tests are done. This spaces in between are estimated by extrapolation. This means the soil at the places where nog measurement is done, can differ from the tests.*
  Threat 2: The small distance to adjacent structures form the risk big damage occurs due to construction work in the soil.
- *Mechanism 1: Not enough load bearing capacity of the foundation piles.*
  Mechanism 2: Damage to the adjacencies due to excessive settlements.
- *Measure 1: Not all soil studies are done yet. When this is done, more or longer piles can be added to the design.*
  Measure 2: The geotechnical engineer will make an interaction calculation with the surroundings, with which the influences on the existing buildings will be determined.

c. Identified accidental actions like fire, explosions and impacts.

- *Threat: Fire, gas explosion, traffic, LPG explosion.*
- *Mechanism: Deterioration to the structure because of fire, failure of structural elements because of an explosion or traffic impact.*
- *Measure: A fire resistance of 120 minutes is designed. For gas explosions nothing is done since the risk is very small (apartments are designed without gas). All the columns that can be damaged by the traffic are designed against these loads according to Eurocode 1-7. The LPG explosion risk is also small, since the area where it could happen is mostly open, so the pressure can escape easily. Furthermore the building is robust designed so it can withstand the remaining pressure.*

d. Unidentified accidental actions.

- *Threat: Apart from the already taken into account actions, also unidentified accidental actions can take place.*
- *Mechanism: Failure of a random structural element due to the unidentified accidental action.*
- *Measure: An alternative load path is designed for the structure.*

e. Low resistance of the structure.

- *Threat: Impairment of the material, design errors or execution errors.*
- *Mechanism: Insufficient strength of the structure to take the loads.*
- *Measure: To protect the materials from water and weather conditions, the materials which are in close proximity of the risks will be treated accordingly. Design errors will be brought down to a minimum by asking another engineering firm for a second opinion on the design calculations. For execution risks, a separate chapter in the risk analysis is made.*

As an annex to the risk analysis, a table is added. In this table all the risks are described with the mechanism, measures and remaining risk.

B2. PIETERS BOUWTECHNIEK

Zandvliet high school (CC2b)

High school 'Zandvliet College' in The Hague is classified as consequences class 2b by this firm. They used the following explanation on how to deal with CC2b buildings for accidental actions:

For CC2 buildings accidental actions can be considered as follows: depending on the specific circumstances of a structure, simplified calculations with models with equivalent forces or prescriptive detailing rules can be used.

Three dimensional ties are installed in combination with key elements. The key elements are calculated at places where the ties would be ineffective or where they would cause a collapse of more than 100 m^2 or 15% of the total floor area of the two attached floors. The columns designed as key elements did not have to be changed in the design, since they were already designed against a stronger load than the 34 kN/m^2 which has to be used for key elements.

Tilburg University (CC3)

The Tilburg University is classified as a consequences class 3 building, so a systematic risk assessment is performed. Both unidentified an identified accidental actions are taken into account in the risk assessment.

Description risk assessment:
A qualitative risk analysis is a technical and organizational description of the considered object. For a building the important aspects are for example the function of the building, the activities which take place in it and the expected amount of people joining these activities. From this description it follows to which aspects attention have to be given and to what depth. The Stufib report 8 gives an indication for it.

Recommended by the Stufib report 8, this firm gives attention to the following aspects:

1. The strategic role of the building for the society. Think about power plants, drinking water supply, transport, economic life, governmental activities, health care, food supply.
    - *For the Tilburg University, an educational building with some side functions as a restaurant, the strategic role for society can be considered low.*
2. The chance on a high number of victims. Think about theaters, shopping malls, stations, stadiums.
    - *The building itself will have a lot of users. At the time of a collapse, many victims inside the building can be expected. Given the location of the University, during a collapse no victims from surrounding buildings will be involved, since there are no other relevant building in the proximity.*
3. The innovative character of the structure and the used materials. Think about forms, heights, spans.
    - *The design for the Tilburg University is not innovative. In The Netherlands this structural system (concrete columns, concrete and steel beams and hollow core slabs and for the large spans trusses) is often used.*
4. The possibilities on extraordinary risks caused by industrial activities, traffic, water, etc.
    - *There are no extraordinary risks that should be taken into account for this building*
5. The probability of terroristic or other attacks. Think about monuments, embassy's, government buildings, banks.
    - *This risk is, given the function of the building, not present.*

The NEN-EN 1991-1-7 gives in Annex B.4.1 some circumstances which can be a threat to the structure.

a. High values of loads, for example design errors
    - *Distinction is made in wind loads, floor loads, design errors and partial factors. All of them are based on the Eurocode, the requirements of the client and the ISO qualified quality system of this firm.*
b. Low resistance of the structure, for example because of material or execution errors.
    - *Expert supervision will be present during the execution.*
c. Different circumstances in the soil, another ground water table or other environmental conditions than expected.
    - *By performing geotechnical investigation, it is known what type of soil lies where. According to this research and the corresponding advice the foundation is designed and dimensioned.*
d. Identified accidental actions, for example fire and impacts.
    - *Road traffic: No threat. The building is situated on the campus, parking places are on more than 10 meters distance.*
    - *Air traffic: No threat. The relative small height of the building make sure no airplanes can hit it.*
    - *Gas explosion: No threat. No gas installations are present in the building.*
    - *Extreme ground water table: As highest ground water table 12,5 meters above NAP is taken into account, conform the report of the geotechnical advisor.*
    - *Fire: small threat. The structural system consists of both concrete and steel. The concrete is fire resistant enough, the steel will get an extra fire resistant layer. It is designed for 60 minutes fire resistance. Also a sprinkler system is available.*
    - *Earthquake: Small threat. Tilburg lies in an area with intensity V, which means a horizontal acceleration of 0,2 m/s^2. Although the consequences of such an earthquake are noticeable (moving paintings), it is not harmful for buildings.*
e. Unidentified accidental actions, like terroristic attacks
    - *One or more of the prescribed methods mentioned in NEN-EN 1991-1-7 paragraph 3.3 has to be executed:*
        1. *Enhanced redundancy. The building has to be checked that removal of a random structural element will not cause a collapse of more than 15% or 100 m^2 of the attached floor areas.*
        2. *Prescriptive rules (for example horizontal and vertical ties).*
        3. *Key element designed to sustain notional accidental action A_d. This action A_d is advised to be 34 kN/m^2 for buildings. The key element and direct adjacent elements have to be able to withstand this load coming from all possible directions.*

This engineering firm mentions that the recommended points by Stufib and the NEN-EN 1991-1-7 are largely similar. The innovative character of Stufib (number 3) is related to the high values of the loads (NEN point a) and low resistance of the structure (b). Extraordinary risks (4) are related to the accidental actions (d). The probability of attacks (5) is related to the unidentified accidental actions (e).

For this design, above mentioned (e) number 2 and 3 are used. Vertical and horizontal ties are designed and at the places where those ties cannot be effective, key elements are designed. The calculations for those elements are added in the report of this engineering firm.

Aspects under attention:

1. Collapse of (parts of) the building can cause a relative large number of victims amongst the users of the building.

Aspects that contribute to the structural cohesion and safety:

1. By using a sprinkler system an dimensioning the structure for the needed fire resistance, the chance on progressive collapse as a result of fire is almost zero.
2. By categorizing the building with a consequences class 3, higher partial factors for the loads are taken into account. This means a higher level of safety is obtained.
3. The main load bearing structure consists mostly of prefab hollow core slabs where the compressive zone in combination with ties provide more robustness and ductility.
4. The columns are already quit robust, because of the large dimensions.
5. Good quality control is done during design and execution.

This firm uses the advised 15% of two attached floors or 100 m^2 as maximum collapse for their calculations of the ties.

B3. BARTELS INGENIEURS VOOR BOUW & INFRA

Multifunctional parking garage RAI

This building, with dimensions 74m x 49m x 30m, is classified as consequences class 3. The first floor has a double floor height and can function as parking garage or exhibition/meeting room. The floors from level 2 have twice as many columns than the multifunctional first floor. The loads from the upper floors are transferred from two columns through a truss to one column of the first floor.

First multiple paragraphs are dedicated to the subject consequences class. In the first phase of the project it was decided that, since the use of the exhibition hall is only temporary, it can be classified as CC2. However a second opinion and specifically following the Dutch Building Regulations conclude CC3 has to be taken into account.

For the risk analysis the Stufib report 8 is used as a guideline.

1. The strategic role of the building for the society. Think about power plants, drinking water supply, transport, economic life, governmental activities, health care, food supply.
    - *The strategic role of this building is considered low.*
2. The chance on a high number of victims. Think about theaters, shopping malls, stations, stadiums.
    - *This is a realistic risk since the building is classified as CC3. Failure of a structural element can cause many victims since the floors are stacked*
3. The innovative character of the structure and the used materials. Think about forms, heights, spans.

- *The used prefab concrete structure with hollow core slabs is a commonly known and used concept in The Netherlands. Also no extra-large spans are designed and the height of the building, 30m, is not extreme. This means this risk can be considered low.*

4. The possibilities on extraordinary risks caused by industrial activities, traffic, water, etc.
    - *No industrial activities take place.*
5. The probability of terroristic or other attacks. Think about monuments, embassy's, government buildings, banks.
    - *The risk on a terroristic attack is considered low because of the function of the building.*

The most common risks mentioned in the Stufib report are considered below.

a. High values of loads, for example design errors
    - *Because of the flexibility of the first floor, a much higher floor load (4 kN/m^2 instead of 2 kN/m^2) is taken into account for the whole building than needed. With this extra load, the risk on even higher load values is low.*

b. Low resistance of the structure, for example because of material or execution errors.
    - *The calculations are done according to the Eurocode, so material factors are taken into account. To reduce the risk that the wrong concrete or steel is used, only one strength of cast-in-situ concrete and one strength of steel is used. Furthermore attention is paid to design- and execution errors and extra checks to avoid them.*

c. Different circumstances in the soil, another ground water table or other environmental conditions than expected.
    - *Geotechnical soil studies show the soil consists of homogeneous sand. The risk at big variations in the soil is small since all the tests show about the same results .The risk on horizontal forces due to heavy equipment around the site is also small. The routes are created in such a way that it will not influence the foundation. Also statically determined systems are used it is not relevant if there are some settlements.*

d. Identified accidental actions, for example fire, impacts and floods.
    - *Fire: The structure is 60 minutes fire resistant, which should be enough. Concrete structures have enough cover and steel is protected with a fire resistant layer. The hollow core slabs are designed according to the new standards for better fire resistance.*
    - *Impacts: No gas is used in the building so the only way a gas explosion can happen is because of an LPG driven car. To reduce the risk the rest of the building collapses because of such an explosion, the columns in the parking garage are designed as key elements when no alternative load path is possible.*

e. Earthquakes
    - *The project location is Amsterdam. Earthquakes are very rare in this area so the risk is considered low.*

f. Impacts by road traffic
    - *The chance a car hits a structural columns is present. Columns for which an alternative load path are not available will be designed as key elements. The truss is of bigger concern. This has to be checked if it is safe enough.*

g. Impact by airplane

- *The location of the project is close to an airport. Although the change an airplane hits the building is small, when it happens it has big consequences. For small airplanes hitting the building only fire is the considering risk. Larger airplanes can cause collapse of columns. For both cases already measures have been taken, so the risk of an impact by airplane is considered low enough.*

To sum up, the following risks have to be considered:

- Impacts by cars and trucks. It has to be determined if the horizontal loads of the standards are enough to consider in the calculations.
- The consequences of collapse are potentially high.
- Explosions from an LPG tank are not completely ruled out.
- Key elements and horizontal and vertical ties are used to create more robustness, like suggested for CC2b buildings. It has to be investigated if these precautions are also enough for a CC3 building.

The following are positive influences for the structural safety:

- The design is based on the Eurocode and CC3, which gives a solid base when structural safety is considered.
- On both the parking decks as the first floor a high value floor load is taken. This gives more extra safety than the difference between the loading factor between CC2 and CC3.
- The columns are over dimensioned and thus robust.
- An alternative load path is created by using vertical and horizontal ties. Where an alternative load path is not possible, the elements are designed as key elements.
- An extra internal and external check, a 100% check of the drawings and calculations, the reporting of inspections, the traceability of the construction materials and an external supervisor during construction give more quality control in all the phases of the project.

Conclusion

The conclusion of the risk analysis is that the original CC2 calculations can be used instead of the CC3 calculations. This is mainly because of the higher floor load taken into account. Even when calculating with CC2, still enough margin is available to guarantee enough structural safety. The used ties, key elements and alternative load path are enough. For all the other elements such as more control and inspections, 100% control and making the risk analysis, CC3 is governing.

B4. BouwQ

This firm is one who checks the technical quality of a building. The most insurance companies ask for a certificate of such a firm to make sure the building is of sufficient quality. The buyer or investor has to hire a firm to do a check and deliver the certificate to the insurance company to get their insurance. This means the buyer or investor is the client for the firm. One of the reports they deliver is a risk analysis on the structural safety. They check all the calculations of the engineering firm and highlight risk factors. The important risks are described and written in a report, which is sent to the engineering firm. The engineer has to either prove that the described risks are of less importance, since they did do the right calculation, or they have to change it. Changing can cause a lot of trouble, since the check is only done at the moment the construction already started or is about to start. Making adjustments at that time can be costly. One example is given for the project Pontsteiger.

<u>Pontsteiger (CC3)</u>

Engineering firm 4 did not design the building Pontsteiger but was hired to do an objective risk analysis. They start in the report with mentioning the structural scheme and outlines of the design. After this the remaining risks are explained. They are numbered and indicated with a risk level.

1. The execution of the foundation piles has a great influence on how they will perform. If not enough attention is paid to this matter, settlements and thus inclination and cracks can occur.
    - Risk level: high.
2. The basement lies 5 to 7 meters under the highest groundwater level. This means the walls have to be watertight. Besides the water pressure, the walls also have to be calculated for shrinkage tension. If not handled carefully, it can cause cracks which make the basement not watertight.
    - Risk level: medium.
3. Creation of an alternative load path is described as ‘where possible’ instead of an obligation. Not executing an alternative load path could have major consequences for the structural safety.
    - Risk level: high.
4. Drastic measures have to be taken to ensure the bridge part of the Pontsteiger will fulfill the 120 minutes fire resistance, since the structure consists of steel and hollow core slabs with a compression layer.
    - Risk level: medium.
5. For designing the structure of the bridge the calculations of a 3D model are used. These outcomes are not checked with a hand calculation. Misinterpretation of results of a model is common, so disastrous consequences could happen if the results are not checked.
    - Risk level: very high.
6. Annex B of NEN-EN 1990 says it is advised to let a third party do a check for CC3 buildings. Since this is not done, a high risk is obtained.
    - Risk level: high.
7. It is not clear if the correct wind loads are used for the lower part of the building, since a higher wind load needs to be taken into account for this part because of the higher towers next to it.
    - Risk level: medium.
8. The connection between and execution of the heavy façade elements to the concrete floors is critical and sensitive to execution mistakes.
    - Risk level: medium.
9. The glass railings of the balconies and their anchorages are essential and critical.
    - Risk level: medium.

The firm advises to clarify these points and let them be checked again afterwards. Especially risk number 5 is not acceptable.

C. HAZARDS

C1. EUROCODE

The Dutch national annex of the Eurocode mentions in NEN-EN 1991-1-7 chapter 3 (CEN, 2006) the following hazards that need to be taken into account.

- Impact by vehicles, trains, ships etc.;
- Gas explosion;
- Extreme ground water table;
- The effect of falling persons on floors, roofs and parapets, as described in NEN-EN 1991-1-1/NB;
- The effect of deliberate opened windows and doors during a storm as described in NEN-EN 1991-1-4;
- Loads by the landing of a helicopter
- The sudden lack of usefulness of a horizontal or vertical tie, as described in NEN-EN 1993-1-11;
- Loads caused by ice pressure on a bridge pillar;
- The effect of the loss of stability elements of another building, on other land. This design situation only holds for housing (not in a residential building) and hotel function not in a hotel-like building. For other building, this structural system is not permitted.

These are identified accidental actions that need to be considered while making the structural design of a building of consequences class 2 and 3. Fire is not included in the list since a separate paragraph about fire is available in the Eurocode. Human errors and other unidentified actions are not mentioned, because the Eurocode handles a method based on localized failure for unidentified accidental actions.

C2. DESIGN AND CONSTRUCTION ERROR EFFECTS ON STRUCTURAL SAFETY

Part of the Journal of Structural Engineering in 1987 (Ellingwood B. , 1987) was addressed to design and construction error effects on structural reliability. Ellingwood compared different researches about structural failures due to errors.

One of the lists he cites is from Analysis of Structural Failures (Blokey, 1977). Blokey mentions eight main causes of structural failure, all due to human errors.

- Inadequate consideration of uncertainty in design variables
- Errors in methods of structural analysis, particularly where behavior is not well understood (e.g., loads not understood, neglect of torsion)
- Extreme hazards not considered (floods, explosions, earthquake, tornado)
- Failure modes not understood (galloping, etc)
- Failures modes recognized but not treated properly
- Errors during construction (e.g., site control, management, communication)
- Financial or political pressures on personnel
- Misuse or willful abuse

Furthermore Ellingwood refers to an article of the Journal for Structural Engineering (A. Nowak, 1985), which identifies three basic types of error.

- Errors of concept (stupidity, ignorance). Includes loads not envisioned, incorrect assumptions, incorrect analytical modeling.
- Errors of execution (carelessness, forgetfulness, negligence). Includes calculation or detailing errors, mistakes in reading drawings and specifications and defective workmanship.
- Errors of intention (venality, irresponsibility). Includes unwarranted shortcuts to save money, substitution of components that may not be equivalent to those originally specified and acceptance of marginal workmanship in order to maintain construction schedules.

C3. COST TU0601

According to a contribution to the conference COST TU0601 (Ton Vrouwenvelder, 2007-2011) there are five main categories in which the accidental actions can be distinguished. First there are the natural hazards, such as an earthquake, landslide or hurricane. The second category are accidental manmade actions, like an explosion, fire or impact by vehicle. The third category consists of human actions which are not accidental, like vandalism or a terrorist attack. Normal loads which differ from the loads taken into account in the calculations are the fourth category. The human errors, like a design or construction error, make up the fifth category. See the table below for the complete overview (Ton Vrouwenvelder, 2007-2011).

Accidental /natural	Accidental/manmade	Human influences	Normal loads	Human Errors
Earthquake	Internal explosion	Vandalism	Self-weight	Design error
Landslide	External explosion	Demonstrations	Imposed loads	Material error
Hurricane	Internal fire	Terrorist attack	Car park loads	Construction error
Tornado	External fire		Traffic	Misuse
Avalanche	Impact by vehicle etc.		Snow	Lack of maintenance
Rock fall	Mining subsidence		Wind	Miscommunication.
High groundwater	Environmental attack		Hydraulic	
Flood				
Volcano eruption				

C4. Manual for the systematic risk assessment of high-risk structures against disproportionate collapse

Manual for the systematic risk assessment of high-risk structures against disproportionate collapse (Cormie, 2013) made a more detailed and longer list, although they mention it is still (deliberately) not complete. They use the same methodology as COST to list the risks: divide them in categories on what the overall cause of the hazard is and then list the possible hazards that could occur.

Design and construction

- Analysis or calculation error
- Uncertainty in the applied loads, and unrecognized effects of variation in the applied load
- Unrecognized action e.g. sensitivity to vibration or to a single dominant action

- Unrecognized structural behavior/structural response
- Factors customarily ignored in design of smaller buildings e.g. wind-induced dynamic oscillation, verticality tolerances, elastic shortening, P-delta effects, soil-structure interaction
- Unrecognized material behavior (e.g. lack of knowledge about new materials)
- Unrecognized sensitivity to design assumptions
- Unrecognized uncertainty in analysis
- Unrecognized load paths i.e. stress distribution not as predicted in analysis e.g. due to indeterminate nature of structure, failure to consider changes in stress distribution due to second-order (P-delta) effects or movement/structural deformation elsewhere in the structure
- Lack of stability
- Detailing error or the failure to appreciate the detailing requirements for the structure
- Failure to communicate the design intent
- Material defects
- Gross construction error (e.g. omission of reinforcement, dimensional error, installation of precast slabs upside-down)
- Unauthorized design change
- Susceptibility of design to inadequate temporary works

Robustness during construction (or demolition/alteration)

- Construction method statement inconsistent with design intent or not competently developed
- Effect of dropped object (e.g. wet concrete load)
- Loading in partially-constructed condition or condition of partial strength
- Incomplete stability system
- Lack of stability during demolition

Permanent, imposed and environmental actions

- Wind, snow, ice accretion, rainwater ponding, flooding
- Excessive loading (whether floor loading due to material stacking or imposed loading due to the malfunction or misuse of plant e.g. overhead craneage)
- Earthquake
- Fire
- Structural deformation/movement
- Subsidence/ground movement
- Groundwater level change (sensitivity to groundwater, upward pressure, buoyancy)
- Influence of groundwater change on foundation/ground loadbearing capacity
- Scour, undermining of foundations
- Dynamic effects e.g. vibration
- Fatigue
- Material degradation, (lack of) durability, corrosion, rot
- Component failure due to fatigue/durability/corrosion/rot, particularly the hidden failure of uninspectable components

Accidental actions

- Vehicle impact

- Fire
- Gas explosion
- Aircraft impact
- Events consequent on plant malfunction
- Dropped objects (in plant)

Malicious actions

- Malevolent vandalism/arson/theft
- Terrorist attack

From use/maintenance

- Overloading
- Fatigue
- Corrosion
- Failure to design for inspection and maintenance
- Failure to implement maintenance and inspection regimes
- Unauthorized alteration
- Deterioration

From procedural failings

- Competence to carry out the risk assessment
- Poor definition of design brief
- Failures in coordination and project interfaces
- Failings associated with division of contractual responsibility
- Lack of design supervision during construction
- Lack of good change management
- Lack of competence in design or construction
- Failings in procurement (e.g. insufficient time/resources)
- Poor design or construction supervision
- Sub-standard specifications or quality of construction
- Poor communication of information, e.g. poor quality management procedures
- Lack of quality assurance and quality control procedures

Sub-standard components e.g. due to counterfeiting of Quality Control markings/certification

This list is meant for the structural engineer to identify hazards, as a first step in making a risk assessment. With this list the engineer is helped by thinking of other factors as well. It makes him or think of possible hazards which might not pop in his mind directly.

C5. KIK

KiK, the quality control instrument of KOMO, a certifying company in The Netherlands, is making a checklist for building projects. For every discipline, such as structural safety, fire safety, water tightness, noise insulation and burglar resistance, a checklist will be made. The responsible quality control company has to make sure these checklists are filled in for every discipline. Structural safety is divided into fundamental load combinations and accidental load combinations. The checklist consists of structural elements which have to be judged by the engineer if they are sensitive to accidental actions.

Per structural element the boxes ‘judged’ and ‘relevant’ can be checked and a textual explanation can be given. Then a box with risk measures has to be filled in, where one of the following can be chosen.

- None
- Manufacturers declaration of its product
- Personal register
- Prototype test
- Certified product
- Certified execution
- Testing

Ongewenste gebeurtenissen	Beoordeeld	Relevant	Toelichting	Risicobeheersing
Bb 2.2 • Statisch evenwicht faalt (bijv. opdrijven, omvallen) binnen ontwerplevensduur	☐	☐		geen Code

In the end the quality control company has to check if every hazard is taken care of and if possible extra checks advised in the explanation box are done.

Since KiK is still in the process of making this tool, the list of hazards themselves is not ready yet. In an interview with Jack van Everdink from KiK he told, according to his experience, some commonly made mistakes or forgotten factors regarding structural safety due to accidental actions.

- Fire spread through a window or opening in the façade to the next room
- Fire resistance in the cavity
- Impact of the environment on concrete
- Soil pollution, especially when the soil has a history of usage
- Check the planning permission for structural relevancies
- Loads during construction
- Extrapolation for structural resistance
- Measures against frost (around the building) during execution
- Vibrations caused by trams, trains or heavy traffic over speed bumps
- Influence of movements by the use of the building

C6. Structural Safety

In the thesis of Karel Terwel (Terwel, 2014) an investigation is done based on project management literature. A list with project characteristics which can influence the successfulness of a project is divided in three levels: macro (external factors), meso (project and company factors) and micro (human factors). These factors, such as safety goals from the company, the given time and budget for the project and technical competencies of the workers, influence the chance and consequences of possible hazards. He concludes that the most crucial factors lie in the project factors. He lists the following factors as being the most crucial for the successfulness of the project.

1. Communication and collaboration
2. Control mechanisms
3. Allocation of responsibilities
4. Structural risk management
5. Safety culture
6. Knowledge infrastructure

When one of these factors is not or not enough present during the project, the changes are bigger an error will be made. The philosophy behind this is that human errors are influenced by the context he or she was working in (Terwel, 2014).

Terwel also analyzed in his thesis which hazards actually caused (partial) collapse, structural damage, material deterioration, insufficient functionality or no actual damage in the past in The Netherlands. He mentions around 90% of the failures are caused by human errors. These human errors can be divided in the design and execution phase.
Design phase:

- Incorrect modelling or calculation error
- Incorrect dimensioning on drawings
- Conflicting drawing and calculation
- Absence of drawing and/or calculation
- Other design error

Execution phase:

- Insufficient quality of materials applied
- Incorrect assembling of elements on the building site
- Insufficient amount of material used
- Erroneous measurements on the building site
- Other execution errors

D. MEASURES

D1. EUROCODE

In the Eurocode different measures are described. Identified and unidentified accidental actions combined, the given measures are the following:

- Preventing or reducing the action (e.g. protective measures)
- Design the structure to sustain the action (e.g. designing key elements, on which the stability of the structure depends, to sustain the effects of a model of accidental action A_d)
- Design the structure to have sufficient robustness (e.g. so that in the event of a localized failure the stability of the whole structure or of a significant part of it would not be endangered, or applying prescriptive design/detailing rules like three-dimensional tying for additional integrity).

Different type of measures are advised to take for different situations.

D2. DESIGN AND CONSTRUCTION ERROR EFFECTS ON STRUCTURAL SAFETY

Ellingwood refers to (Ellingwood B. , Safety Checking Formats for Limit States design, 1982) and (Matousek, 1981) for the following steps for reducing the risk.

- Eliminate hazard
- Reduce hazard to acceptable norm
- Compensate for hazard in design
- Contain hazard by control and monitoring
- Accept hazard as a known risk

These are general steps on how to reduce a risk in theory. No practical examples are given in the paper of Ellingwood.

D3. MANUAL FOR THE SYSTEMATIC RISK ASSESSMENT OF HIGH-RISK STRUCTURES AGAINST DISPROPORTIONATE COLLAPSE

The Manual for the systematic risk assessment of high-risk structures against disproportionate collapse (Cormie, 2013) gives recommendations on which aspects attention needs to be paid during design and execution. It is divided into general design recommendations and general procedural recommendations:

General design recommendations

Robustness is generally enhanced and risks reduced by application of the following principles:

1. Ductile design and the ability to dissipate energy is an overriding principle of a robust design
2. Systematic procedures should be employed to identify weaknesses in the structural form. This will also lead to the identification of the critical elements in a structure.
3. The structural design should provide alternative load paths, with explicit checks undertaken of their ability to carry loads redistributed from the loss of a member.
4. The horizontal and vertical load path should be separated, such that horizontal actions will not cause failure of the vertical load path.

5. The designer should ensure compatibility between the strength-based assumptions made in developing resistance against progressive collapse and the necessary ductility to support those assumptions, and ensure the ductility provided is adequate throughout the design.
6. Design of vertical loadbearing elements such that failure is produced in the adjoining slab/beam rather than in the column ('strong column/weak beam'), will limit the extents of damage.
7. Continuity through improved connection detailing generally enhances robustness of structures. In some structural forms this will exacerbate the collapse because the structure is incapable of carrying the redistributed loads. In these cases, discontinuities in the form of expansion joints or structural fuses can be beneficial in confining the spread of damage.
8. Design for robustness should consider the consequences of loss of/damage to elements of the stability system, not just elements forming the vertical load path.
9. For particularly severe hazards local to a specific part of the building such as a screening area or loading bay, compartmentalization can be beneficial, by providing a structural discontinuity such that the damage does not spread to the adjoining structure or a secondary, sacrificial structure.
10. The local absorption of energy is important in containing the damage and is a key role of the structural connections. Brittle connections should not be used.
11. Large spacing between columns or supports significantly increases the extents of the potential damage. Reducing the spans so that redistribution of load becomes possible should be considered, but if the large spans are necessary, the columns or supports become critical. Attention should then move to eliminating the hazards and minimizing the risks that could impair the columns or supports (refer to section 4.10).

General procedural recommendations

Procedural measures employed to reduce risks can be structured around the following principles:

1. Single point of responsibility: as with the overall coordination of the structural design, the lead structural engineer should be directly responsible for the overall control of the design with respect to all issues relating to stability and robustness [3,94-98] , and the contracts should be written to permit this.
2. Design team interfaces should be clearly identified and controlled such that there is explicit agreement between the parties on either side of each interface as to where the responsibilities lie, and how the design interface is to be managed.
3. Design information, e.g. loads, load case combinations, connection forces should be clearly and unambiguously communicated and steps taken to ensure each designer has a clear understanding of them.
4. Design change should be clearly managed and controlled.
5. Good management processes with adequate checks to eliminate errors, should be in place for both the design and the construction.
6. Risks should be kept under regular review during the design process. That is, the initial risk assessment should be undertaken at the earliest stages of the design and should keep pace with the design through periodic review and further development of the detail as the design progresses to take account both of the increasing level of detail and of design changes. It should be updated as the design is finalized, and should be updated again to reflect the as-built design once construction is completed.

7. Robust quality management procedures should be designed and enforced to manage the flow of information and document control such that the risk of failures in the communication of information is minimized.
8. The structural engineer should develop an appropriate inspection and maintenance regime for the structure which is developed as a core part of the design activities, and not merely as an after-thought shaped to fit the design after it has been finalized. This should be agreed with the client during the development of the design and must be properly communicated by the designer before the design can be said to be complete.
9. The required level of competence to construct the building to the quality required should be determined together with identification of the means by which this will be evaluated and controlled.
10. Rigorous measures should be implemented for quality management in the design process, which should be commensurate with the level of risk on the project. Design measures that are associated with large reductions in risks or where a high level of residual risk remains in the design are indicative of where additional measures are warranted in the checking and review of the design, up to and including an independent peer review of the design. Site testing should be specified for those aspects of the construction where the design intent depends upon the quality of workmanship, in order to ensure the structure will behave as intended.

Rigorous measures should be implemented for quality assurance both through the supply chain and in the construction itself, proportional to the level of risk in the design. Examples indicative of where particularly close supervision and testing of the construction is warranted include elements:

- known to be particularly important to the robustness of the structure
- in which there is a high risk of mistakes or errors being made
- where supervision is known to be difficult during construction
- where a high degree of reliability is necessary because subsequent inspection and maintenance will be difficult.

The items in this list are more guidelines on what the structure should perform than a list of concrete measures. For example ‘design change should be clearly managed and controlled’ is a statement that it should be done, but not *how* this can be done. The part of how these points can be accomplished, is left for the engineer to decide. A reason for this could be that most civil projects are different so different methods should be used in different situations to get to the same outcome.

D4. KiK

In the meeting with KiK the following measures to reduce the mentioned risks were discussed.

- Check if a window or opening is designed in the neighborhood of a gas installation, so it opens when over pressure occurs.
- Check if in earthquake areas the foundation piles are not designed to be made of wood with a concrete part on top or that concrete foundation piles have sufficient reinforcement to withstand horizontal forces.
- Check if in earthquake area shock-absorbers are used between the piles and foundation

- Check if enough attention is paid to the following risks:
    - Fire spread through a window or opening in the façade to the next room
    - Fire resistance in the cavity
    - Impact of the environment on concrete
    - Soil pollution, especially when the soil has a history of usage
    - Structural relevancies in the planning permission not seen by the engineer
    - Other loads than expected during construction
    - Extrapolation for structural resistance
    - Measures against frost (around the building) during execution are forgotten
    - Vibrations caused by trams, trains or heavy traffic over speed bumps
    - Influence of movements by the use of the building

These measures are extra checks for items that need to be done according to the Eurocode, but are often forgotten. Actually the general measure here can be described as 'the design is according to the concerning rules and regulations'.

D5. STRUCTURAL SAFETY

In his thesis Karel Terwel summed up measures that can be taken against the organizational factors (Terwel, 2014).

Safety culture

- Central organization Structural Safety
- Mandatory failure reporting
- Improve awareness/attention to safety related issues
- Constructive attitude towards safety
- Adequate response after warnings
- Assessment system structural safety

Allocation of responsibilities

- Improved clearness and completeness contracts
- Sufficient budget/tender on price and value/financial incentives
- Mutual trust
- Lead engineer (single point responsibility)
- Mandatory certification of lead engineer
- Shift accountability to advisors
- Maximum number of subcontractors
- Integrated contracts/chain integration

Risk management and control

- Guidance on performing structural risk analysis
- Mandatory risk analysis for CC3, light version for CC2
- Positive attitude towards control
- Application of effective control

- Independent checking design and execution CC3
- Shift accountability
- Standardization
- Prefabrication
- Real time structural monitoring

Communication and collaboration

- Design review by contractor
- Site engineer for CC3
- Chain integration/integrated contracts
- BIM/clash detection
- Shift accountability to advisors
- Mutual trust and interest

Knowledge infrastructure

- More attention technical knowledge in higher education
- HR management
- Knowledge management

These measures differ in who can execute them. Terwel makes a distinction in legal, organizational and behavioral measures. For the tool of this report the legal measures will be left out of the scope. This is done because the tool will be used by someone who is not able to change legal regulations at the time of usage. The legal measures should be adapted by for example the government.

E. Risk assessment case study: Cooltoren

Step 1: Definition of scope

Goal and objective of the risk assessment

The goal of making this risk assessment is to verify if the risks on accidental actions are low enough for the Cooltoren in Rotterdam, and thus the tower can be considered safe enough designed against accidental actions.

Project description

The Cooltoren will be built in the center of Rotterdam, in Baankwartier, directly behind the Schiedamsedijk. The tower will consist of 52 floors with a total height of 154,4 meter. The total floor area is circa 37.000m^2.

FIGURE 18 COOLTOREN 3D IMPRESSION

Structural system

Tower: 7th – 49th floor

The tower will consist of a combination of cast in situ concrete elements (floors, core and outriggers) and prefab concrete columns. The walls of the core will be built with self-climbing formwork. The cast in situ floors will have a thickness of 250mm. The stairs and terraces are made of prefab concrete. The outer core walls will have a thickness of 500mm and the inner ones of 250mm, 200mm and 100mm. From the 45th floor until the roof the 500mm thick walls will stop. The stability will be provided by the concrete walls of the core, the concrete outriggers (16th-19th and 32nd-35th) and the concrete columns under the outriggers.

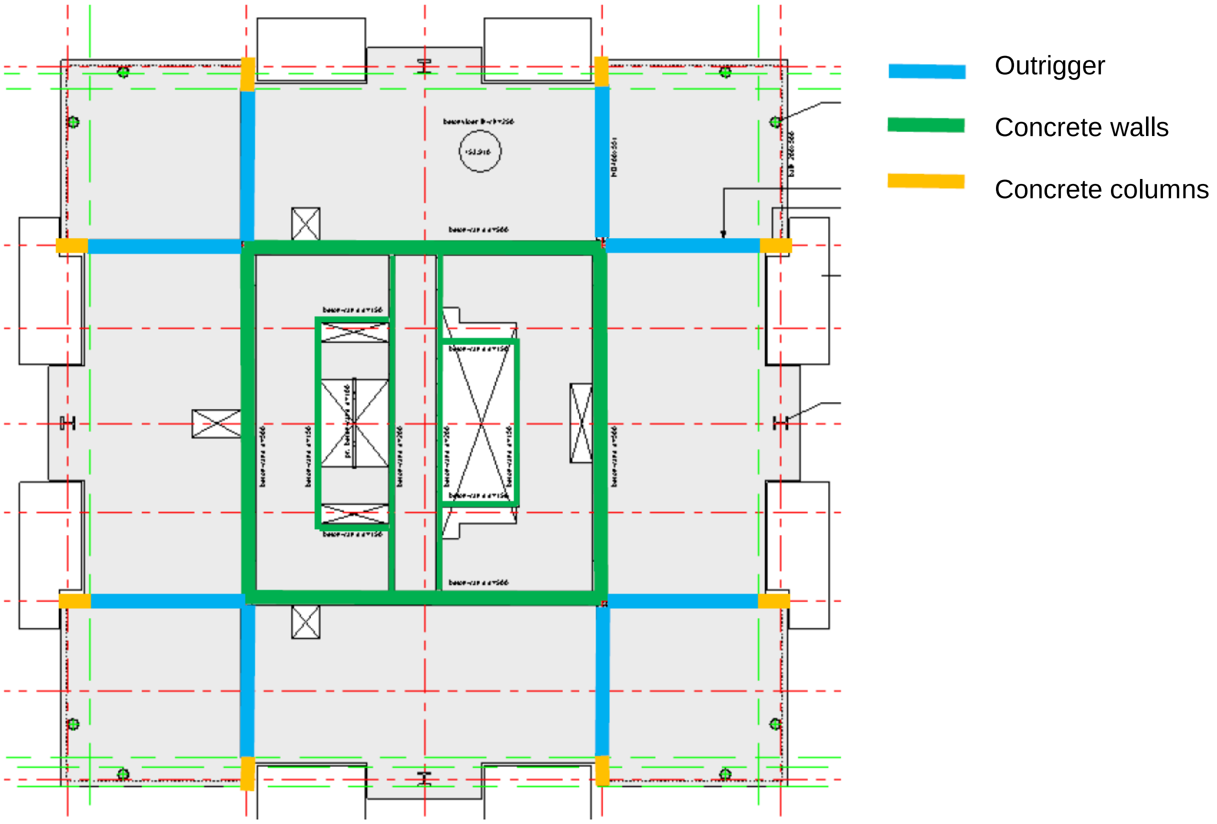

FIGURE 19 STABILITY ELEMENTS TOWER (18TH FLOOR)

Plinth: ground floor till 6th floor

Just like the tower the plinth will consist of a cast in situ structure.

The wall thicknesses of the outer walls of the core and the walls at the sides of the building (axis 3, axis 6, D) are 500mm. the walls of the wings of the plinth are 250mm. The cast in situ floors have a thickness of 250mm. At the backside of the building the columns between axis H and I will be supported by the steel trusses which distribute the forces to the concrete wall of 800mm thickness on axis I and the concrete walls on axis G. This steel structure will be the transfer structure over the Hoombrekerstraat. Because of possible settlement differences between the tower and the plinth, the wings of the plinth will have no foundation. With cantilevered concrete walls the wings will distribute their forces to the foundation of the tower. The stability will be provided by the concrete core walls and the concrete walls on the sides of the tower.

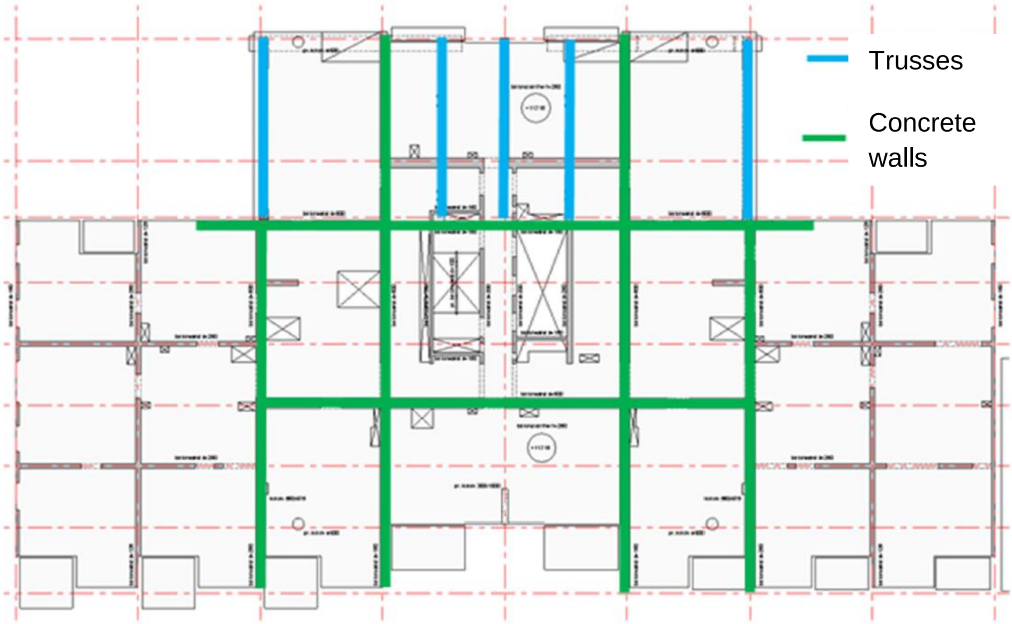

FIGURE 20 STABILITY ELEMENTS PLINTH (4TH FLOOR)

Foundation and subsoil

The soil mechanical investigation is done by Mos Grondmechanica. See their report R1501396-RH_8 dd 14-05-2018. Because of the neighboring buildings the pile system will be vibration free. Also the pile advise is made by Mos Grondmechanica. They chose a Tubex pile. See their report R1501396-RH_7 dd 12-10-2017. Indication for the piles: 192 Tubex piles Ø762/950; capacity F_{Rd} = 6590 kN.

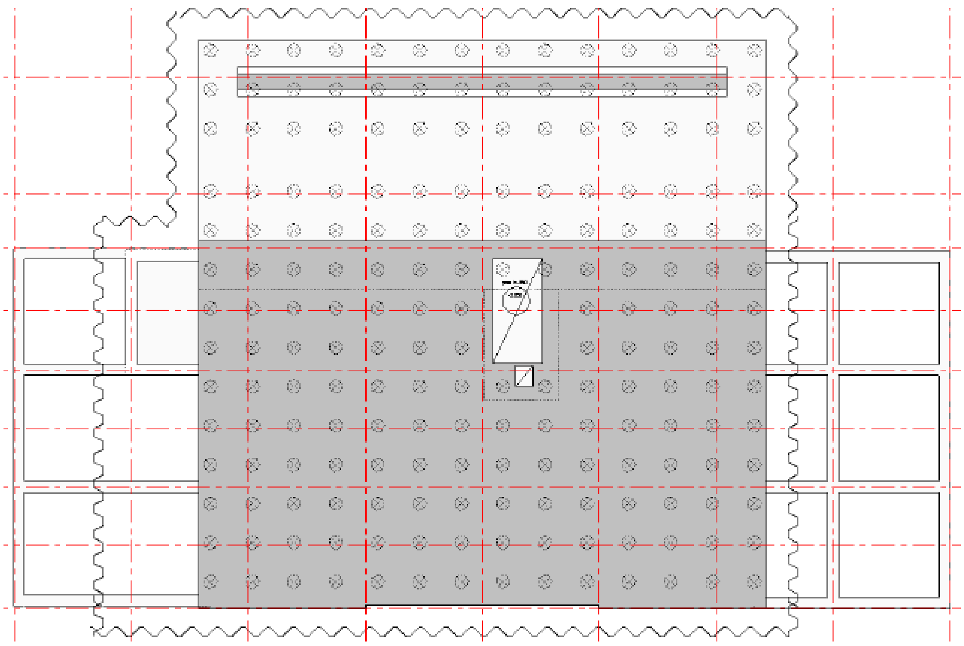

FIGURE 21 PILE FOUNDATION

The strategic role of the building for the society

The Cooltoren is mainly meant for housing. Only the first and second floor are occupied by retail stores.

The probability on a high number of victims

This building belongs to the group for which a high number of victims is surely possible. The Cooltoren is indicated as consequences class 3 from Eurocode 1-7.

The innovative character of the structure and the used materials

The building is designed in a, in The Netherlands, well-known structural method. The structure consists of cast-in-situ concrete in combination with steel, in a stackable construction.

The possibilities on extraordinary risks caused by industrial activities, traffic, water, etc.

- Industrial activities: no industrial activities take place in the surroundings so this is not a threat.
- Water: no water is in the direct surroundings of the building so this is no threat.
- Traffic: the probability the traffic under and next to the building will cause collision with a structural element is high. This means these elements have to be designed on these loads according to Eurocode 1-7.

The probability of terroristic or other attacks

Given the function of the building, it is not necessary to dimension the structure on terroristic attacks. No special attention is paid to this matter in the design. In the building an alternative load path is designed so in the rare case an attack does happen, the building is still robust enough.

STEP 2 AND 3: DETERMINE ALL RELEVANT HAZARDS AND DESCRIBE FAILURE SCENARIOS

The given list of possible hazards is used as a basis. The hazards which have a negligibly small probability of occurring are already taken off the list. No extra hazards are added. See table 10 for all hazards and failure scenarios used in the risk assessment for the Cooltoren.

	Hazard	Failure scenario
Organizational factors	Communication and collaboration error	Communication and collaboration error
	Control mechanisms error	Control mechanisms error
	Allocation of responsibilities error	Allocation of responsibilities error
	Structural risk management error	Structural risk management error
	Safety culture error	Safety culture error
	Knowledge infrastructure error	Knowledge infrastructure error
Design phase	Incorrect modeling or calculation error of the structural engineer	- Collapse of vertical structural elements due to more load than anticipated - Collapse of horizontal structural elements due to more load than anticipated
	Incorrect dimensioning, conflicting or absence of drawing and/or calculation	- Collapse of vertical structural elements due to more load than anticipated - Collapse of horizontal structural elements due to more load than anticipated
	Not taking environmental factors into account	building materials will be negatively affected by the soil or groundwater
	Not taking loads during construction into account	Parts of the structure can be damaged by which leads to less strength due to loads during construction
Execution phase	Not using accurate measures against weather conditions	Concrete can get less strong than predicted due to weather conditions
	Insufficient quality or amount of materials applied	- Insufficient concrete quality used which causes the structural elements to be less strong - not enough or wrongly placed reinforcement - insufficient steel quality
	Incorrect assembling of elements on the building site	- Critical details are not correctly executed, which causes them to fail - Placing structural elements at the wrong place
	Erroneous measurements on the building site	- Collapse of vertical structural elements due to more load than anticipated - Collapse of horizontal structural elements due to more load than anticipated
	Falling elements	Parts of the structure can be damaged by which leads to less strength due to falling elements
	Deviation from the design in execution or circumstances taken into account	- The soil is less strong than calculated with due to extrapolation of the soil strength - Other materials or plants are used than determined in the design
	Formwork, bracing or erection error	Parts of the structure can be damaged which leads to less strength due to formwork, bracing or erection error
During use	Insufficient maintenance	Materials become less strong due to insufficient maintenance
	Insufficient inspection	Materials become less strong due to insufficient inspection
	Deviate from the use for which it was designed	Structural element collapses due to more load than anticipated

	Fire	The load bearing structure will collapse due to fire
	Explosion (gas leak, dust or chemical, bomb, excavation blast)	The structure will collapse due to a LPG explosion
	Impact by vehicle (car/train/truck, ship, airplane)	Car or truck damages structure by impact
	Soil pollution	Concrete foundation can get damaged due to soil pollution
	Larger load than expected	- Collapse of vertical structural elements due to more load than anticipated - Collapse of horizontal structural elements due to more load than anticipated
	Falling objects, like collapsing structures	- Collapse of vertical structural elements due to more load than anticipated - Collapse of horizontal structural elements due to more load than anticipated

TABLE 10 HAZARDS AND FAILURE SCENARIOS COOLTOREN

Step 4: Describe the consequences

All consequences are of the type '(partial) collapse', other consequences are not considered.

Step 5: Determine risk reduction measures

Since the Cooltoren is already in the execution phase, the risk reduction measures were already determined before this risk assessment was performed. The measures that were taken for the Cooltoren are the following:

- Alternative load path
- Extra ductility
- Fire resistance of 120 minutes
- Sprinkler installation for fire
- Many openings in the garage so pressure due to a LPG explosion can escape
- Four eye principle during design
- Second opinion by external firm on the structural design
- Control of the structural engineer of Van Rossum at the site
- Concrete and details are designed to sustain soil and water influences
- Quality control on the construction site takes place via the TIS system
- Extra cone penetration tests (CPT) after installing the foundation piles

Step 6: Determine maximum allowable probability per consequence class

The protocol describes the following maximum allowable probabilities per consequence class per 50 years that an incident occurs and causes a specific consequence:

$$P_{CC1,max} = b * 4 * 10^{-4}$$
$$P_{CC2,max} = b * 7 * 10^{-5}$$
$$P_{CC3,max} = b * 8 * 10^{-6}$$

For b no value is given in this report. For this case study, $b = 0{,}8$ is used, inspired by the unity check of CC3 buildings where the factor 0,8 is used as well.

Step 7: Quantify consequences

Table 9 (chapter 4) is used to determine the consequence class per hazard scenario. See table 11 for the classification for the Cooltoren.

STEP 8: QUANTIFY PROBABILITY

To estimate the probability of each failure scenario, the method presented in chapter 4 is used. The probability an incident happens and causes the consequence of interest per 50 years per building is calculated, per consequence class, as follows:

$$P_{CC1}(F) = P(I) * \sum_{i=1}^{p} P_{CC1}(F_i|I)$$

$$P_{CC2}(F) = P(I) * \sum_{j=1}^{q} P_{CC2}(F_j|I)$$

$$P_{CC3}(F) = P(I) * \sum_{k=1}^{r} P_{CC3}(F_k|I)$$

Where $P(I) = a * 6 * 10^{-5}$ per 50 years per building. The factor a is not given in the report, only suggested is that it should be greater than or equal to one. Suppose this factor is 2, so in reality the probability an incident happens per building is two times as high than the number of times an incident happened in the 16 years Cobouw investigated.

The engineer estimated the $P_{CC1}(F_i|I)$, $P_{CC2}(F_j|I)$, and $P_{CC3}(F_k|I)$ according to the indications given in chapter 4. See table 11 on the next page for the estimations per failure scenario. In this case the $P_{CC1,2,3}(F_{i,j,k}|I)$ are divided in the probability a given incident is caused by a specific hazard, and the probability a specific failure scenario follows that hazard. These multiplied give the $P_{CC1,2,3}(F_{i,j,k}|I)$, see the last column in table 11.

In table 12 all probabilities per consequence class are summed up to obtain the total probability an incident happens and causes a consequence of class 1, 2 or 3.

Together, this gives the following probabilities per consequence class per building per 50 years:

$$P_{CC1}(F) = 2 * 6 * 10^{-5} * 0{,}011 = 1{,}3 * 10^{-6}$$

$$P_{CC2}(F) = 2 * 6 * 10^{-5} * 0{,}41 = 4{,}9 * 10^{-5}$$

$$P_{CC3}(F) = 2 * 6 * 10^{-5} * 0{,}31 = 3{,}7 * 10^{-5}$$

Furthermore, in table 12 the sum of all conditional probabilities are taken and checked if it is below 1, according to the following equation.

$$\sum_{i=1}^{p} P_{CC1}(F_i|I) + \sum_{j=1}^{q} P_{CC2}(F_j|I) + \sum_{k=1}^{r} P_{CC3}(F_k|I) = 0{,}011 + 0{,}41 + 0{,}31 = 0{,}73 \leq 1$$

Failure scenario	CC	Probability given incident is caused by specific hazard	Probability failure scenario follows the hazard	Probability a given incident is caused by failure scenario $P_{CC1,2,3}(F_{i,j,k}\|I)$
Communication and collaboration error	2	0,05	1	0,05
Control mechanisms error	2	0,05	1	0,05
Allocation of responsibilities error	2	0,05	1	0,05
Structural risk management error	2	0,05	1	0,05
Safety culture error	2	0,05	1	0,05
Knowledge infrastructure error	2	0,05	1	0,05
Collapse of vertical structural elements due to more load than anticipated (incorrect modeling)	3	0,15	0,5	0,075
Collapse of horizontal structural elements due to more load than anticipated (incorrect modeling)	2	0,05	0,5	0,025
Collapse of vertical structural elements due to more load than anticipated (wrong drawings)	3	0,05	0,5	0,025
Collapse of horizontal structural elements due to more load than anticipated (wrong drawings)	2	0,05	0,5	0,025
building materials will be negatively affected by the soil or groundwater	3	0,01	1	0,01
Parts of the structure can be damaged by which leads to less strength due to loads during construction	2	0,01	1	0,01
Concrete can get less strong than predicted due to weather conditions	3	0,01	1	0,01
Insufficient concrete quality used which causes the structural elements to be less strong	3	0,01	0,33	0,0033
not enough or wrongly placed reinforcement	3	0,05	0,33	0,0167
insufficient steel quality	3	0,01	0,33	0,0033
Critical details are not correctly executed, which causes them to fail	3	0,05	0,5	0,025
Placing structural elements at the wrong place	3	0,05	0,5	0,025
Collapse of vertical structural elements due to more load than anticipated (incorrect measurements on building site)	3	0,05	0,5	0,025
Collapse of horizontal structural elements due to more load than anticipated (incorrect measurements on building site)	2	0,05	0,5	0,025
Parts of the structure can be damaged by which leads to less strength due to falling elements	3	0,01	1	0,01
The soil is less strong than calculated with due to extrapolation of the soil strength	3	0,01	0,5	0,005
Other materials or plants are used than determined in the design	3	0,01	0,5	0,005
Parts of the structure can be damaged which leads to less strength due to formwork, bracing or erection error	3	0,01	1	0,01
Materials become less strong due to insufficient maintenance	2	0,01	1	0,01
Materials become less strong due to insufficient inspection	2	0,01	1	0,01
Structural element collapses due to more load than anticipated	1	0,01	1	0,01
The load bearing structure will collapse due to fire	3	0,05	1	0,05
The structure will collapse due to a LPG explosion	3	0,001	1	0,001
Car or truck damages structure by impact	3	0,01	1	0,01
Concrete foundation can get damaged due to soil pollution	3	0,001	1	0,001
Collapse of vertical structural elements due to more load than anticipated (larger load than expected)	2	0,001	0,5	0,0005
Collapse of horizontal structural elements due to more load than anticipated (larger load than expected)	1	0,001	0,5	0,0005
Collapse of vertical structural elements due to more load than anticipated (falling objects during use)	2	0,001	0,5	0,0005
Collapse of horizontal structural elements due to more load than anticipated (falling objects during use)	1	0,001	0,5	0,0005
Total (must be ≤1):				**0,73**

TABLE 11 FAILURE SCENARIOS COOLTOREN

Failure scenario	$P_{CC1}(F_i\|I)$	$P_{CC2}(F_j\|I)$	$P_{CC3}(F_k\|I)$
Communication and collaboration error		0,05	
Control mechanisms error		0,05	
Allocation of responsibilities error		0,05	
Structural risk management error		0,05	
Safety culture error		0,05	
Knowledge infrastructure error		0,05	
Collapse of vertical structural elements due to more load than anticipated (incorrect modeling)			0,075
Collapse of horizontal structural elements due to more load than anticipated (incorrect modeling)		0,025	
Collapse of vertical structural elements due to more load than anticipated (wrong drawings)			0,025
Collapse of horizontal structural elements due to more load than anticipated (wrong drawings)		0,025	
building materials will be negatively affected by the soil or groundwater			0,01
Parts of the structure can be damaged by which leads to less strength due to loads during construction		0,01	
Concrete can get less strong than predicted due to weather conditions			0,01
Insufficient concrete quality used which causes the structural elements to be less strong			0,003
not enough or wronly placed reinforcement			0,017
insufficient steel quality			0,003
Critical details are not correctly executed, which causes them to fail			0,025
Placing structural elements at the wrong place			0,025
Collapse of vertical structural elements due to more load than anticipated (incorrect measurements on building site)			0,025
Collapse of horizontal structural elements due to more load than anticipated (incorrect measurements on building site)		0,025	
Parts of the structure can be damaged by which leads to less strength due to falling elements			0,01
The soil is less strong than calculated with due to extrapolation of the soil strength			0,005
Other materials or plants are used than determined in the design			0,005
Parts of the structure can be damaged which leads to less strength due to formwork, bracing or erection error			0,01
Materials become less strong due to insufficient maintenance		0,01	
Materials become less strong due to insufficient inspection		0,01	
Structural element collapses due to more load than anticipated	0,01		
The load bearing structure will collapse due to fire			0,01
The structure will collapse due to a LPG explosion			0,001
Car or truck damages structure by impact			0,01
Concrete foundation can get damaged due to soil pollution			0,001
Collapse of vertical structural elements due to more load than anticipated (larger load than expected)		0,0005	
Collapse of horizontal structural elements due to more load than anticipated (larger load than expected)	0,0005		
Collapse of vertical structural elements due to more load than anticipated (falling objects during use)		0,0005	
Collapse of horizontal structural elements due to more load than anticipated (falling objects during use)	0,0005		
Total	**0,011**	**0,41**	**0,31**

TABLE 12 PROBABILITIES PER CONSEQUENCE CLASS

STEP 9: CHECK IF THE LIMITS ARE MET

In this step the probabilities estimated in step 8 are compared to the given limit in step 6:

$$P_{CC1}(F) + P_{CC2}(F) + P_{CC3}(F) \leq \mathrm{b} * 4 * 10^{-4}$$

$$P_{CC2}(F) + P_{CC3}(F) \leq \mathrm{b} * 7 * 10^{-5}$$

$$P_{CC3}(F) \leq \mathrm{b} * 8 * 10^{-6}$$

Using the probabilities given in step 9:

CC1:	$1{,}3 * 10^{-6} + 4{,}9 * 10^{-5} + 3{,}7 * 10^{-5} = 8{,}7 * 10^{-5} < 0{,}8 * 4 * 10^{-4}$	okay
CC2:	$4{,}9 * 10^{-5} + 3{,}7 * 10^{-5} = 8{,}6 * 10^{-5} > 0{,}8 * 7 * 10^{-5}$	not okay
CC3:	$3{,}7 * 10^{-5} > 0{,}8 * 8 * 10^{-6}$	not okay

Not all three limits are met, so measures need to be taken.

STEP 10 AND 11: PERFORM A COST-BENEFIT ASSESSMENT AND DETERMINE WHICH RISK REDUCTION MEASURES WILL BE IMPLEMENTED

For the Cooltoren the measures are already implemented so it is less useful to perform a cost-benefit assessment to see which measures are best to implement considering the cost-benefit ratio. However to be complete and to gain insight in which measures are most cost-effective, this step is performed anyway, see table 13. Because the consequences for the cost-benefit assessment have to be quantified in square meters floor area that collapses if the hazard scenario occurs, the following numbers are used (based on the consequence class classification table 9 of chapter 4): CC1: 10m^2, CC2: 50m^2, CC3: 100m^2.

The following measures are the most effective, according to this cost-benefit assessment:

1. Many openings so pressure due to an explosion can escape (€0/m^2)
2. Control of the structural engineer at the site (€14.306.152/m^2)
3. Four eye principle (€22.296.544/m^2)
4. Alternative load path (€27.530.008/m^2)
5. Second opinion by external firm (€55.741.360/m^2)
6. Fire resistance of 120 minutes (€82.508.251 /m^2)
7. Concrete and details are designed to sustain soil and water influences (€136.363.636/m^2)
8. Extra ductility (€163.398.693 /m^2)
9. Quality control on the construction site takes place via TIS system (€168.804.862/m^2)
10. Extra cone penetration tests (CPT) after installing the foundation piles (€2.500.000.000/m^2)
11. Sprinkler installation for fire (€7.650.273.224/m^2)

It should be taken into account that all hazards with a CC3 consequence have a value 100m^2 that will collapse due to the hazard scenario, even though some might have a much larger consequence than 100m^2 and thus the effectiveness becomes much more positive.

Measure	Has effect on failure scenario	Effect factor measure on probability	Costs measure	original probability $P(F)$ per 50 years	new probability $P(F)$ per 50 years	original consequence class	new consequence class	Original probability x consequence [m2]	New probability x consequence [m2]	Risk reduction	Total risk reduction in square meters collapse	Cost/benefit (€/m2)
alternative load path	Communication and collaboration error	1	€ 100.000,00	0,000006	6E-06	2	1	0,0003	0,00006	0,0002	0,0036	€ 27.530.008
	Control mechanisms error	1		0,000006	6E-06	2	1	0,0003	0,00006	0,0002		
	Allocation of responsibilities error	1		0,000006	6E-06	2	1	0,0003	0,00006	0,0002		
	Structural risk management error	1		0,000006	6E-06	2	1	0,0003	0,00006	0,0002		
	Safety culture error	1		0,000006	6E-06	2	1	0,0003	0,00006	0,0002		
	Knowledge infrastructure error	1		0,000006	6E-06	2	1	0,0003	0,00006	0,0002		
	Collapse of vertical structural elements due to more load than anticipated (incorrect modeling)	0,5		0,000009	4,5E-06	3	3	0,0009	0,00045	0,0005		
	Collapse of horizontal structural elements due to more load than anticipated (incorrect modeling)	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Collapse of vertical structural elements due to more load than anticipated (wrong drawings)	1		0,000003	3E-06	3	2	0,0003	0,00015	0,0002		
	Collapse of horizontal structural elements due to more load than anticipated (wrong drawings)	1		0,000003	3E-06	2	1	0,0002	0,00003	0,0001		
	building materials will be negatively affected by the soil or groundwater	1		0,0000012	1,2E-06	3	3	0,0001	0,00012	0		
	Parts of the structure can be damaged by which leads to less strength due to loads during construction	1		0,0000012	1,2E-06	2	1	6E-05	1,2E-05	5E-05		
	Concrete can get less strong than predicted due to weather conditions	1		0,0000012	1,2E-06	3	2	0,0001	0,00006	6E-05		
	Insufficient concrete quality used which causes the structural elements to be less strong	1		3,96E-07	4E-07	3	2	4E-05	2E-05	2E-05		
	not enough or wronly placed reinforcement	0,5		1,98E-06	9,9E-07	3	3	0,0002	9,9E-05	1E-04		
	insufficient steel quality	1		3,96E-07	4E-07	3	2	4E-05	2E-05	2E-05		
	Critical details are not correctly executed, which causes them to fail	1		0,000003	3E-06	3	2	0,0003	0,00015	0,0002		
	Placing structural elements at the wrong place	1		0,000003	3E-06	3	2	0,0003	0,00015	0,0002		
	Collapse of vertical structural elements due to	1		0,000003	3E-06	3	2	0,0003	0,00015	0,0002		

	more load than anticipated (incorrect measurements on building site)											
	Collapse of horizontal structural elements due to more load than anticipated (incorrect measurements on building site)	1		0,000003	3E-06	2	1	0,0002	0,00003	0,0001		
	Parts of the structure can be damaged by which leads to less strength due to falling elements	1		0,0000012	1,2E-06	3	2	0,0001	0,00006	6E-05		
	The soil is less strong than calculated with due to extrapolation of the soil strength	1		0,0000006	6E-07	3	3	6E-05	0,00006	0		
	Other materials or plants are used than determined in the design	1		0,0000006	6E-07	3	2	6E-05	0,00003	3E-05		
	Parts of the structure can be damaged which leads to less strength due to formwork, bracing or erection error	1		0,0000012	1,2E-06	3	2	0,0001	0,00006	6E-05		
	Materials become less strong due to insufficient maintenance	0,5		0,0000012	6E-07	2	2	6E-05	0,00003	3E-05		
	Materials become less strong due to insufficient inspection	0,5		0,0000012	6E-07	2	2	6E-05	0,00003	3E-05		
	Structural element collapses due to more load than anticipated	1		0,0000012	1,2E-06	1	1	1E-05	1,2E-05	0		
	The load bearing structure will collapse due to fire	0,5		0,000006	3E-06	3	3	0,0006	0,0003	0,0003		
	The structure will collapse due to a LPG explosion	0,5		1,2E-07	6E-08	3	3	1E-05	6E-06	6E-06		
	Car or truck damages structure by impact	1		0,0000012	1,2E-06	3	2	0,0001	0,00006	6E-05		
	Concrete foundation can get damaged due to soil pollution	1		1,2E-07	1,2E-07	3	3	1E-05	1,2E-05	0		
	Collapse of vertical structural elements due to more load than anticipated (larger load than expected)	1		6E-08	6E-08	2	1	3E-06	6E-07	2E-06		
	Collapse of horizontal structural elements due to more load than anticipated (larger load than expected)	1		6E-08	6E-08	1	1	6E-07	6E-07	0		
	Collapse of vertical structural elements due to more load than anticipated (falling objects during use)	1		6E-08	6E-08	2	1	3E-06	6E-07	2E-06		
	Collapse of horizontal structural elements due to more load than anticipated (falling objects during use)	1		6E-08	6E-08	1	1	6E-07	6E-07	0		
Extra ductility	Collapse of vertical structural elements due to more load than anticipated (incorrect modeling)	0,5	€ 50.000,00	0,0000045	2,3E-06	3	3	0,0005	0,00023	0,0002	0,00031	€ 163.398.693
	Collapse of vertical structural elements due to	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		

	more load than anticipated (wrong drawings)											
	Parts of the structure can be damaged by which leads to less strength due to loads during construction	0,5		0,0000012	6E-07	1	1	1E-05	6E-06	6E-06		
Fire resistance of 120 minutes	The load bearing structure will collapse due to fire	0,5	€ 25.000,00	0,000003	1,5E-06	3	3	0,0003	0,00015	0,0002	0,0003	€ 82.508.251
Sprinkler installation for fire	The load bearing structure will collapse due to fire	0,5	€ 1.400.000,00	0,000003	1,5E-06	3	3	0,0003	0,00015	0,0002	0,00018	€ 7.650.273.224
Many openings so pressure due to an explosion can escape	The structure will collapse due to a LPG explosion	0,5	€ 0	6E-08	3E-08	3	3	6E-06	3E-06	3E-06		€ 0
four eye principle during design	Control mechanisms error	0,5	€ 10.000,00	0,000006	3E-06	1	1	6E-05	0,00003	3E-05	0,00045	€ 22.296.544
	Collapse of vertical structural elements due to more load than anticipated (incorrect modeling)	0,5		0,0000045	2,3E-06	3	3	0,0005	0,00023	0,0002		
	Collapse of horizontal structural elements due to more load than anticipated (incorrect modeling)	0,5		0,0000015	7,5E-07	2	2	8E-05	3,8E-05	4E-05		
	Collapse of vertical structural elements due to more load than anticipated (wrong drawings)	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Collapse of horizontal structural elements due to more load than anticipated (wrong drawings)	0,5		0,000003	1,5E-06	1	1	3E-05	1,5E-05	2E-05		
	building materials will be negatively affected by the soil or groundwater	0,5		0,0000012	6E-07	3	3	0,0001	0,00006	6E-05		
	Parts of the structure can be damaged by which leads to less strength due to loads during construction	0,5		0,0000012	6E-07	1	1	1E-05	6E-06	6E-06		
second opinion by external firm	Control mechanisms error	0,5	€ 25.000,00	0,000006	3E-06	1	1	6E-05	0,00003	3E-05	0,00045	€ 55.741.360
	Collapse of vertical structural elements due to more load than anticipated (incorrect modeling)	0,5		0,0000045	2,3E-06	3	3	0,0005	0,00023	0,0002		
	Collapse of horizontal structural elements due to more load than anticipated (incorrect modeling)	0,5		0,0000015	7,5E-07	2	2	8E-05	3,8E-05	4E-05		
	Collapse of vertical structural elements due to more load than anticipated (wrong drawings)	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Collapse of horizontal structural elements due to more load than anticipated (wrong drawings)	0,5		0,000003	1,5E-06	1	1	3E-05	1,5E-05	2E-05		
	building materials will be negatively affected by the soil or groundwater	0,5		0,0000012	6E-07	3	3	0,0001	0,00006	6E-05		
	Parts of the structure can be damaged by which leads to less strength due to loads during construction	0,5		0,0000012	6E-07	1	1	1E-05	6E-06	6E-06		

Control of the structural engineer at the site	not enough or wrongly placed reinforcement	0,5	€ 5.000,00	9,9E-07	5E-07	3	3	1E-04	5E-05	5E-05	0,00035	€ 14.306.152
	Critical details are not correctly executed, which causes them to fail	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Placing structural elements at the wrong place	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Collapse of vertical structural elements due to more load than anticipated (incorrect measurements on building site)	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Collapse of horizontal structural elements due to more load than anticipated (incorrect measurements on building site)	0,5		0,000003	1,5E-06	1	1	3E-05	1,5E-05	2E-05		
	Parts of the structure can be damaged by which leads to less strength due to falling elements	0,5		0,0000012	6E-07	2	2	6E-05	0,00003	3E-05		
	Parts of the structure can be damaged which leads to less strength due to formwork, bracing or erection error	0,5		0,0000012	6E-07	2	2	6E-05	0,00003	3E-05		
Concrete and details are designed to sustain soil and water influences	building materials will be negatively affected by the soil or groundwater	0,5	€ 9.000,00	0,0000012	6E-07	3	3	0,0001	0,00006	6E-05	0,000066	€ 136.363.636
	Concrete foundation can get damaged due to soil pollution	0,5		1,2E-07	6E-08	3	3	1E-05	6E-06	6E-06		
Quality control on the construction site takes place via the TIS system	Concrete can get less strong than predicted due to weather conditions	0,5	€ 75.000,00	0,0000012	6E-07	2	2	6E-05	0,00003	3E-05	0,00044	€ 168.804.862
	Insufficient concrete quality used which causes the structural elements to be less strong	0,5		3,96E-07	2E-07	2	2	2E-05	9,9E-06	1E-05		
	not enough or wronly placed reinforcement	0,5		9,9E-07	5E-07	3	3	1E-04	5E-05	5E-05		
	insufficient steel quality	0,5		3,96E-07	2E-07	2	2	2E-05	9,9E-06	1E-05		
	Critical details are not correctly executed, which causes them to fail	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Placing structural elements at the wrong place	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Collapse of vertical structural elements due to more load than anticipated (incorrect measurements on building site)	0,5		0,000003	1,5E-06	2	2	0,0002	7,5E-05	8E-05		
	Collapse of horizontal structural elements due to more load than anticipated (incorrect measurements on building site)	0,5		0,000003	1,5E-06	1	1	3E-05	1,5E-05	2E-05		
	Parts of the structure can be damaged by which leads to less strength due to falling elements	0,5		0,0000012	6E-07	2	2	6E-05	0,00003	3E-05		

	The soil is less strong than calculated with due to extrapolation of the soil strength	0,5		0,0000006	3E-07	3	3	6E-05	0,00003	3E-05		
	Other materials or plants are used than determined in the design	0,5		0,0000006	3E-07	2	2	3E-05	1,5E-05	2E-05		
	Parts of the structure can be damaged which leads to less strength due to formwork, bracing or erection error	0,5		0,0000012	6E-07	2	2	6E-05	0,00003	3E-05		
Extra cone penetration tests (CPT) after installing the piles	The soil is less strong than calculated with due to extrapolation of the soil strength	0,5	€ 75.000,00	0,0000006	3E-07	3	3	6E-05	0,00003	3E-05	0,00003	€ 2.500.000.000

TABLE 13 COST-BENEFIT ASSESSMENT MEASURES COOLTOREN

STEP 12: EVALUATION AND SENSITIVITY CHECK

Evaluation

No extra hazards have to be added to the list due to taken measures, nor do changes have to be made in the assumptions made in the beginning.

When taking the implemented measures into account the risks on accidental actions for the Cooltoren are acceptable:

$$P_{CC1}(F) = 3{,}8 * 10^{-5}$$
$$P_{CC2}(F) = 1{,}2 * 10^{-5}$$
$$P_{CC3}(F) = 5{,}2 * 10^{-6}$$

The following equations should be true:

$$P_{CC1}(F) + P_{CC2}(F) + P_{CC3}(F) \leq \mathrm{b} * 4 * 10^{-4}$$

$$P_{CC2}(F) + P_{CC3}(F) \leq \mathrm{b} * 7 * 10^{-5}$$

$$P_{CC3}(F) \leq \mathrm{b} * 8 * 10^{-6}$$

Using the 'new probability P(F)' and new consequence classes of table 13:

CC1:	$3{,}8 * 10^{-5} + 1{,}2 * 10^{-5} + 5{,}2 * 10^{-6} = 5{,}5 * 10^{-5} < 0{,}8 * 4 * 10^{-4}$	okay
CC2:	$1{,}2 * 10^{-5} + 5{,}2 * 10^{-6} = 1{,}7 * 10^{-5} < 0{,}8 * 7 * 10^{-5}$	okay
CC3:	$5{,}2 * 10^{-6} < 0{,}8 * 8 * 10^{-6}$	okay

All three limits are met. This means that taking the measures into account, the probabilities an incident happens with a CC1, CC2 or CC3 consequence is acceptable.

Sensitivity check

1. When small changes in assumptions can have a big influence on the risk verification, the small changes in assumptions must be the governing to take into account for the design (chapter 3).

No extreme situations will occur when small changes are made, so the quantifications will not be changed due to this sensitivity check.

2. Do the risks meet the rules set in the Dutch Building Decree (see chapter 2):
   - A building structure does not collapse during its intended life, as prescribed in NEN-EN 1990, during exposure to accidental load combinations, as prescribed in NEN-EN 1990, if this leads to collapse of another structure* not in the direct proximity of this structure. Hereby the identified accidental actions, as prescribed in NEN-EN 1991, are assumed.
   - A roof or floor does not collapse during the design life, as prescribed in NEN-EN 1990, during exposure to accidental load combinations, as prescribed in NEN-EN 1990. Hereby impacts as described in NEN-EN 1991 are assumed.

Because the Cooltoren is designed with an alternative load path, both points of the Dutch Building Decree are met.

RECONSIDERATION

The risks are already low enough and no further changes have to be made according to step 13, so no reconsideration is needed.

STEP 13: RISK ACCEPTANCE AND COMMUNICATION

Normally in this step the remaining risks will be communicated to the client. But since this case study is only a test and not a real risk assessment, nothing will be done in this step.