Towards Cost Benefit Analysis of Measures to Improve Structural Safety

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on 17 August 2018 at 10.00

Student number:	4630319
Project duration:	December 21, 2017 – 17 August 2018
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Abstract

Building construction is a complex industry. A wide range of requirement should be achieved within the limited resources by a multidisciplinary team. Hence, errors are likely to occur, and the accumulation of individual mistakes might lead to building failure. Even though construction is tightly regulated, failure of the modern date buildings still happened.

As a part of the investment, safety measures need to be applied to prevent failure. Engineers often neglect the safety measure because its efficiency regarding risk reduction and the financial matter is not known. To examine the effectiveness of measures, this thesis is carried out by learning from ten cases of both collapse and near-collapse situation. A quantitative approach is taken for this thesis.

There are two types of safety measures: technical and procedural. In this thesis, procedural measures are proposed as the solution. The safety measures are applied to counter the deficiencies of the six meso level critical organizational factors in a building project. Information from literature and questionnaire result are two primary inputs of the research. The contribution of critical factors and the impact of the safety measures are quantified using the 5-Point Likert Scale scoring system. The value is determined by conducting a questionnaire survey to obtain engineering judgement from construction professionals and academics. Meanwhile, the benefit is estimated using the extended cash-flow analysis throughout the 30 years lifespan of the building.

The questionnaire result shows that the shortcoming in ”Control mechanism” is expected to be the most contributing factor to the failure cases. Attention should also be paid to the absence of ”Structural risk management”, ”Knowledge infrastructure”, and ”Communication and collaboration”. Meanwhile, issues related to ”Allocation of responsibilities” and ”Safety culture” are rarely found and barely influence the failure.

On average, the building failure incurred a cost of more than three times the initial investment. The main contributor is the loss of statistical life. It is also observed that reconstruction requires a higher budget than the value of collapsed building part. The financial consequence due to the failure might be even higher if the broader economic loss is assessed.

Regarding the impact, this study shows that ”Structural modelling” is the most efficient among the six proposed measures. By performing ”Structural modelling” prior to the construction, the behaviour of the final design can be evaluated. Accumulated shortcomings of various factors can be anticipated using ”Structural modelling”. ”Supervision” becomes the second most efficient measure, followed by ”Survey inspection”, ”Planning and responsibility”, and ”Integrated coordination” with relatively moderate impact. At last, ”Knowledge infrastructure” might be neglected. Overall, taking a particular safety measure results in the Profitability Index after 30 years lifetime of 1.47. The benefit is immense compared to the Profitability Index of -1.54 in the actual collapse situation.

Preface

”The great liability of the engineer compared to men of other professions is that his works are out in the open where all can see them. His acts, step by step, are in hard substance. He cannot bury his mistakes in the grave like the doctors. He cannot argue them into thin air or blame the judge like the lawyers. He cannot, like the politicians, screen his shortcomings by blaming his opponents and hope the people will forget. The engineer simply cannot deny he did it. If his works do not work, he is damned” - Herbert Hoover 31^{st} *President of USA*

This thesis marks the completion of my Master of Science study in Building Engineering Department, Delft University of Technology. This report summarizes my knowledge and courage of integrating civil engineering and construction management aspect in building practice. It is an honour for me to be able to gain knowledge and experience in TU Delft, one of the best universities in civil engineering.

I would like to thank my graduation committee for their guidance through my research. Dr. ir. K. C. Terwel and Dr. ir. drs. J. G. Verlaan as my daily supervisors, and my thesis advisor Prof. ir. R. Nijsse. I also would like to thank Dr.ir. S. I. Suddle for the inspiring discussion. It has been such a great experience to work and gain knowledge from the expert in my future professional field.

My utmost gratitude to my family in Indonesia, who always support me unconditionally, as well as all my friends here in Delft. Finally, I would like to thank Lembaga Pengelola Dana Pendidikan (LPDP), the Indonesia Endowment Fund for Education for the financial and moral support through scholarship. Hopefully, my knowledge will contribute to better Indonesian construction industry.

Ad Maiorem Dei Gloriam

Christophorus Dwiadi Cahyabudi
Delft, August 2018

Contents

1 Introduction

This chapter starts with the background of this thesis project. The problem statement, thesis goals, and research boundaries are addressed afterwards. Finally, reporting outline is closing this chapter

1.1. Background

Building construction is a complex industry. Many stakeholders are involved in the project, legal and functional requirements are demanded, with all the targets need to be accomplished within a particular limitation of resources. A trade-off between aspects is inevitable, and subsequently, a wide range of potential risks should be considered. This complexity raises a question, what might go wrong in building construction?

Construction field is tightly regulated, with almost all the steps and requirements are prescribed in building code, such as Eurocode. Nevertheless, failure still happens. In The Netherlands, one latest example is the collapse of Eindhoven Airport parking garage. While the exact cause of the collapse remains unclear by the time reports were made (September 2017) [1], the incident gained public awareness that failure is not always caused by overloading, as the parking garage was still under construction, but errors might happen during the design and construction phase.

To assure building safety, measures to prevent failure are applied. Applying safety measures means additional investment. Another question might come up, how much does the safety measure worth for a building project? Budget is inevitably one of the determining resources in building industry. Financially evaluating a building project as an investment is considered noteworthy, since both investments and risks could be expressed in the same unit [67]. This research aimed to get a general vision regarding the financial benefit of applying safety measures in the building projects.

In this research, the study will be focused on learning from failures. The cause of failure from several cases are examined, and the possible relevant safety measures are proposed. The impact of safety measures will be quantified, and finally, financial models are developed to answer the research goal.

1.2. Problem Statement

Failure mostly results from the combination of conditions, mistakes, oversights, misunderstandings, ignorance, incompetence, dishonest performance [24]. One incident might be the trigger of the failure, exposing the accumulated chain of a failure event. Matousek and Schneider (1976) have found that 85% of building failures to be originated from human error [9]. Related to the activity where mistakes were found, research by Allen (1977) concluded that planning and design contributed up to 52%, while 47.5% and 0.5% are in the construction phase and occupancy phase respectively [9].

The idea to implement safety measures was sounded in mid 80's in the USA following several notable building collapses. Three conferences were held, and as concluding remarks, two types of safety measures were proposed. First is technical measure, for example by applying higher safety factor and increase structural ductility. The second type is procedural measure, concerning the management factor in a building process, such mandatory certification for engineers, external checking of the design, and unified insurance [24]. However, up to now, the effectiveness of measures versus their impact on the life-cycle cost of a building is not known.

1.3. Research Objectives

This study aims to identify the amount of potential benefit by taking safety measures. Each measure has different cost and impact throughout the building lifetime. Comparison between measures in various cases gives the insight of the overall financial benefit, and finally, the most beneficial safety measure can be recommended for building industry.

1.4. Research Questions

The following question is used as a guideline for this research:

What is the most financially beneficial procedural safety measure based on the case studies?

Four key questions are examined to answer the main research question:

1. What are the organizational cause(s) of failure in the sample cases?
2. How much is the cost incurred due to the building failure?
3. How much is the impact of taking a certain safety measure regarding the failure probability?
4. How much is the benefit of applying the procedural safety measures?

1.5. Research Scope

This study is limited to the safety-related cases of public buildings by learning from failures. The impact of the organizational factors and procedural measures is examined using the engineering judgement provided by professionals and academics. The financial model is based on the cash-flow analysis, considering the monetary value of human life and compensation cost as additional entities in the cash-flow. Other economic aspects and qualitative cost-benefit are not within the scope of this thesis. The financial model is developed as a supporting tool for decision making rather than an economic forecast.

1.6. Reporting Structure

- Chapter 1: Introduction

  General information regarding the research background and problem formulation

- Chapter 2: Theoretical Framework

  Introduce terms and definitions based on the context, and introduce the research limitation

- Chapter 3: Research Methodology

  A brief explanation of the overall research process, including the selection of cases, safety measures simulation, and financial modelling

- Chapter 4: Study of the Failure Cases

  Description of the building information, failure analysis, lessons learned, and financial components of the failure cases

- Chapter 5: Results and Discussions

  Elaboration of the answers to the research questions and the result limitation

- Chapter 6: Conclusions and Recommendations

  Addresses the conclusions of this thesis and recommendations for building industry and future research of the similar field

2

Theoretical Framework

This chapter elaborates the theories regarding structural safety and project financial analysis as the basis for the entire research. The limitations of this study are defined in the later section of this chapter.

2.1. Context

The Main Research Question becomes the starting point of this research:

What is the most financially beneficial procedural safety measure based on the case studies?

Contextual explanation regarding the Main Research Question is addressed in this section. Three essential terms are elaborated as the fundamental knowledge for this research:

- Structural failure
- Safety measure
- Financial benefit

2.1.1. Structural Failure

Structural failure can be defined as an inadequate performance of a structure that creates or might create an unsafe situation [71]. An upper boundary is determined, and if it is exceeded, the structure is considered failed. Failure is divided into two types [24]:

- Serviceability problem (e.g., indoor environment problem, premature deterioration)
- Structural failure (e.g., column failure, foundation settlement, roof collapse)

The majority of structural failures and the associated costs are caused by the errors in planning, design, construction, and utilization [22]. Types of errors for the less successful project are shown in Figure 2.1 - 2.3 [70]. It is important to note that for the majority of cases, the type of error is not known.

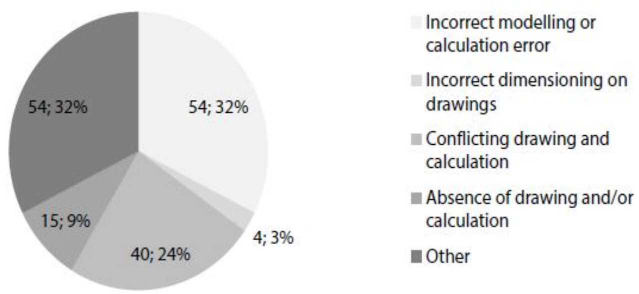

Figure 2.1: Type of errors when largest risk is in the design phase [70]

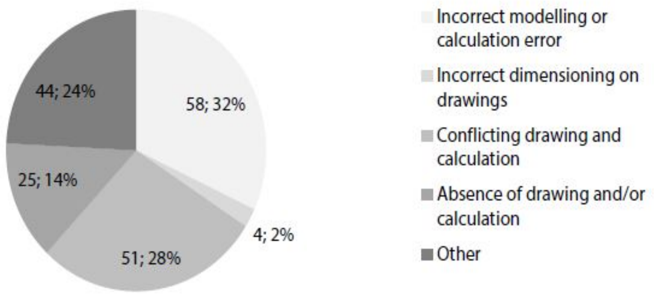

Figure 2.2: Type of errors when largest risk is in the detailed engineering phase [70]

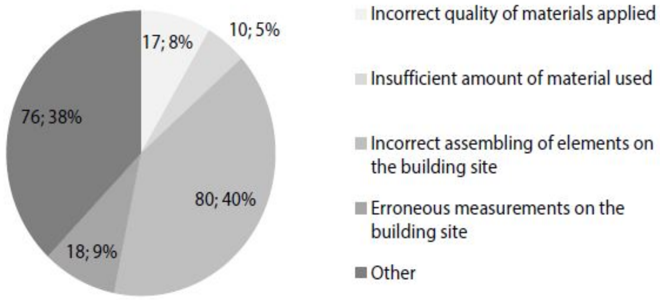

Figure 2.3: Type of errors when largest risk is in the construction phase [70]

Concerning the state-of-the-art technology development, construction industry tends to be conservative, while the demand for applying innovative supporting technology is rising. A narrowly focused innovation is sometimes interpreted too optimistically. The application can be pushed to a broader range than is justified [55]. Moreover, with the development of computer programs, the structural challenge is increasing because of the ability of computational modelling. Although every problem seems to be solvable, it is solved in the model, not in reality [81]. The real behaviour of the built structure is often underestimated.

2.1.2. Safety Measures

Structural Safety

Safety is defined as the state of being safe and protected from danger or harm [33]. The danger is a threat to one's life, health, or financial situation. The structural safety of buildings is focused on ensuring the risks will remain within the acceptable limits [7]. In Eurocode structural safety is defined as the "capacity of a structure to resist all action(s), as well as specified accidental phenomena, it will have to withstand during construction work and anticipated use" (NEN-ISO 6707-1: 2004 art. 9.3.82 in [70]).

Building safety is the result of contributions from various parties in the project. In general, there are three levels of underlying factors from human/organizational aspect which creates a framework of structural safety [70]: macro level, meso level, and micro level.

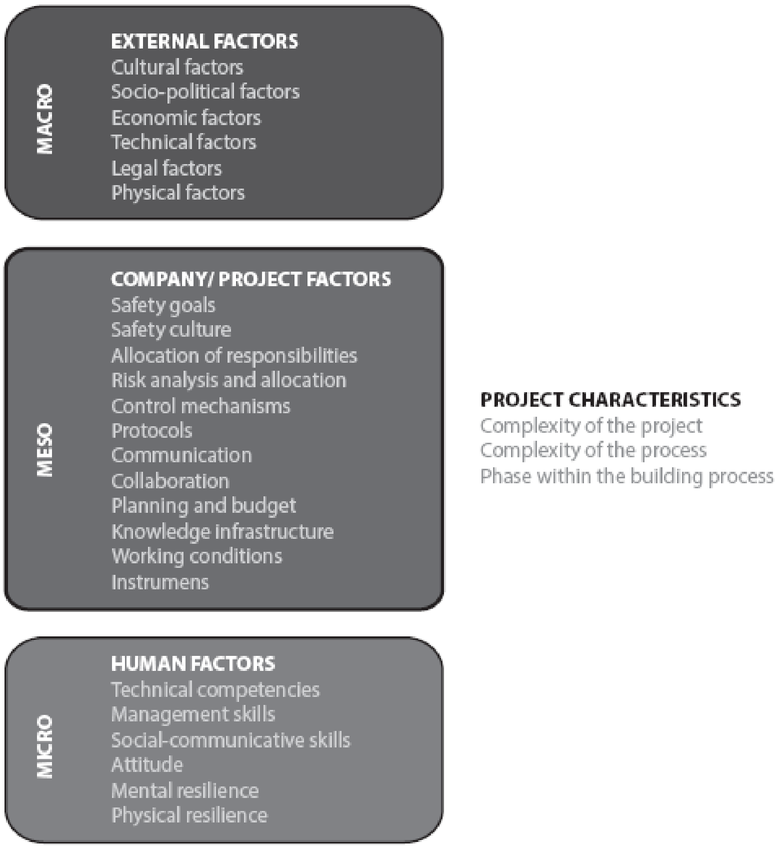

Figure 2.4: Overview of possible underlying factors according to Terwel (2014) [70]

- Macro level:
  1. Culture: the way safety is approached in the country if the project
  2. Socio-political: public concern for structural safety and the way the government involved in the building industry
  3. Economic: the general financial situation of a country
  4. Technical: the state of technology development in a country
  5. Legal: quality of codes, regulations, and their enforcement
  6. Physical: location, climate, and the existence of the natural hazard
- Meso level:
  - Project Characteristics
    1. Complexity of the project: various features of a structure which affect overall complexity
    2. Complexity of the building process: the complexity of the organization, constructibility of a project [19]
    3. Phase of the building process: the influence of construction method to the risk level
  - Project and Company factors
    1. Safety goals: objectives of the organization concerning structural safety
    2. Safety culture: practices, conventions, and the way the organization is dealing with risks

3. Allocation of responsibilities: share of responsibility that is given to a person or organization
4. Risk analysis and allocation: the process of identification and assignment of risks, application of resources to prevent unwanted events
5. Control mechanisms: monitoring, warning systems, and reviewing the delivered product
6. Protocols: rules describing how tasks should be performed
7. Communication: the exchange of information within a company or among the multiple project partners
8. Collaboration: the way different project partners cooperate with each other
9. Planning and budget: the available time and budget to deliver a product
10. Knowledge infrastructure: cumulative technical competencies of actors (education, experience, training)
11. Working conditions: site and company environment, working time of the day, adequacy of man-machine-interface and operational support [32]
12. Instruments: provided tools (software or equipment) to perform the tasks properly

- Micro level:

  1. Technical competencies: ability to apply knowledge and skills for the design and construction
  2. Management skills: ability to lead oneself and others, make planning and decisions
  3. Social-communicative skills: interpersonal communication within a project team
  4. Attitude: constructive position and commitment towards safety by the various participants
  5. Mental resilience: the way in which an individual can cope with stress [74]
  6. Physical resilience: the way in which an individual can cope with long-term and heavy physical loading [74]

Meanwhile, in another literature, van Herwijnen in his book ”Leren van instrortingen” formulated five fundamental factors contributing to the safety level of a building [76]:

1. Knowledge of engineers

   Knowledge of engineers are related to hard skill competency and experience on the specific project, recognized by the academic degree held by the engineer, certification, and experience

2. Calculation tools

   Calculation tools are including computer programs, the availability of the required database as references, and building decree as the legal and technical guidance

3. Economics and technology development

   The budget as a decisive resource is related to the current economic situations within the project or even the national level, while technology development triggers innovations to deal with problems that previously cannot be solved

4. Application of new and robust material

   The use of new material needs to be tested before implemented, as there might be unforeseen properties affecting the quality of construction

5. Communication and informed consent

   The interrelation between parties needs to be considered, not only to make a robust design for each component but also to make a reliable overall system

These five factors can also be found in the formulation by Terwel in [70]. Deficiencies of the underlying factors affect the safety level of the final product.

Approach on Safety Measure

When the signs of failure are realized in time, safety measures can be taken to anticipate the threat. Safety measures can be divided into two major types [24]:

- Procedural measures:

  Actions that do not explicitly increase the ability of a structure to withstand the load, but contribute to guarantee the quality of the product. For example by performing structural verification, internal peer review, and mandatory certification for engineers.

- Technical measures:

  Actions to technically increase the ability of the structure to withstand the load. For example by providing a secondary load path, and applying safety factors for human error.

Decision-makers always opt for the optimum solution. The safety measures have to be effective in both budget and threat reduction. To create strategic safety measures, the critical factors for structural safety need to be determined. A factor is considered critical when it appears more often in an unsuccessful project than the others, and moreover, become one of the primary causes of failure [71]. The critical factors of structural safety found in project level are [70]:

- Communication and collaboration
- Control mechanisms
- Allocation of responsibilities
- Structural risk management
- Safety culture
- Knowledge infrastructure

It is essential to focus on the meso level factors because macro factors are hardly affected by a single project and lie beyond the scope of this thesis. Meanwhile, the micro factors are relatively manageable by taking action to the meso factors.

2.1.3. Benefit

A project can financially be seen as an accumulation of expenditures (cash outflow) and receipts (cash inflow) [79]. Included in the expenditure are the investment (e.g., concrete work, groundwork, HVAC) and operational expenses (e.g., contractor's salary, taxes). During the service life, a project receives revenue (e.g., building rent, commercial income, etc.). The purpose of having investment is gaining benefit, to maximize the wealth of the stakeholders [8].

A benefit is advantages one can get by making an investment. A financial benefit is a form of benefit regarding monetary value. Investment needs to be financially analysed to help stakeholders optimizing their assets. In project finance, there are several investment criteria for decision making: NPV, Payback Period, Internal Rate of Return, and Profitability Index [8] [79].

- Net Present Value (NPV) Rule

  The net present value method sums the cash flows over the life cycle, taking into account the time value of money. Investment is acceptable if a positive NPV is obtained.

- Payback Period

  Payback period is the period until the net value of the project is exactly zero. Time value of money is not taken into account. If the payback period is shorter than the time limit set for the payback, the investment is acceptable.

- Internal Rate of Return

  The internal rate of return is the rate at which the NPV of the project is zero. Investment is acceptable if the IRR is higher than the opportunity cost of capital (the interest rate on investing in financial securities).

- Profitability Index

  Profitability index is the ratio between the net present value and investment. Investment is acceptable if the ratio is higher than ”1.0”.

Every criterion has advantages and disadvantages. Decision preferred in one method is not always recommended if the case is analysed using another method [8].

2.2. Research Limitations

Structural failure has an unlimited possibility. It is not feasible to manage all the risk in the complex nature of building construction. The following limitations are applied to this research:

2.2.1. Type of Structural Failure

The sample cases are limited to the structural failures which lead to structural collapse or near collapse situation. Collapse becomes the upper boundary for the ultimate limit state (ULS), and therefore related to the definition of safety (Section 2.1.2). Meanwhile, near collapse situation might be underestimated by engineers, because fatalities were never found in near collapse cases [76]. However, a near collapse situation poses a threat to human life. Action should be taken to avoid casualties.

Note that collapse is not always the biggest risk in building construction due to its low probability of occurrence ($risk = probability * occurrence$) [77]. The samples for this thesis are taken from Dutch and international cases.

2.2.2. Type of Measures

The type of safety measure assessed is limited to procedural measure only. The procedural measure is arguably more strategic to prevent failure. Technical aspects such as loads, material properties, and the upper limit of failure probability are standardized in the building codes [76]. Hence engineers should have the exact solution, legally and technically.

Eurocode approaches safety within two key figures: the resistance calculation of elements and coherence between components, and the quality of management [70]. While the technical aspects have been settled, organizational factors are still emerging. The critical factors for structural safety in Section 2.1.2 are dominantly related to procedural measure as the solution to the organizational issues. Project associated factors (meso factors) are essential to assure safety level of a structure [71]. Therefore, this research is focusing on meso level factors.

2.2.3. Investment Criteria

The investment is analysed using the NPV rule and Profitability Index (Section 2.1.3). The term of present value is referred to as 2018 Euro. NPV rule is more accurate for the financial model with multiple cash flows [79]. The cash-flow components in this thesis are investment (negative cash flow), revenue (positive cash flow), and failure cost (negative cash flow). Besides, Profitability Index is an appropriate parameter to compare the analyses of different projects with different types, values, and time.

This thesis examines an extended cash-flow analysis, with two economic entities as additional failure cost components: monetary value of human life and compensation for injuries. The two additional entities are included for the calculation because of their direct relation to the context of building safety and possess a quantitative unit. Moreover, the two features have a significant influence on the financial evaluation of a failure case [67]. Building tax, asset depreciation, commercial activity, and intangible economic aspects are not taken into account.

The scope of the cash-flow analysis is limited to micro-economic analysis. Introducing economic components due to the failure becomes the step towards the cost-benefit analysis. As the financial report of the failure case is usually undisclosed, the cost units and parameters are derived from the investigation reports and related literature. Finally, assumptions and generalization are applied to the model (Section 3.5).

3
Research Methodology

This chapter explains the methodology to answer the research questions. First, terms and definitions are specified. Second, the research boundary is set up. Third, the process to collect information related to the case study is described. The quantitative assessment approach of the safety measures impact is elaborated, and finally, the financial analysis method is explained.

The research methodology is developed to answer Key Research Questions, with the Main Research Question as the final goal. A brief description of the step by step to answer the research questions is presented in this chapter. The summary is shown in Figure 3.1.

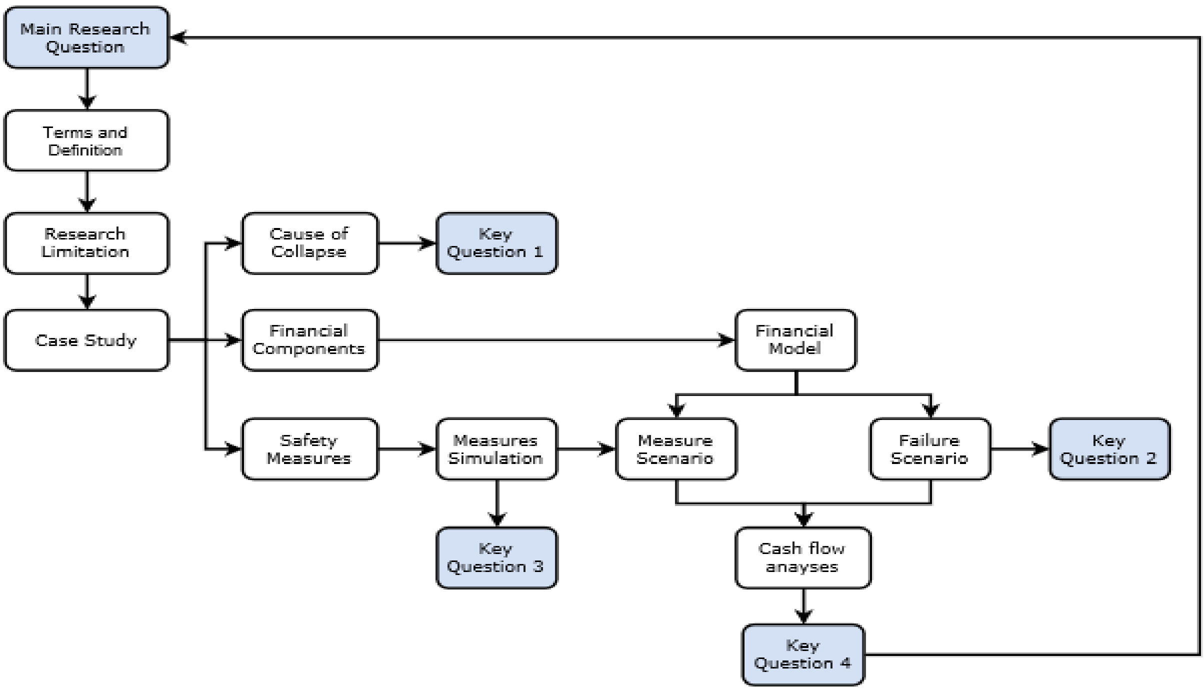

Figure 3.1: Research Flowchart (Source: author)

3.1. Defining Terms

As a starting phase, the definition based on the research context of the terms supporting the Main Research Question is determined. The result of this step is elaborated in section 2.1. The three important terms as the basis to answer the four Key Questions are:

- Structural failure
- Safety measures
- Financial benefit

3.2. Creating Research Limitations

It is not feasible to assess all possible failure cases and the safety measures because every project is unique. Therefore, limitations are applied to this research. The research limitations are determined based on the context (Section 2.1) and research scope (Section 1.5). The outcome is elaborated in Section 2.2. Four key points become the boundaries of this research.

- Analyse collapse and near collapse cases
- Analyse procedural measures related to the critical organizational factors
- Analyse financially accountable cases
- Analyse the extended project cash flow as an initial study towards the cost-benefit analysis

3.3. Case Study Analysis

The following phase of the research is collecting scientific references of failure cases. Twelve notable failure cases are selected as the candidates:

- Berlin Congress Hall (1980)
- Hyatt Regency, Kansas City (1981)
- Ice skating hall, Bad Reichenhall (2006)
- Terminal 2E CDG Airport, Paris (2004)
- Patio Sevilla, Maastricht (2003)
- Hartford Civic Center, Connecticut (1978)
- Kemper Arena, Kansas City (1979)
- Parking Garage Hotel van der Valk, Tiel (2002)
- Ronan Point, London (1968)
- Bos en Lommerplein, Amsterdam (2006)
- Amoco Tower, Chicago (1988)
- Parking Garage Eindhoven Airport, Eindhoven (2017)

To obtain a relevant and accountable set of information, the sample candidates are evaluated using the three steps filter (Figure 3.2). The detailed elaboration is presented in Appendix A.

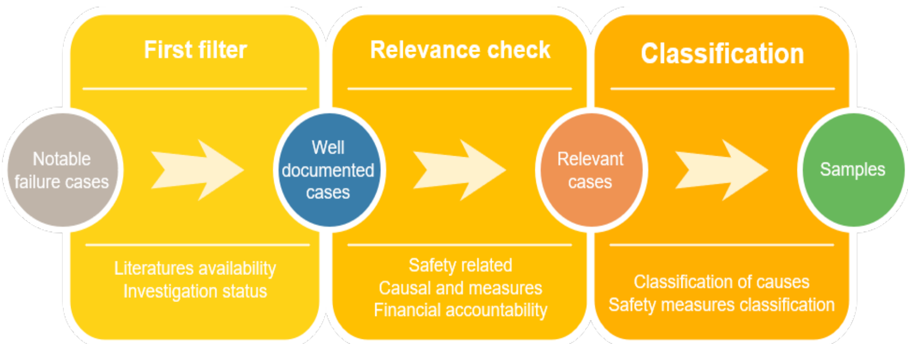

Figure 3.2: Flowchart of Sample Case Selection (Source: author)

3.3.1. First Filter

The aim of the first filter is to evaluate the availability of literature. In this research, the author does not perform the investigation of the cases. Reliable investigation reports are the primary tool for this research. Two questions are made as the first step of case selection.

1. Does the case candidate have multiple investigation reports?
2. Is the investigation already settled?

As a result, two cases are eliminated: Parking Garage Eindhoven Airport and Parking Garage Hotel van der Valk (Appendix A.1).

3.3.2. Relevance Check

The relevance of the remaining cases to the Research Scope (Section 1.5) and Research Limitations (Section 2.2) are analysed. A list of questions is formulated to perform the relevance check of each case.

- Type of failure related questions:
  1. Which part of the building had failed?
  2. Is the failure caused/might cause fatalities?
- Causal and measures related questions:
  1. What are the unique characteristics/challenges of the project that requires more attention?
  2. What are the causes of the failure according to the investigation reports?
  3. What are the safety measures proposed in the investigation reports?
- Financial accountability related questions:
  1. What are the cost components of direct/indirect loss presented in the investigation reports?
  2. What are the components of the income cash flow?
  3. What are the cost components of the safety measures?

The outcome of this step shows that all of the ten remaining cases are considered relevant and accountable (Appendix A.2).

3.3.3. Classifications

The result of the case study has a wide range of variations. Case by case cannot directly be compared. For educational purpose, the failure causes, the safety measures, and the financial components are classified to make them comparable.

Cause of Collapse Classification

The cause of the collapse is classified based on the six critical factors found in meso/project level formulated by Terwel (2014) [70]. The elaboration of these underlying factor is presented in Section 2.1.2.

Safety Measures Classification

This research is limited to procedural measures (Section 2.2.2). The proposed safety measures are grouped as follows:

- Integrated coordination

  Activities to handle the communication issue within a project, for this research is assumed as the implementation of construction information management systems (CIMS) [78]

- Planning and responsibility

  Activities related to the allocation of tasks and responsibility, project scheduling, contract issue, and budget management

- Supervision

  Activities related to the control mechanism of the project such as peer review, independent review by qualified engineers or other professional company, and superintendence during construction

- Structural modelling

  Activities related to the computational or physical modelling to assess the performance of the design or material

- Survey and inspection

  Activities related to maintenance, routine inspection, and on-site survey

- Employees competency

  Activities to improve human resource quality in the project team, such as hiring more competent labour and arranging a development training for the employees

Financial Components Classification

The failure cases occurred in a different place and different time. An actual financial comparison between cases is not possible to be assessed due to such diversity. Moreover, as the financial information is usually undisclosed, approximation approach is taken for this study. In this research, a life cycle financial model is developed using the following parameters:

- Initial investment
- Operation-maintenance cost
- Cost due to the failure
- Cost of safety measures
- Income cash flow

The cost components due to the failure are classified into four elements that represent the loss incurred on the project. Accountability becomes the primary aspect of determining the four safety related cost elements. The total cost due to the failure is referred to as ”Financial Consequences (C)”, and addressed as negative cash flow in the financial model. The cost unit and the application to the financial model are explained in Section 3.4.2.

- Material loss (C1)

  The monetary value of the collapsed building; estimated based on the structure, size, function, and initial investment

- Reconstruction (C2)

  The monetary value of rebuilding activity; calculated based on the unit cost and the magnitude of the reconstruction

- Loss of human life (C3)

  The monetary value of statistical life in such circumstances

- Compensation (C4)

  The cost incurred due to the compensation paid to the injured victims

The cost incurred due to the implementation of safety measures are derived from the classification of measures in Section 3.3.3. The classification is presented as follows:

- Cost of implementing Construction Information Management Systems (CIMS) (I1)
- Cost of time delay (I2)
- Cost of performing supervision (I3)
- Cost of performing physical or computational modelling (I4)
- Cost of performing inspection during the lifetime or additional survey (I5)
- Cost of hiring labours with the higher competency level (I6)

The sources of income for public buildings are rental price, commercial revenue, and economic activity. In this research, only rental income is taken into account, except the information about other revenue is available. In case the building is being reconstructed, it is assumed unusable unless stated otherwise. The absence of the income cash flow is not considered as a part of the failure cost but addressed as zero cash flow throughout the idle time in the life-cycle financial model. The nominal of each element is specified in Section 3.5.

3.4. Measures Simulation

3.4.1. General Description

As a part of risk management, the risk-reducing measures need to be evaluated. *"The weighted risk analysis"* by Shahid Suddle (2004) [65] is adapted to analyse the impact of the safety measure quantitatively. This method is developed to compare different decision-making aspects in the same unit, such as monetary value [67]. Weighing factors are used to determine the influence of a single event to the overall risk in a project. The standard risk expression of probability and consequence is multiplied by the weighting factor of the related event. The weighted risk is formulated as [67] [65]:

$$R_w = \sum_{j=1}^{n} \alpha_j * \sum_{i=1}^{n} P_f * C_f \tag{3.1}$$

With R_w is the weighted risk (fatalities per year or money per year); α_j is the weighting factor of a single event (money, severity, etc.); P_f is the occurrence probability of the hazard (year^{-1}); C_f is the consequences of the hazard (fatalities or money);

Finally, to assess the economic consequences, the total cost is calculated using Equation 3.2 [67] [65]:

$$C_{tot} = C_0(y) + \sum_{j=1}^{n} \frac{R_{wj}}{(1+r)^j} \tag{3.2}$$

With C_{tot} is the total cost (money); C_0 (y) is the investment in a safety measure "y"; j is the number of years; and r is the interest rate.

The result of *The weighted risk analysis* contains uncertainties and subjectivities, depending on the interpretation taken for the weighting factors [67]. Nevertheless, the purpose of this method is to facilitate the decision makers. Although the result is not absolute, the decision can be taken by comparing the analyses of different elements relative to the neutral (without measures) condition. A thorough description of this method can be found under TU Delft repository "Physical Safety in Multiple Use of Space" by Shahid Suddle (2004) [65].

3.4.2. Adapted Method of "The Weighted Risk Analysis"

The application of *The Weighted Risk Analysis* in this thesis is to determine the risk reduction impact of safety measure and to address the risk in the financial model. Considering the scope of the research and workability aspect, the simulation of safety measure scenarios using *The Weighted Risk Analysis* is simplified for this research. The work-flow is summarized in Figure 3.3.

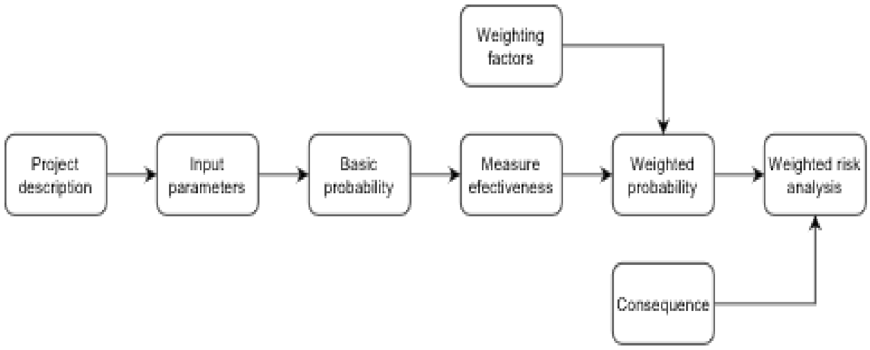

Figure 3.3: Adapted method of The Weighted Risk Analysis (Source: author)

The quantitative analysis is conducted by calculating the weighted risk, considering the weight of factors, the effectiveness of measures to reduce failure probability, and the financial consequence of failure. The calculation flow is shown in Figure 3.4.

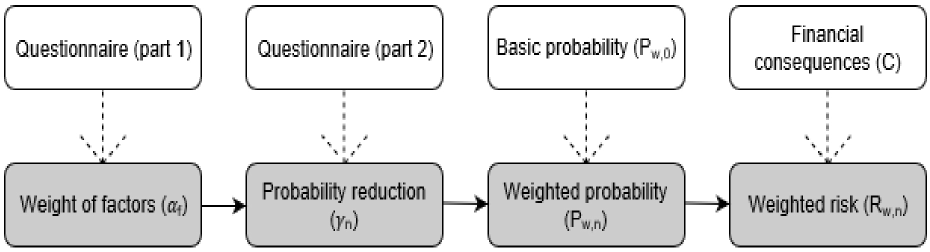

Figure 3.4: Calculation flow of the adapted method of "The Weighted Risk Analysis" (Source: author)

The value of "weight of factor" is determined based on the questionnaire result (Section 3.4.3 and Equation 3.6). The "probability reduction" is determined based on the questionnaire result (Section 3.4.3), applied to Equation 3.4. The calculation of "weighted probability" is based on Equation 3.5. The weighted risk as the final result of measure simulation is calculated using Equation 3.3:

$$R_{w,n} = P_{w,n} * C \tag{3.3}$$

With $R_{w,n}$ is the weighted risk for scenario "n" (€/year); $P_{w,n}$ is the weighted failure probability of scenario "n" ($year^{-1}$); and C is the financial consequences due to the collapse (€), assumed constant for every scenario. All monetary values used in the thesis are analysed in terms of present value (2018 €).

Weighted Probability ($P_{w,n}$)

The probability of collapse resulted from the accumulation of the shortcomings in various critical factors (Section 2.1.2). Each factor has a specific percentage of contribution to the failure (α_f). The value is determined from the questionnaire result (Section 3.4.3).

The occurrence probability of the failure case without safety measure ($P_{w,0}$) is assumed 10^{-4} per year [20], taken as the basic probability. When safety measure "n" is applied, the failure probability will be reduced. For each factor, the probability reduction is proportional to its weight of contribution. The reduction of the collapse probability is calculated as:

$$\gamma_n = \sum \alpha_f * \beta_f \tag{3.4}$$

With γ_n is the probability reduction (%); α_f is the weight of factor "f" (%); and β_f is the degree of impact (5-point Likert scale) obtained from questionnaire result (Section 3.4.3). Subsequently, the weighted probability for Scenario "n" is calculated using Equation 3.5:

$$P_{w,n} = P_{w,0} - \gamma_n * P_{w,0} \tag{3.5}$$

The scenario which produces lowest $R_{w,n}$ is the most effective in lowering the risk. The result of the risk analysis in this chapter is answering Key Question 3 *"How much is the impact of taking a certain safety measure regarding the failure probability?"*. The "Yearly Risk ($R_{w,n}$)" is addressed as a cash outflow in the Net Present Value calculation (Section 3.5.1).

Financial Consequences (C)

The collapse incident incurred costs to the stakeholders. The cost components analysed in this research are elaborated in Section 3.3.3. Unless the specific information is available, the following assumption of the cost parameters are taken to calculate the financial consequences:

- Exchange rate

  The approximated exchange rate for the currency used in the literature, for fiscal year 2017-2018 is: US $ 1 = €1; Canadian $ 1 = €0.67; £1 = €1.2

- Interest rate

  An interest rate of 3% is set, based on the suggested value for the Dutch public building in 2017 [13]. The interest rate is assumed constant in every case study. Note that in reality, the interest rate differs per country, per project, and per fiscal year. Deviation of ±2% is taken as the sensitivity analysis for the financial model (Section 3.5.2).

- Material loss

  Material loss is estimated by calculating the construction cost of the collapsed building part. One of the following two methods are used: the method by De Jong and Wamelink (2008) in "Building cost and eco-cost aspects of tall buildings" [16] or using the construction cost database in "Rsmeans Cost Data" [44]. In the method by De Jong and Wamelink, the input data for the estimation are building height, gross floor area, structural cost, completion cost, and land cost. Meanwhile, the "Rsmeans Cost Data" provides the cost per (area/volume/unit) of the various construction works.

- Reconstruction cost

  The reconstruction cost per m^2 is assumed €361 for high-rise and medium-high-rise (more than four storeys), and €155 for low rise (less than four storeys) building based on the post-earthquake repair cost for reinforced concrete building [17].

- Monetary value of human life

  The monetary value of human life is approached as a range of value. In the paper "Costs of occupational injuries and diseases in Québec" (Lebeau et al., 2014), every statistical life is worth 2006 Canadian $ 1,000,000 - $ 5,000,000 [38]. Meanwhile, Suddle (2009) estimated a range of €1,000,000 up to €20,000,000 for the fatality cost [67]. For the calculation in this thesis, the value is assumed €5,000,000 per statistical life. An increase of the cost up to €10,000,000 is taken as the sensitivity analysis for the financial model (Section 3.5.2).

- Compensation cost

  Lebeau et al. (2014) estimated a range of 2006 Canadian \$ 37,000 - \$ 62,000 for the compensation cost of occupational injuries per person [38]. In the other reference, "Occupational Safety and Health Administration" of the "United States Department of Labor" estimates an average cost of 2007 US \$ 50,000, with the maximum value up to \$ 107,000. Included in the compensation cost are wages (30%) and medical expenses (70%) [49]. For this thesis, the assumed value is €50,000 per wounded person. An increase of the cost up to €100,000 is taken as the sensitivity analysis for the financial model (Section 3.5.2).

3.4.3. Questionnaire

The value of the weighting factors (α_f) and the impact level of the safety measure (β_f) are determined based on engineering judgement since there is no statistical data available. To improve objectivity, second opinions by construction experts, professionals, and construction management graduate students are examined using questionnaire. In the questionnaire, three kinds of information are given:

- The brief description and illustration of the ten cases
- Analysis of the critical factors for every case
- Proposed safety measures for every case

All the information provided in the questionnaire is pre-described by the author based on the literature study. The respondents are asked to give scores on the following aspects:

- Part 1: Contribution of the critical factors
- Part 2: Impact of safety measures for each factor

The scoring system of 5-Point Likert Scale is used for the questionnaire (1= very low; 2= low; 3= moderate; 4= high; 5= very high). An averaging formula is applied to determine the average scores of α_f and β_f [54].

$$A_f = \frac{1}{N} * \sum_{x=1}^{N} A_x \tag{3.6}$$

With A_f is the average score; N is the total number of respondents; A_x is the individual score given by the respondents.

The value of the weighting factors (α_f) is translated into a percentage of contribution (%) while the value of the impact level (β_f) is used to calculate the risk reduction (Equation 3.4). The web-based questionnaire was open for two weeks (30 April 2018 - 14 May 2018).

3.4.4. Advantages and Disadvantages

The main advantage of *"The weighted risk analysis"* is the ability to combine and compare various events that contribute to the total risk. In this thesis, the events are defined in forms of the six critical factors. The impact of safety measure can also be quantitatively approached using this method. Moreover, since the risk is expressed in terms of monetary value, it can be addressed in the financial model. Evaluation of the life cycle model emphasises the importance of strategic investment on the building project.

Meanwhile, the disadvantage of this method is subjectivity of the engineering judgement and the pre-described information in the questionnaire. Due to the absence of statistical data, personal opinions are collected to determine the weight of factors (α_f) and the impact level of the safety measure (β_f). Besides, in practice, some of the aspects such as human life cannot be valued as an exact monetary value. Finally, the adaptation of *"The weighted risk analysis"* in this research does not include a thorough multi-criteria analysis as performed by the original author.

Nevertheless, *"The weighted risk analysis"* is proposed as an additional tool in the decision-making process within a project [67]. There will never be an exact numerical answer regarding risk analysis of such intangible entities and social aspects. Inaccuracy is acceptable as long as the procedure is consistent and reasonable.

3.5. Financial Analysis

The financial analysis is carried out using extended cash-flow analysis. In the cash-flow analysis, only cash-in (revenue) and cash-out (expenditure) are taken into account. In this thesis, two economic aspects (monetary value of human life and injury compensation) are included in the calculation to extend the assessment towards the cost-benefit analysis. The two safety-related cost components are expected to be expenditures that stakeholder has to bear in the case of building failure. The broader analysis gives a better picture of the life cycle financial assessment. Other economic components such as commercial value and indirect cost or benefit are beyond the Research Limitation (Section 2.2.3).

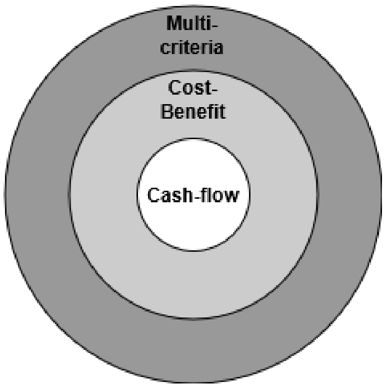

Figure 3.5: Levels of project financial analysis [79]

3.5.1. Net Present Value Calculation

The financial model is generated by considering the expected cash flows during the assessed time. Mathematically including the yearly risk in the model might be ambiguous because "risk" is not a definite expense for the project, but assumed as an expected expenditure in this research.

The principle of the Net Present Value is used (Section 2.1.3), and the limitations mentioned in Section 2.2.3 are applied. All values are analysed using their present value (2018 €). Formula 3.7 is used for the scenario without measure (Scenario 0).

$$NPV = -C_0 + \sum_{x=1}^{y} C_{rev} - \sum_{x=1}^{y} C_{om} - C \tag{3.7}$$

Meanwhile, the formula for the scenario with measures is:

$$NPV = -C_0 - C_m + \sum_{x=1}^{y} C_{rev} - \sum_{x=1}^{y} C_{om} - \sum_{x=1}^{y} R_w \tag{3.8}$$

With C_0 is the initial investment of the project; C_m is the additional investment due to safety measure implementation; C_{rev} is the annual revenue; C_{om} is the yearly operation-maintenance cost; C is the financial consequences due to the failure (Section 3.4.2); R_w is the yearly risk; and y is the period of assessment.

The following assumptions are applied to all the scenarios unless specific information is mentioned in this report:

- Exchange rate and interest rate

  The assumed exchange rate and interest rate elaborated in Section 3.4.2 is applied to the financial model.

- Assessment period

  The assessment period is 30 years after building completion. The assumption is taken based on the estimated corrosion initiation time in reinforced concrete structure [51].

- Construction cost

  The construction cost is determined using the method by De Jong and Wamelink (2008) ”Building cost and eco-cost aspects of tall buildings” [16] or using the database of construction cost in ”Rsmeans Cost Data” [44] (Section 3.4.2). The elaboration of construction cost is presented in Appendix C.

- Annual operation-maintenance

  The average annual operation-maintenance cost for public buildings is £36 per m^2 per year (in 1994) [3]. The value is equivalent to the present value €87.82 per m^2 per year. Every five years of service, the cost is assumed 50% higher due to the extensive maintenance activity.

- Safety measure implementation cost

  The implementation of safety measure incurs additional investment. The value of each component is assumed as follows:

  – Construction information management systems (CIMS) cost (I1)

    The average cost to implement CIMS in a building project is €90,000. Included in the cost are device purchasing, software license, and employees training [78].

  – Time delay cost (I2)

    The average cost overrun is approximately 1% of the project cost per month of delay. The value is estimated based on the studies of residential construction projects in Kuwait [36]. In this thesis, the assumed delay duration is six months. An additional of six other months of delay is taken as the sensitivity analysis (Section 3.5.2).

  – Supervision cost (I3)

    The average wage for experienced supervisor in the United States is €75,000 per year according to (www.payscale.com). The amount of supervisors required in the associated project is determined based on the estimated contractor size [72]. The contractor size is estimated based on the project value [36].

  – Structural modelling cost (I4)

    The cost to develop a physical model is assumed 1% of the project value. For computational modelling, the average price to create a full building model is approximately 0.25% of the project value [6].

  – Survey/inspection cost (I5)

    The average total cost of building inspection is €6.72 per m^2 per year [3]. The average salary for professional topographical surveyor is €69,000 per year according to the open source (www.payscale.com).

  – Skilled labour cost (I6)

    Labour cost is approximately 14% of the project value [14] and the salary of specialist labour is 150% of the common labour (www.payscale.com). Therefore, the total additional cost to hire specialist labours is assumed 7% of the project value.

The net present value is compared with the total investment to assess the profit or loss of the project (Profitability Index, Section 3.5.3). The case by case elaboration of the financial model can be found in Appendix C.

3.5.2. Sensitivity Analysis

The input parameter for the financial model is taken as a definite number. In reality, the values are subject to uncertainty. Sensitivity analysis is carried out to understand how the model behaves in response to changes of parameters [51]. There are four types of sensitivity performed to the financial model:

- Sensitivity 1: increase of interest rate to 5%;
- Sensitivity 2: decrease of interest rate to 1%;
- Sensitivity 3: €10,000,000 per fatality and €100,000 per injury
- Sensitivity 4: additional delay of 6 months for the measures before the service stage

Other financial parameters are kept constant. The result of the sensitivity analyses are combined with the model without sensitivity to obtain the average result.

3.5.3. Profitability Index

As the final assessment, Profitability Index (Section 2.1.3) is calculated using Formula 3.9, providing the building depreciation is not taken into account (Building value in year 0 = Building value in year 30). The Profitability Index shows the comparison of the financial benefit between measures.

$$PI = 1 + \frac{NPV}{C_0 + C_m} \times 100\% \tag{3.9}$$

With PI is the profitability index (%); NPV is the net present value (€) calculated using Formula 3.7 and Formula 3.8; C_0 is the initial investment of the project; C_m is the additional investment due to safety measure implementation.

Profitability Index larger than 100% means that the investment is acceptable [8], resulting in profit. Subsequently, the amount of profit or loss gained from the project can be derived from the Profitability Index using Formula 3.10. A positive value indicates that the project generates profit and vice versa.

$$Profit/loss = \frac{NPV}{C_0 + C_m} \times 100\% \tag{3.10}$$

The monetary value of the failure cases is broadly diverse. One million of profit in a single dwelling does not value the same as one million of profit in an airport project. Profitability Index is a suitable tool to compare the overall profit or loss of various cases as the final result is expressed relative to the investment.

4
Study of the Failure Cases

This chapter elaborates the finding of the literature study regarding the failure cases. Substantial building information and analyses from investigation reports are briefly explained, combined with the author's critical thinking.

Ten failure cases obtained from case selection process (Section 3.3) are described in this chapter. In-depth information of the buildings and investigation reports can be found under the references. Each section in this chapter represents one case study, consisted of the following five subsections:

- General information
- Structural information
- Failure analysis
- Lessons learned
- Financial information

As an overview, the deficiencies of critical factors, the type of measures proposed, and the financial components of each case are listed in Table 4.1 and Table 4.2. The type of safety measures and the cost components are classified based on Section 3.3.3. In the case description, the key information is highlighted using the specified index.

Table 4.1: Observed critical factors and proposed safety measures

Case	Critical factors						Safety measures					
	F1	F2	F3	F4	F5	F6	M1	M2	M3	M4	M5	M6
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Integrated coordination	Planning and responsibility	Supervision	Structural modeling	Survey and inspection	Employees competency
Berlin Congress Hall	●	●		●				●		○	●	
Hyatt Regency	●	●		●			○	●	●			
Ice Skating Hall Bad Reichenhall		●		●		●				●	○	
Terminal 2E CDG Airport	○	●		●		●			○	●		
Patio Sevilla	○			●			●		○	●		
Hartford Civic Center		●	●	●	●	●		●	●	●		
Kemper Arena		●		●		●			○	●	○	
Ronan Point		●	○	●	●	○		●	●	●		
Bos en Lommerplein	●	●	●		●	●	●		●			●
Amoco Tower		●				●				●	○	

Table 4.2: Components of cost of failure and cost of safety measures

Case	Financial consequences				Cost of measures					
	C1	C2	C3	C4	I1	I2	I3	I4	I5	I6
	Material loss	Reconstruction	Loss of human life	Compensation	CIMS cost	Time delay cost	Supervision cost	Structural modeling cost	Survey/inspection cost	Skilled labour cost
Berlin Congress Hall	○	○	○	○		○		○	○	
Hyatt Regency	●	○	○	●	○	○	○			
Ice Skating Hall Bad Reichenhall	○		○	●				○	○	
Terminal 2E CDG Airport	●	●	○	○			○	○		
Patio Sevilla	○	○	○		○		○	○		
Hartford Civic Center	○	○				○	○	○		
Kemper Arena	○	●				○	○	○	○	
Ronan Point	○	○	○	○		○	○	○		
Bos en Lommerplein		○		●	○	○	○			○
Amoco Tower	○	●						○	○	

The full bullet indicates that the related category is presented explicitly in the literature, while the hollow bullet means that the respective component is observed implicitly. The empty cell shows that the particular aspect is not governing in the corresponding case.

4.1. Case 1: Berlin Congress Hall

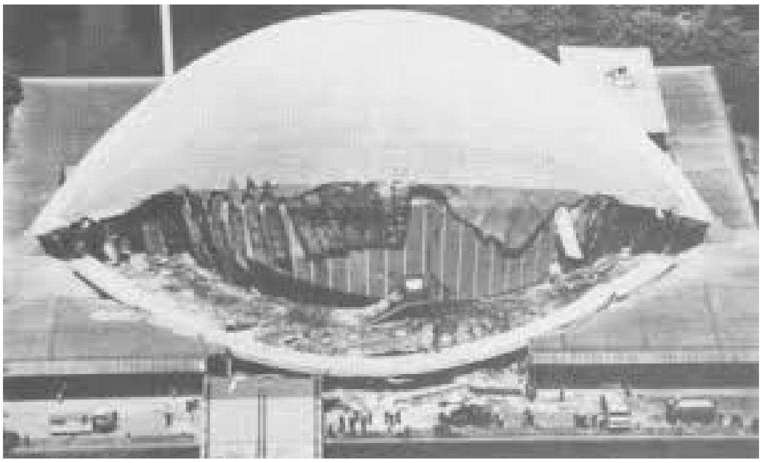

Figure 4.1: Roof collapse of Berlin Congress Hall [31]

4.1.1. General Information

Berlin Congress Hall was designed by an American architect Hugh Stubbins. The building had a shape of an elongated dome, with segments at both north and south sides were forming wing-like curves [37]. The concept of the design was pretty much comparable with J. S. Dorton Arena (previously known as State Fair Arena) in North Carolina, USA. On 21 May 1980, a collapse of the southern part of the roof occurred. The pre-stressed cable at southern part, connecting curves with the ring beam, failed after 23 years. The incident caused one fatality and five injuries [76].

4.1.2. Structural Information

Figure 4.2: J. S. Dorton Arena. (credit: www.ou.edu)

The congress hall was constructed out of hyperbolic paraboloid (hypar shell) made from pre-stressed concrete structure [76]. The structural system of this building was slightly different than J. S. Dorton Arena. In J. S. Dorton Arena, the two slanted concrete hyperboloid roof decks are supported by curves lie on base supports. The hypar shell is loaded in compression, and the facade supported by vertical columns is loaded in tension.

Meanwhile, in the Berlin Congress Hall, the curved beams supporting 3500m^2 roof area lied on slender vertical disks [76]. The curved beams were the only supporting system of the roof structure. The thickness of the roof deck was 70mm, with a ring beam of $2 \times 0.4m^2$ designed to carry the inner deck [76]. The curves supported the hanging outer deck. Such structure had never been built in this manner before, and pre-stressed concrete structures with complicated details were not common in Germany at that time [31].

4.1.3. Failure Analysis

On 21 May 1980, the roof at the southern section of the hall suddenly collapsed. Eight panels were torn out from the supporting curve beam. The inner roof structure remained almost undamaged. All failed tendons were located in the south-east quarter of the building [31].

It was found that failure of pre-stressed cable triggered the incident. The possible cracked condition of the shell was not taken into account when designing the load (F4) [76]. It was also determined that the unusual structure did not have the proper load path as the structural design tried to follow the architectural design without recognizing the consequences (F1) [76].

Shell structure should be loaded only in compression, but in this case, it also took the tensile stress. Cracks were formed and subsequently allowing moisture to intrude the concrete matrix. A fountain under the southern deck was suspected as the source of humidity [76]. The concrete cover depth of the failed part was only 2cm was insufficient to prevent corrosion. At the time of construction (1957), the requirements for reduced corrosion-inducing and advancing components, as chlorides, in the concrete mass did not exist. For some specimens, chloride content tested in 1980 was exceeding the current (2014) limit [31].

Figure 4.3: Poor workmanship of pre-stressed tendons [31]

According to the structural design, it was intended to locate the tendons in the axes of the external roof plates. The distribution of the wires inside the tendon was incorrect, and the location of the ducts was deviated (F2). It was also observed that there was no concrete grout as a protective substance inside the pack of the tendons (F2) [31].

4.1.4. Lessons Learned

The rebuilding of Berlin Congress Hall was finished in 1982. Concrete roof decks are now directly supported by strengthened edge arches, and the arches are clamped at the supporting point. The reinforced concrete shell is simplified and thickened up to 110mm [31]. The designer realized that an architectural design which does not allow a logical load transfer might cause unjustified simplification. Physical modelling before construction is a reliable solution for this issue (M4). Regarding the steel protection, it is suggested to assume chloride content up to the maximum level [76].

Meanwhile, on a macro level, the old type of pre-stressing wire is no longer used due to its sensitiveness to corrosion cracking [31]. It is also suggested to justify the time management since the planning stage because short construction time might lead to unsupervised tasks [76]. Allocation of extra time in the project could minimize the risk (M2). Regular maintenance and inspection of public buildings during lifetime need to be considered in the planning phase (M5) [76].

4.1.5. Financial Information

The investigations reports do not mention the cost incurred by this incident. However, based on the previous subsections, the cost of failure can be estimated. The components are building material loss (C1), reconstruction cost (C2), compensation for injured victims (C4), and the monetary value of human life (C3).

On the other hand, the additional investment incurred to implement safety measures are the material cost to the increased thickness of concrete or higher quality of steel, regular inspection cost (I5), modelling cost (I4), delay due to longer allocated construction time (I2).

4.2. Case 2: Hyatt Regency, Kansas City

Figure 4.4: Hyatt regency walkways collapse [46]

4.2.1. General Information

The construction of the Hyatt Regency Hotel began in 1978 and finished in 1980. The hotel had sky bridges connecting residential tower and conference area on the other side. The sky bridges were hanging from the steel truss of the atrium roof. It was a fast-track construction, where the construction team had begun to build the hotel while the design team was still finalizing the detailed plans [56]. On the night of the collapse in July 1981, there was a dance party in the atrium lobby. The hanging bridges suddenly fell, 114 people had died, and 186 others were injured [76].

4.2.2. Structural Information

The sky bridges spanned 36m and had a width of 2.5m. Each span was supported by two main beams in the long direction. Every 9m, a box girder was placed as a cross beam. The box girder hangs on the deck using a 32mm steel hanger [76]. Due to the fast-track method, the engineers left the detail unspecified. As consequences, the sky bridges were not built according to the original plan [39]. The constructor thought it was not necessary to strengthen the connection of suspension bar and box girder. The hanger detail was also changed for a practical reason. Two possible scenarios were suspected for this change. First, the fabricators were unable to obtain rods long enough to construct the walkways with single rods. Second, the construction team realized that threading 30 feet long rods for the required nuts would be impractical, if not unsafe [56].

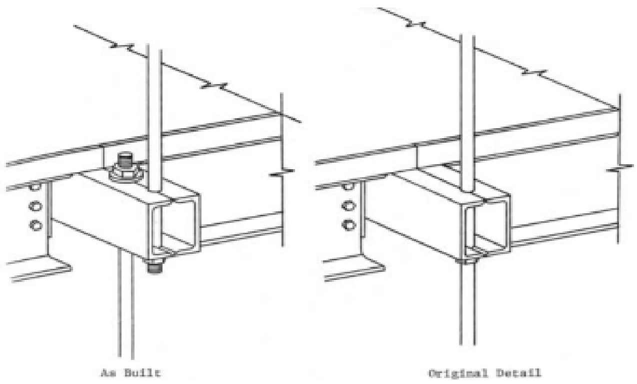

Figure 4.5: Change of the detailed drawing (left: as-built, right: original design) [46]

The change of detail was brought to the day-to-day lead engineer. He did look at the shop drawing but did not assess the box-beam connection [61]. Meanwhile, no original design calculations were found for the box beam that failed [62].

4.2.3. Failure Analysis

It was concluded that the structure was under-designed and lack of redundancy (F4) [39]. The static load when collapse was predicted as much as 0.83$\mathrm{kN\,m^{-2}}$. The static design load itself was supposed to be 5$\mathrm{kN\,m^{-2}}$. The dynamic load of collapse (1.1Hz) was also much lower than its natural frequency (7.1Hz). The original design could even only carry 60% of the required capacity by the local standard [39].

Regarding the organization, control mechanism issue was suspected. For this such complex structure, each of approximately ten associate engineers was supervising six or seven other projects at a time, less attention paid to this project (F2) [56]. The team failed to perform the standard procedure for processing a change of order (F1). Another evidence of poor communication was found in the existence of cement topping, even though the additional load did not trigger the failure. The cement layer on the top of every deck was not shown in the detailed drawing [39].

4.2.4. Lessons Learned

Reconstruction was done to the bridges, to keep the function as the connector between two towers. Conservative concept was then applied, as the bridges are supported by ten columns [76]. Hyatt Regency disaster alarmed the construction industry in the USA about the importance of head contractor as the supervisor [76]. The significance of supervising increases in fast-track project, as it requires extra diligence in the planning and execution (M3) [52]. Having project engineers who are currently handling multiple projects is not recommended (M2) [52].

Within a project team, modification of details without consent from original designer should not be allowed (M1). The original designer is the person who knows the mechanics of a structure and the consequences if something changes [76]. Ambiguity in design, such as the hanger detail in this sample case, will increase the risk because one might fail to interpret engineer's intention [61].

4.2.5. Financial Information

A total of $78,000,000 was paid out to settle civil lawsuits filed by the victims and their families (C4) [56]. The contract for the hanging bridge construction was reported as $390,000 [41]. From the reports, it can be derived that building material loss (C1) and reconstruction cost (C2) were present. Finally, loss of human life (C3) was the significant cost incurred from the incident.

If safety measures are implemented, engineering cost for supervision (I3), delay cost due to supervision in fast-track project (I2), and cost to perform real-time project communication (I1) are incurred.

4.3. Case 3: Ice Skating Arena, Bad Reichenhall

Figure 4.6: Collapse of the ice skating arena in Bad Reichenhall. Credit: www.calgaryherald.com

4.3.1. General Information

The $75 \times 48\text{m}^2$ arena was constructed in 1972, located in Bad Reichenhall, Bayern, Germany. The roof of 33 years old building collapsed under the snow load on 2 January 2006. There was an uncommon heavy winter season with snow in Europe at that time [82]. Reports of leaks of the roof had been made before the collapse, and formal complaints had been made due to sights of buckets placed to catch water from leaks. However, the arena was still operating normally. There were 15 people died, and 30 others were heavily injured due to the incident [76].

4.3.2. Structural Information

Figure 4.7: Box girder components of the ice skating roof [82]

The roof structure was made of glue-laminated timber. The timber roof construction was using 7.5m traverse box girders and 4m cantilever, with the height of 2.87m. In total, it was a 48m long hollow box girder, divided into three parts. The connection between elements was designed as glued finger joint. The type of glue used for the construction was urea-formaldehyde (UF) glue. This ice arena was the first timber construction of that size [76]. The safety factor required for such naturally-degrading structure is usually up to 2.0.

4.3.3. Failure Analysis

Series of investigations performed by TU Munich and TUV Sud proved that snow was not the cause of failure. The maximum snow load of $1.5\,\text{kN}\,\text{m}^{-2}$ applied in the static calculation was not exceeded at the time of the accident [82].

Figure 4.8: Damaged glue laminated box girder [82]

The failure was caused by a chain failure. As one of the box girders failed, the load was then restrained by the neighbouring girders, creating a chain of the excessive load until the roof collapsed. The bearing capacity of the box girder due to the long-term moist on the glue was concluded as the primary cause of the collapse [76]. UF glue was only admissible in a dry ambient climate, as they are not permanently moisture-proof (F6) [82].

Deviations of the inspection certificate were found in the construction. The maximum height of such type of girder was supposed to be 1.2m according to the standard, but in the execution, 2.87m girder was installed. The joint between girders and webboards with the thickness of 35– 50mm was supposed to be secured by nails based on the German regulation at the time of construction (F2) [82].

Regarding the non-technical aspects, several problems also suspected. Firstly, in Germany, the “four-eye-principle” is obligatory for the static calculation of special buildings. A so-called ”check engineers” must have reviewed the design before giving the green light to the construction. This step was not performed in the project (F2) [82]. Secondly, there was no maintenance recorded during the lifetime, even though the sign of defect had been found (F4) [76].

4.3.4. Lessons Learned

Technically, for a long span laminated timber structure it is better to use an elastic type of glue such as resorcinol glue (RF). For the structural calculation, exposure to humidity should not be disregarded. Maintenance wise, it is not recommended to use hollow girder in a humid environment, as there are non-accessible areas for investigation. In correlation to its natural degradation, routine inspection is also necessary for timber structure (M5). Finally, a new technique or innovation should be tested beforehand (M4) [76].

4.3.5. Financial Information

One of the reports mentioned that as compensation, €54,000 was charged as the legal settlement (C4) [76]. There is no other financial information found. From the investigation reports, it can be derived that material cost (C1) and the monetary value of human life (C3) were present in this case. It is also assumed that the injured victims received compensation (C4). The building was not reconstructed after the incident.

Accident prevention measures for this failure case will cause extra spending due to routine inspections (I5), physical or computational modelling of the innovative structure (I4), and additional construction cost of using the different type of glue or dowel connection.

4.4. Case 4: Terminal 2E, Charles de Gaulle Airport, Paris

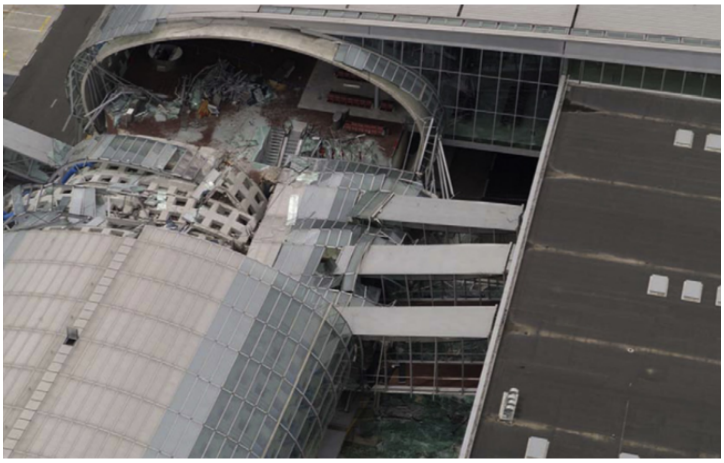

Figure 4.9: Collapse of Terminal 2E Charles de Gaulle Airport [60]

4.4.1. General Information

Terminal 2-E of Charles de Gaulle Airport (CDG) is an additional terminal built in 1997 [75] and opened in 2003 [83]. The design was made by French architect Paul Andreu, with the concept of tunnel construction [76].

CDG 2–E was designed as a 220,000m^2 hub with an estimated capacity of 11 million passengers per year [75]. In May 2004, the collapsed happened, killing four and injuring three others [76].

Terminal 2E building was set to remain closed until the repairs were completed. All the flights scheduled to and from terminal 2E was reorganized and reallocated to other terminals [34]. Several areas were partially reopened on 15 July, while the whole area was re-opened in March 2008 [75].

4.4.2. Structural Information

The structural concept of the terminal building was a column-free concrete tube, with the dimension of 650m x 30m, and height of 12m. The tubular structure was divided into ten segments in the long direction supported by concrete arches. These arches were supported by edge beams which were supported by columns every 4m. Each arch was consisted of three prefabricated reinforced concrete elements, with 300mm of thickness. Segments were clamp connected [76].

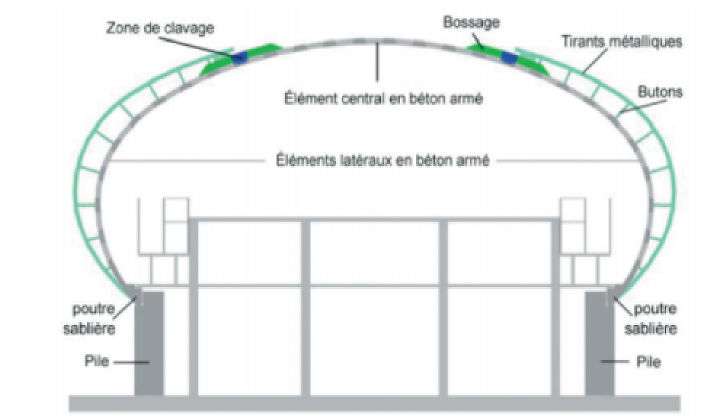

Figure 4.10: Cross section image of Terminal 2E CDG Airport [83]

Two curved steel trusses were installed to resist the tension force, one on each outer side of the arch to increase stiffness. To maintain the functional requirements, the concrete construction was kept at constant at a temperature of 20°C for the indoor temperature [76].

4.4.3. Failure Analysis

Set of investigations performed by National Council of Engineers and Scientists of France (CNISF) concluded that the incident was the result of the progressive collapse, started from the outer segment of the concrete arch until finally, the beam collapsed. The steel truss was subject to change of the outdoor temperature. Due to the rigid connection, thermal expansion is restrained (F4) [76]. It was reported that on the day of the collapse, morning temperature was 4°C, and day temperature was 25°C [76].

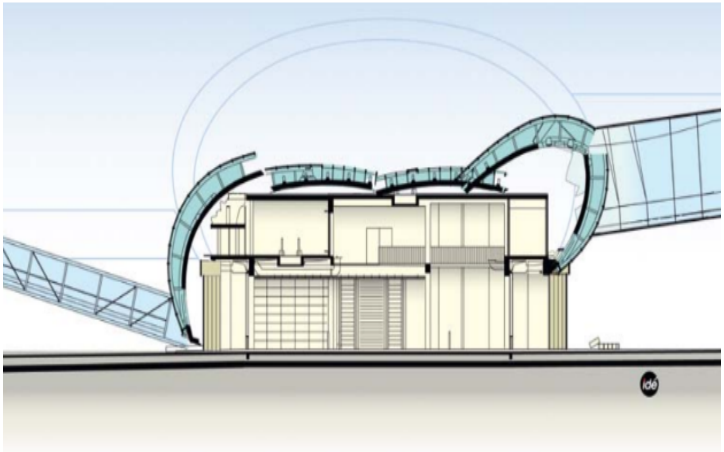

Figure 4.11: Collapse mechanism of the structure [83]

The structural concept was considered unusual. The complexity makes it hard to analyse the forces distribution (F4) [83]. The two-dimension model created by the design office was inadequate. The model failed to measure long-term effect of the structure (F6) [60].

Non-technical aspects also played a prominent role. First, there were around 400 different firms and organizations as stakeholders [75]. Coordination error and accumulation of individual mistakes were very likely in the project (F1). Furthermore, it was reported that the architect was very idealist, as he forced his particular design regardless of costs, risks, and efficiency. Other terminal building in CDG airport designed by the same architect also had problems with the workability. Finally, Aéroports de Paris as the client (ADP) had always been both judge and jury when it comes to the design and construction, no external control within the project (F2) [75].

4.4.4. Lessons Learned

It was concluded that a complete design analysis would have predicted all structural deficiencies in the project [60]. One example of the proper design analysis is by making a rigorous 3D model, where the behaviour of the building parts can be analysed (M4) [83]. The model itself should not neglect temperature load especially for such a high stiffness construction [76]. Moreover, for a multi-stakeholder, quality control from an independent third party is necessary (M3).

If the original architectural design is maintained, additional tensional members to the arch might help by creating a secondary load path. It is also suggested to improve the strength of concrete components by using 55MPa instead of the existing 40MPa [60].

4.4.5. Financial Information

The investment of Terminal 2E was up to 750 million Euro, with 150 million Euro spent in the collapsed boarding area (C1) [75]. The reconstruction was estimated to cost around 100 million Euro [34] (C2). Three injured persons were provided with medical care (C4) [75], and loss of human life (C3) was present.

If the safety measures are applied to the failure case, investments are needed for supervision (I3) and modelling cost (I4).

4.5. Case 5: Patio Sevilla, Maastricht

Figure 4.12: Collapse of the balconies of the Patio Sevilla apartment. Credit: www.architectenwerk.nl

4.5.1. General Information

Patio Sevilla is a complex of 97 apartments located at Avenue Céramique in Maastricht. The complex was designed in 1999 and finished in 2002. Each apartment in Patio Sevilla has one outward balcony on each story [76].

On 24 April 2003, five balconies collapsed, and the façade ripped off, resulting in two fatalities [15]. The collapsed balconies were restored, as well as the other balconies in the apartment complex. There were at least five parties involved in the construction of the balconies. The incident raised public awareness of the organizational factor as a determining aspect for the quality of a construction project.

4.5.2. Structural Information

The focus of the building structure in Patio Sevilla is the balconies construction. The trapezium balconies were made of prefabricated concrete. Each balcony plate was supported on three points: at two column with *"isokorven"* and one tubular steel column. The *isokorven* column was designed as thermal insulation connector of the balcony plate and the floor. The vertical support reaction of the *isokorven* column was provided by a stainless steel structure inside the insulation system [76].

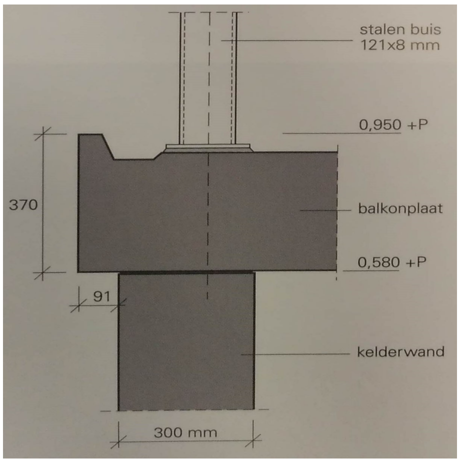

Figure 4.13: Original design of the column [76]

In the original design, the tubular steel of $121 \times 8\text{mm}^2$ was supposed to be placed at the corner of the balcony plate. It was designed to be right on the top of the ring wall, hence no eccentricity to the structure.

When the project was ongoing, the column was changed to a square column of $100 \times 100 \times 10$mm by request of the architect and the placement was also altered [80]. Aesthetics and building physics aspects were the considerations of the decision by the architect [48]. A ridge (such a cantilever, an extension of the floor plate) was created to place the column. The column was then not directly supported by the wall, but the contractor made steel console under the ridge to function as the wall.

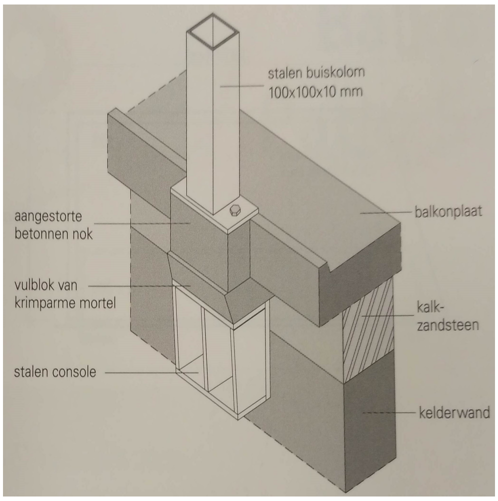

Figure 4.14: Modification of the original design [76]

4.5.3. Failure Analysis

The root of the problem was never clear as the investigation results were opposing one another [76]. However, it was agreed that the failure of the ridge of the ground floor balcony or first-floor balcony was the cause of the total collapse [80]. Balcony plates of the first floor up to the fifth floor were rotated due to the placement of the *isokorven* at the façade. The *isokorven* column was only designed to resist shear force but not rotation. This fact was somehow not realized by the contractor (F1) [76]. Evidence showed that the calculation of the steel console was based on the original design drawing, where the column was placed at the corner (F1). There was no adjustment made to assess the structural capacity (F4) [80].

4.5.4. Lessons Learned

From the previous section, it can be determined that the coordination between design, construction, and service was the source of the problem. Parties involved in the project seemed to work individually as there was no adjustment made to comply with the most recent design. Moreover, the change of drawings during the construction phase should be avoided. If it is essential, all parties involved should be informed (M1) [76].

To assure the constructed product is of relevance to the design, it is suggested to hire superintendents during the construction phase (M3). Load transfer should be made sure, all connections should be tested (M4), and a secondary load path should be prepared in case of failure of building parts [76].

4.5.5. Financial Information

There is no failure cost mentioned in the investigation reports. The failure cost components present in the references are reconstruction cost (C2), material cost (C1), and value of human life (C3).

As the consequence of taking safety measures, additional investment costs are incurred. Those are supervising cost during design and construction (I3), the cost of implementing an integrated project communication (I1), and physical testing (I4).

4.6. Case 6: Hartford Civic Centre, Connecticut

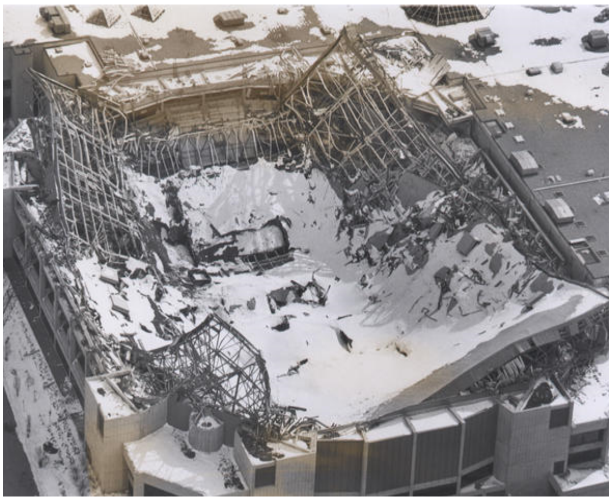

Figure 4.15: Collapsed roof of the Hartford Civic Centre. Credit: Hartford Courant

4.6.1. General Information

Hartford Civic Centre (currently known as XL Centre) was an arena for various concerts, hockey games, and basketball games. The former largest space frame structure in the US was opened in 1973. The 108,000 square feet roof collapsed under a heavy snowfall on 18 January 1978 [35]. No victim reported on that incident.

The special structure was an innovative design at that time. The designer chose space frame structure to save $500,000 compared to the conventional flat truss [39]. An engineering firm was appointed to perform the computational modelling [76]. The roof frame was assembled entirely on the ground to save more time and money. There were several shreds of evidence of distress during construction, but the project manager had not heeded the warnings. Before the erection, the deflection at the midpoint was already twice than it was predicted [42].

The incident revealed the danger of using a computer model as unproven technology at that time. There were too many variations in the roof design, while there was not enough statistical data about the performance of built physical construction [81]. The area was reopened in 1980, with several modifications carried out. The roof was modified as simpler two parallel space frames, with six secondary space frames [39]. The roof was raised 3.6m to increase the capacity. It was built on the existing columns which remain intact after the incident [76].

4.6.2. Structural Information

Hartford Civic Centre Coliseum was constructed on a square grid of 9×9m. Each node on the space frame was connected with diagonal bars [76]. The 6.3m tall space frame was supported by the concrete column at position 13.5m inwards from the edges. The roof slab was made out of steel plate and concrete floor with the total height of 75mm. The slab was placed on the top of 900mm steel spacer and welded at the nodes of the upper side of the space frame [76]. The design was the modification of standard space frame, developed solely using the output from the computer program [81].

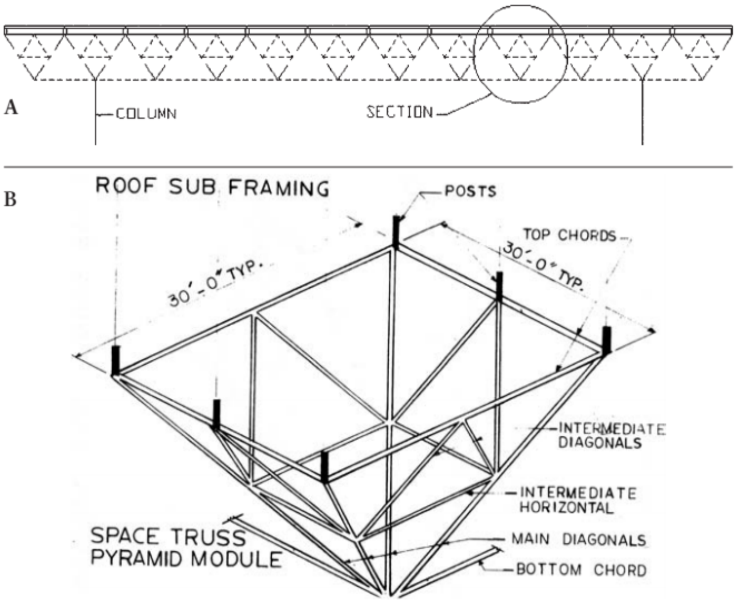

Figure 4.16: Original design of roof structure [18]

4.6.3. Failure Analysis

The failure case of Hartford Civic Centre became a wake-up call for engineers about the danger of blind reliance to the computer model [81]. Computer program assumed an ideal condition of construction, while in reality, everything is far from perfect. Imperfection and the human factor are often underestimated by the engineers (F6) [76]. Several investigations were performed after the incident. The general conclusions were [39]:

- Negligence, for example, there was no action taken when the signs of failure were found during construction (F4)
- The control mechanism was inadequate, for example, some amount of the bracing bars presented in the computer model were not installed, design misinterpretation, and no independent supervising (F2)
- Under-designed structure, for example, due to the false assumption of the structural concept, a progressive collapse was inevitable (F6) [18]

Two notable investigations (by Lev Zetlin Association and Loomis & Loomis) were presented in the book "Leren van instortingen" by van Herwijnen (2009) [76]. The summary of both reports is shown as follows:

- Investigation by Lev Zetlin Association

  Even though the actual snow load was just 50% (occurring snow load was 0.35 $\mathrm{kN\,m^{-2}}$, the required capacity was 0.7 $\mathrm{kN\,m^{-2}}$), the investigator found that the designed capacity was only 0.36 $\mathrm{kN\,m^{-2}}$ in an ideal condition. The self-weight of the roof was found 25% higher than it was calculated for the design (F6) [76].

- The investigation by Loomis & Loomis

  Design errors were responsible for the progressive collapse of the roof. On the upper frame, torsional buckling was exceeded. If the upper edge bars were four times stiffer, the failure could have been avoided. One way to make it more rigid for example by adding just about 50 diagonal bars.

Concerning the organizational aspects, the absence of a full time registered structural engineer experienced in the design of long span special structures is believed to be crucial (F2) [81]. The architect already recommended that a qualified structural engineer should be hired to oversee the construction, but the committee refused the idea for the sake of saving initial cost (F5) [81]. The contract of Hartford Civic Centre project was divided into five subcontracts coordinated by a construction manager. This mechanism caused responsibility confusion within the project (F3) [42]

On a higher level, it was realized that the Hartford Department of Licenses and Inspection did not require the project peer review in its construction prescription. This procedure is commonly required for projects of this magnitude due to its importance [18].

4.6.4. Lessons Learned

First of all, for a space frame structure, additional load transfer mechanism should be prepared. Secondly, in the construction industry, a real model with physical simulation is still preferred rather than a computational model (M4) [76]. Thirdly, peer reviews are essential for high-occupancy buildings and structures experimenting with new design techniques. The absence of a full-time registered structural engineer experienced with such a special structure was a severe mistake (M3) [42]. Finally, it is suggested to have a unified contract and insurance under the same organization to clarify responsibilities (M2) [42].

4.6.5. Financial Information

From the literature study, there is no information regarding failure cost of this incident. Therefore, financial components are derived from the case description presented in the references. It can be concluded that only material loss (C1) and reconstruction cost incurred due to the incident (C2).

Meanwhile, the safety measures proposed are causing extra cost, namely design and construction supervision cost by an experienced structural engineer (I3), physical modelling cost (I4), possible delay due to supervision in such a fast project (I2).

4.7. Case 7: Kemper Arena, Kansas City

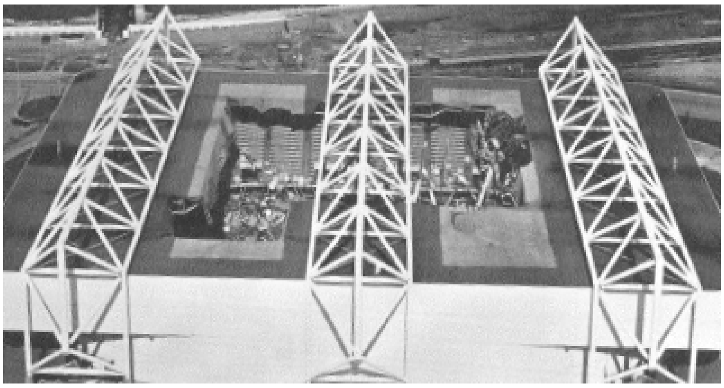

Figure 4.17: Partial collapse of the roof in Kemper Arena [64]

4.7.1. General Information

Kemper Arena is a sports hall located in downtown Kansas City, Missouri. The arena was opened in 1973. What made the arena special was the design of the suspended roof, as it featured uninterrupted sight lines. The innovative design earned the architect an Honor Award from the American Institute of Architects [18].

On 4 June 1979, part of the roof collapse following a storm with 110 km/h winds and heavy rains [39]. There was no victim reported on that incident. About 4,000m^2 roof had to be replaced [64]. The arena was re-opened in 1981 after reconstruction with some modification of the built construction [39].

4.7.2. Structural Information

The 16,000 m^2 flat roof was made of reinforced concrete. The roof was suspended using hangers from three large space frame cantilever trusses as the supporting structure. This system was considered unusual for such a large arena [39]. The steel trusses were supported by three portals of 108m long and 24m high. The portals sat on conical footings made from reinforced concrete. Total weight of roof was about 1500 ton (1.3$kN\,m^{-2}$). This structure made up a large undisturbed interior space of 108×97×18m [39].

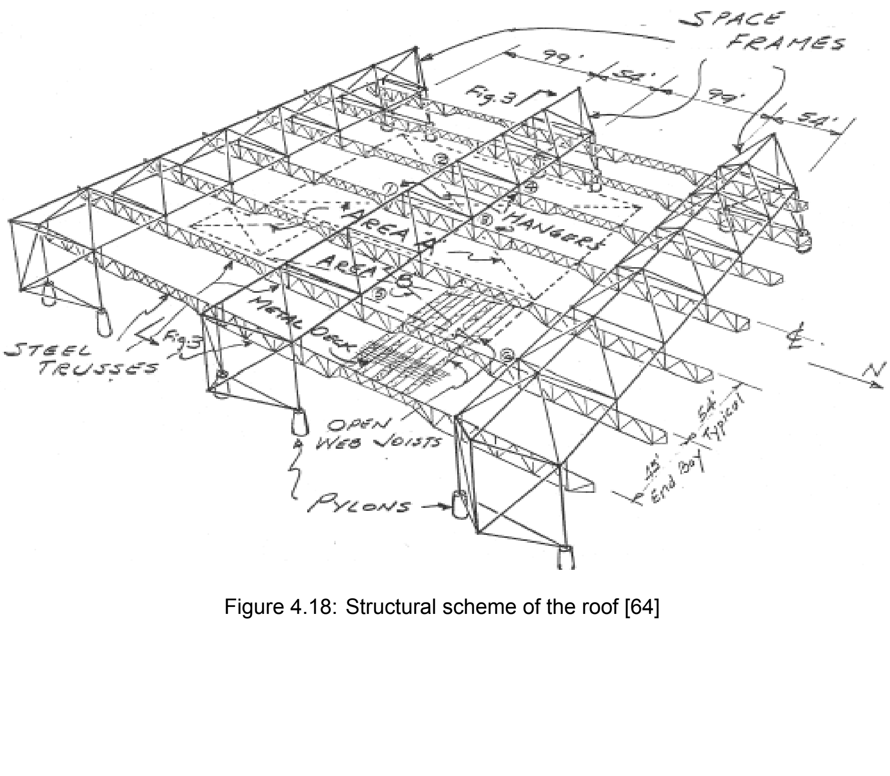

Figure 4.18: Structural scheme of the roof [64]

The roof was also functioned as temporary rain reservoir. There were only eight drains on the roof, each with a diameter of 120mm. As a reservoir, the roof was designed as stiff structure [39]. Therefore, the hangers were intended as a rigid connection, using ASTM A490 high-strength bolts as connectors. This type of bolt is not recommended for fatigue loads as it has low flexibility [24]. Nevertheless, considering minimum deformation allowed for the reservoir roof, this type of bolt was chosen [18].

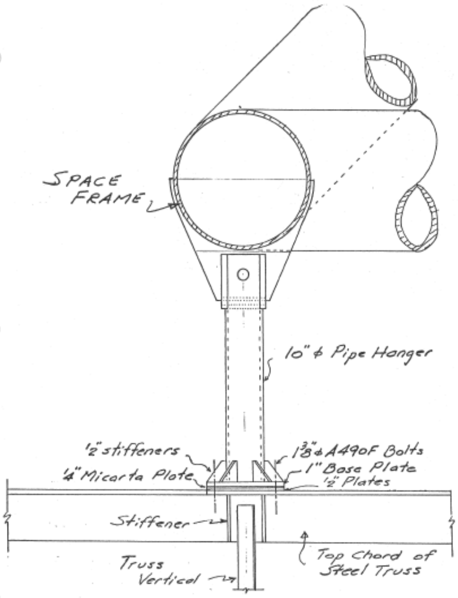

Figure 4.19: Design of the roof hanger [64]

4.7.3. Failure Analysis

The heavy storm initiated the collapse. Ponding combined with the wind was the most likely explanation for the failure load [18], but the hanger was failed at a load of just 1/4 to 1/5 of the static design strength [64]. Another finding was that the local code required eight times as many as the installed drainage capacity (F2) [64]. Several investigation results are presented in the book "Beyond Failure" by Norbert J. Delatte Jr (2008) [18]. The analyses of failure are summarized as follows:

- Report by Weidlinger Associates (worked on behalf of the subcontractors)

  It was concluded that the roof was susceptible to ponding. As a stiff structure, the roof did not allow much deflection, and as a consequence, extra water load could not be carried. The hanger system became the only load transfer mechanism. Such structural characteristic should have been recognized by the engineers (F6). Finally, the hangers had probably been weakened by fatigue cycles over the six years (F4).

- Report by Roger McCarthy from Failure Analysis Associates (worked on behalf of the steel manufacturer):

  The roof could not take extra load due to its stiffness. The flexibility of the roof had been accentuated by the looseness of the roof bolts, which suspected had never been appropriately tightened (F2).

4.7.4. Lessons Learned

The storm on the day of the incident was one of the biggest in few years, but that does not mean the risk is unforeseen. In the Kemper Arena project, sufficient wind analysis was never performed. Such risk should have been considered for a long span structure (M4) [64]. As an anticipation of the ponding effect, a topographical survey of the roof structure before installation is necessary (M5) [64]. It is also recommended to analyse the roof in three dimensions, not just two, to determine the flexibility and ponding susceptibility (M4) [18]. Finally, supervision or peer review is essential to assure the compliance of regulations (M3).

After the reconstruction, the hangers detail was revised, all hangers were replaced using ductile welded steel bars. The roof was raised to create a slope, and the amount of drainage was increased. The roof membrane was attached to a metal deck to provide redundancy [64]. For the rest of the lifetime, routine inspection is necessary to anticipate loosening of the bolts, in case the same low quality of workmanship happened during reconstruction (M5).

4.7.5. Financial Information

The construction cost of Kemper Arena was reported around $23.2 million. There were multiple sources of funding, namely by the municipality, sponsor, and several bonds [39]. The collapse caused loss of investment (C1) and reconstruction cost (C2). The reconstruction cost was reported to be around $6 million [81].

If safety measures are taken, there will be additional investments in engineering cost for structural modelling (I4), for the topographical survey during construction and routine inspection (I5), delay cost due to the extra survey (I2), and supervision (I3).

4.8. Case 8: Ronan Point, East London

Figure 4.20: The collapse of Ronan Point apartment [11]

4.8.1. General Information

Ronan Point was built in 1966 and opened in 1968 to accommodate the demand for housing after the second world war. There were 110 apartment units in the building, five on each story. The building contained 44 two-bedroom apartments and 66 one-bedroom apartments, where it was near full occupancy [18]. Since the need for immediate dwellings was high at that time, prefabricated construction technique was used for the high rise apartment building [55].

On 16 May 1968, the south-east corner of the Ronan Point Tower collapsed. There was a gas explosion from one of the kitchens in the apartment [55]. Four people died, and seventeen others were injured due to the incident [39]. A restoration was taken, but in 1984 cracks were again found on the wall. In 1986, it was decided to demolish the whole building, since it was estimated that the repair would cost six times the cost of making a new building. This incident was causing hundreds of identical buildings in the UK being demolished [39]. Meanwhile, nobody was found to be directly responsible for either the explosion or the collapse [11].

4.8.2. Structural Information

Ronan Point was built using Larsen-Nielsen system, where prefabricated wall panels as load-bearing structure were stacked to minimize on-site construction work. Each floor was supported by the load-bearing walls directly beneath it. This mechanism became the only load path of the structure [18]. In this system, the joints have no reinforcement. The joint between components was designed to be filled with mortar as the glue [39]. When the Larsen–Nielsen system was developed, it was not intended to be used in buildings more than six floors high [11]. Moreover, at the time Ronan Point was erected, the building codes did not adequately address the system. It was claimed by the designer that Ronan Point would have a life expectancy of 60 years [18].

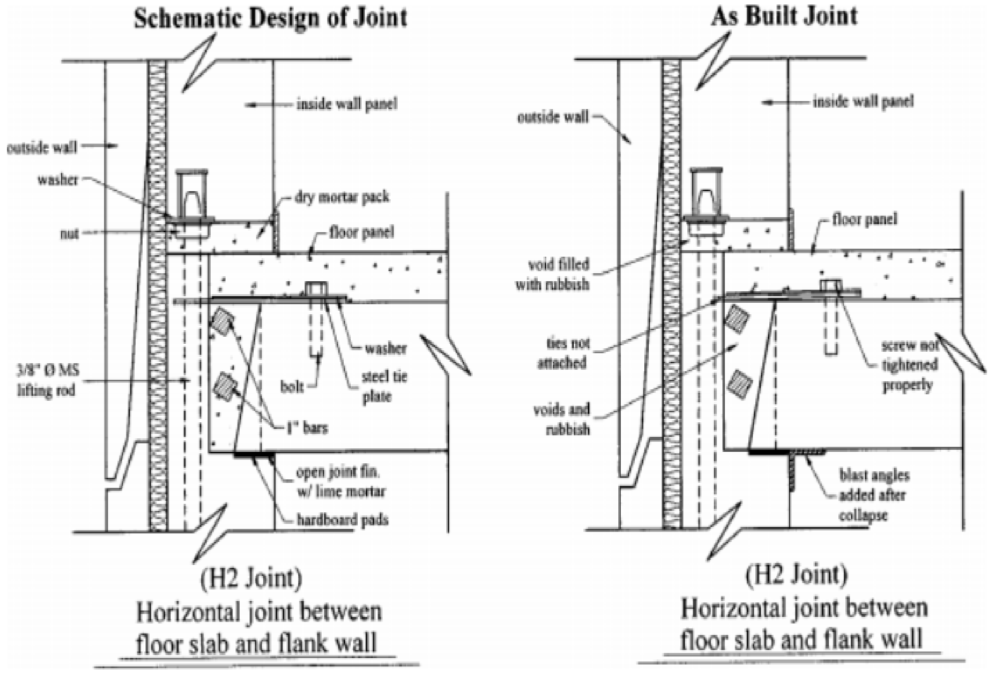

Figure 4.21: Comparison between designed (left) and as built (right) joint [18]

4.8.3. Failure Analysis

Following several investigations, it was concluded that the collapse of Ronan Point occurred due to the lack of structural redundancy. There was no structural frame, and no secondary load path provided by the structure (F4) [47]. The panels could easily be pushed out by horizontal force because the joints were not strengthened [39]. This characteristic might be the best explanation of why the system was intended for low rise building only (F6). In high rise building, the impact of horizontal loads such as wind or earthquake is magnified.

Moreover, the structure had been designed to comply with fifteen-year-old wind load codes that did not take into account the current (the 1960's) building heights [55]. Poor workmanship was also suspected, as some of the joints had less than fifty percent of the mortar specified (F2) [11]. There was a tendency to finish the project as quick as possible, generating as much profit as it could (F5) [11]. As nobody was found to be responsible for the collapse, the absence of a lead engineer is assumed for this failure case (F3).

4.8.4. Lessons Learned

The concerns over the structural integrity of existing building eventually led to the demolition of Ronan Point in May 1986 and other Larsen–Nielsen buildings in England [39]. The need for quality control in the construction process was reinforced, and the presence of full-time skilled supervisors at the construction site is strongly advised (M3) [18].

To ensure the safety of the structural system, the structural behaviour due to thermal expansion (such as in the event of a fire) need to be tested, and the connection between precast elements need to be physically verified (M4) [11]. Regarding organizational factor, it is suggested to have one party responsible for the overall stability of the structure, especially for such a 'hybrid' structures like Ronan Point (M2) [11].

4.8.5. Financial Information

There is no information regarding the failure cost. However, there were at least five cost components of failure found in the literature. Those are the monetary value of fatalities (C3), compensation for injured people (C4), reconstruction cost (C2), building material loss (C1), and indirect cost due to the demolition of other similar buildings. Finally, the cost of safety measures are modelling cost (I4), supervision during construction (I3), delay cost to supervise a fast project (I2), and additional material to increase robustness.

4.9. Case 9: Bos & Lommerplein, Amsterdam

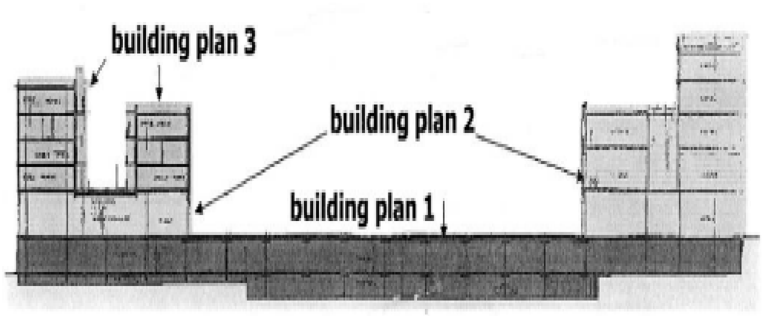

Figure 4.22: Building plan of Bos en Lommer complex [58]

4.9.1. General Information

The Bos & Lommer is a multifunction plaza in Amsterdam. The construction of the project started in 2001, finished in 2003, and officially delivered in 2004. Bos & Lommer was a complex project due to the various programs and its location in a busy area. It consists of 395 houses, 24,000 m^2 offices, 6,000m^2 central functions, 3,500m^2 socio-cultural amenities, and a two-stories parking lot for about 500 cars [58] [69]. The commercial programs (employment agency, travel agents, etc.) were planned for the ground floor of the building [66].

On 1 February 2006, there was an 11-ton truck went to the parking lot, initiating significant damage. A concrete half-joint underneath the deck as a part of the load-bearing structure had failed [27]. The area was evacuated for two days and occupied again after an immediate action was taken. However, in July 2006 this whole area had to be urgently cleared because its safety could not be guaranteed [58], and remained empty until December 2006. There was no casualty caused by this structural failure.

4.9.2. Structural Information

The building of Bos & Lommer has a total floor space of 20,000m^2 distributed over two buildings of six floors each of 9,000m^2 and 11,000m^2, respectively [66]. The grid size of the ground floor was different than the grid size of the upper programs. For retail shops on the ground floor, the grid size was 8.1m, while for the residential part on top was 5,4m [69]. The thickness of the failed floor was 1m, functioned as transfer floor.

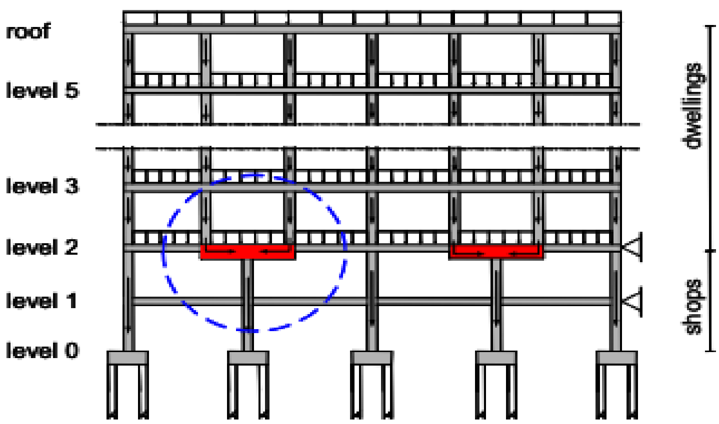

Figure 4.23: Structural scheme of the near collapse building in Bos en Lommerplein [58]

There were several changes to the programs, mainly due to the demand of the stakeholders. There were changes in the number of dwellings, increased from 52 to 77 to 96 in a relatively short time, and the shrunk of apartment breadth from 8.10m to 5.40m [58].

4.9.3. Failure Analysis

Figure 4.24: Structural failure of the parking lot [27]

The heavy truck caused 4cm of local deformation on the floor plate, and the struts under the concrete slabs also failed. Various shortcomings were identified and suspected due to the complex nature of the project. It was a high complexity project: there are a lot of programs, dynamic preparation, and situated in a dense urban area [57].

Multiple errors were recognized in the detailed design and execution of the structure. Load distribution was problematic due to the difference in grid sizes. The details in the reinforcement of concrete floor between the apartments and the shop were questionable [58]. A modelling error was likely to occur because a finite element program was not developed or commonly used at that time (F6) [69]. The amount of reinforcement was insufficient, and the placement has deviated (F2) [27]. Language problems (F1) might be the reason as the labours were foreigners with uncertified competency (F6) [69]. Communication problem between parties might happen as there were over 50 subcontractors involved during construction (F1). More importantly, there was no independent inspection either internally or externally (F2) [69].

Aside from the technical-related aspects, organizational problems were also suspected. Firstly, there was no common safety goal set for this project (F5). The allocation of responsibilities was unclear, as two developers were hiring three architects and two structural engineering firms (F3) [69]. Secondly, the market players were price oriented. They tried to avoid duplicate work (e.g., strength proofing), the structural engineers were selected by price instead of quality, and the board was adamant to appoint a senior coordinating consultant engineer (F5) [58]. Finally, on a higher level, the information which the plan assessors (mostly municipality) had at their disposal was usually incomplete [57]. Some of the mandatory reports were not submitted, and procedurally, the safety should not be guaranteed. Nevertheless, the building permit was still given.

4.9.4. Lessons Learned

The case of Bos & Lommer revealed the importance of quality organization within the project. As explained in the previous section, the root of technical problems was the procedural issues. In the two papers used as the reference for this study, suggestions to improve the organizational aspect were mentioned, summarized as follows:

- Construction safety: An analysis of systems failure, the case of the multifunctional Bos & Lommerplein estate, Amsterdam [58]:

  - Apply interface management, not only the quality of the components that need to be guaranteed but also how the elements and the tasks fit together (M1)
  - The employees should be adequately trained and have sufficient experience, proved with certification (M6)
  - Make the presence of coordinating structural engineer as a legal obligation for internal supervision (M3)

- Contributing human and organizational factors for damage of Bos & Lommer plaza in Amsterdam [69]
  - Building control by municipality should be improved
  - As finite element method was not prevalent at that time, checking by a different company experienced in projects with similar complexity or non-standard solution will help to guarantee the safety (M3)

4.9.5. Financial Information

The evacuation of the area cost the municipality over €8 million (C4) [58]. There is no other financial information found in the literature.

Aside from the evacuation cost, cost due to structural repair was also incurred (C2). The loss of economic activity due to evacuation were also present, but it is not within the scope of this study. Only the absence of the building rental income will be considered in the financial model.

Finally, to apply the safety measures suggested in the references, investments are necessary for conducting expert supervisions (I3), interface management (I1), delay cost due to supervision (I2), and the cost of hiring more competent reinforcing labour (I6).

4.10. Case 10: Amoco Tower, Chicago

Figure 4.25: Amoco Tower in Chicago suffered from façade problem. Credit: Chicago Architecture Info

4.10.1. General Information

Amoco Tower (now AON Centre) was the workspace for Amoco Corporation, a chemical and oil company. It was built in 1970 and opened in 1974. The building envelope was deteriorating severely in 1988 [39]. The façade bowed out up to 38mm and had a significant risk of falling [30]. No victim reported because safety responses were taken immediately after the sign of collapse was found. The cladding was designed using thin marble panels to save some money from a cheaper supporting structure. However, the saving from the use of thin marble was reported only less than 1% of the previously planned cost [39].

4.10.2. Structural Information

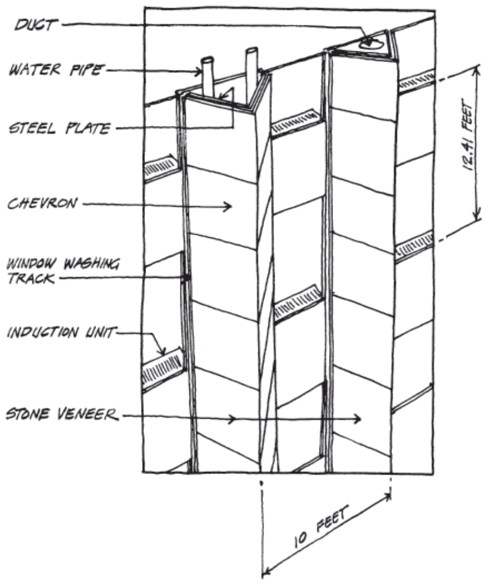

Figure 4.26: Structural scheme of the façade panels. [39]

Amoco Tower is an 80 stories building, 342m tall, stood on a square based of 57m. The façade was designed using thin marble panels to reduce the amount of required supporting steel structure, reducing the total building cost [39]. The designer created a tube structure instead of the commonly used steel frame structure.

The material for the façade itself was white Carrara marble. In total there were 43,000 panels of $1.27m \times 1.14m$ installed, with each panel had a thickness of 32-38mm [39]. The marble panels were failed within 14 years of service life, and the 125kg marble panels were taken off replaced by 180kg, 50mm thick pieces of granite [4]. Granite is proven to be less sensitive to chemical corrosion than marble.

4.10.3. Failure Analysis

Based on a test before construction, a minimum flexural strength of 9.65MPa and maximum 40% strength loss due to thermal cycling should be expected [40]. Investigations concluded that the maximum flexural strength of the installed panels was 7.5MPa, and the average was 5.24MPa. There was a significant difference between the samples and the installed panels (F2) [40].

In 1988, 30% of marbles were already bowed out by 13-38mm. Immediate action was taken to prevent collapse by bolting the panels to the load-bearing structure [39] and secured with stainless-steel straps [4].

Marble is sensitive to creep and shrinkage due to thermal load [30]. In Amoco Tower, thermal movement was prevented by semi-rigid bolt connection, resulting in extra stress to the façade. The major contributor to the failure was concluded as the use of inappropriate material for the thin façade (F6). The slenderness ratio of the façade was 138, way exceeding the upper boundary of 120 [39].

4.10.4. Lessons Learned

From this failure case, it can be learned that routine inspection might prevent a building from collapse. It is also essential to inspect the material samples throughout a big project (M5) [40]. Having a uniform quality of construction material is impossible. Therefore deviation of the designed properties must be taken into account. Moreover, the temperature effect on the material is often underestimated. In an exposed environment, slenderness and behaviour of the material under temperature change will determine the lifetime of a structure [39]. Modelling of long-term durability can be taken by performing a laboratory test to the material during the design phase (M4).

4.10.5. Financial Information

The façade problem in Amoco Tower was causing material loss (C1) and façade replacement cost (C2). The initial investment of the tower was reported to be $120 million, while the cost for façade restoration was $80 million [39]. No other information related to the value of loss found in the literature. Meanwhile, the safety measures incurred cost of sample testing cost (I5), and modelling cost (I4).

5
Results and Discussions

This chapter presents the elaboration of the results. First, the questionnaire respondents are explained. The contribution of critical factors, financial consequences, and the impact of safety factors are explored afterwards. This chapter is closed with the cash flow analysis. The contents of this chapter are answering the four Key Questions (Section 1.4). The case by case analysis can be found in Appendix B (Measures Simulation) and Appendix C (Financial Model).

5.1. Questionnaire Respondents

5.1.1. Occupation

The questionnaire targets construction experts, professionals, and construction management graduate students as the respondents. In total there were 31 respondents, and 28 (90%) had completed the questionnaire. The population is presented in Figure 5.1.

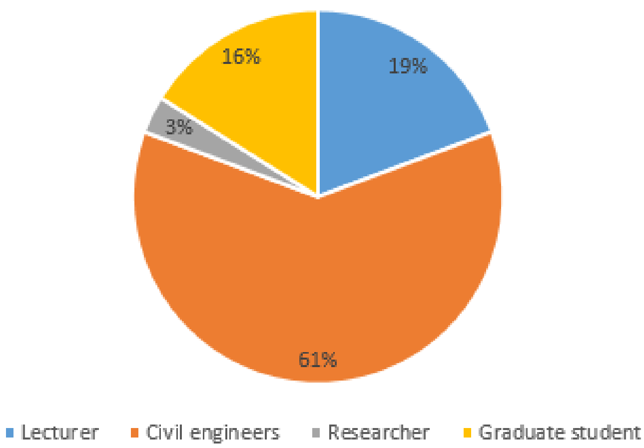

Figure 5.1: Occupation of the respondents

Nineteen (61%) respondents were professional civil engineers, seven (22%) were academics (lecturers and researcher), and five (16%) were graduate students. Based on the distribution of respondents, engineering judgements can be expected.

5.1.2. Academic Background

The academic background is a prominent factor to ensure the understanding of the respondents to the information provided in the questionnaire. The case description (Chapter 4) contains specific terms and analyses from the perspective of the construction field. Respondents with the background related to civil engineering are expected to grasp the substantial information provided in the questionnaire.

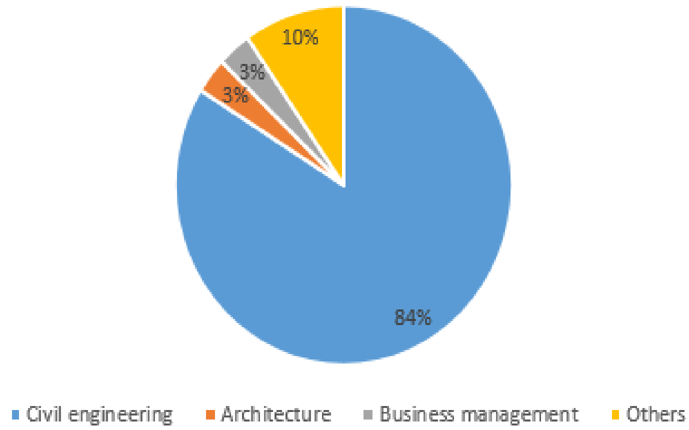

Figure 5.2: Academic background of the respondents

Twenty-six (84%) respondents studied civil engineering, one (3%) was from architecture, one (3%) studied business-management, and three (10%) were from other disciplines. The majority of the respondents held a master degree or higher, and all of the respondents were at least graduated from the undergraduate study (bachelor or equivalents). It can be expected that the respondents were able to give his/her engineering judgement in the questionnaire.

5.1.3. Experience

Experience in construction field might play a significant role to the quality of the engineering judgement. The experienced respondent is expected to have a better sense of the dynamics within a building project. However, due to the limited information provided in the questionnaire and the number of cases which need to be analysed in a short time, the importance of experience become less relevant.

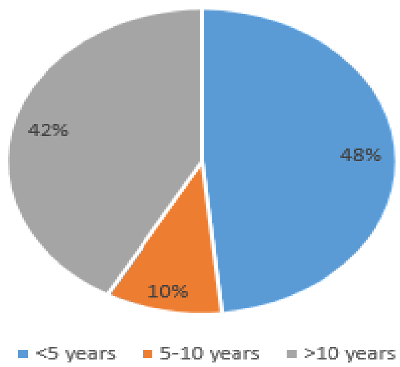

Figure 5.3: Years of experience in construction field

5.2. Weight of Critical Factors (α_f)

5.2.1. Questionnaire Result

The first part of the questionnaire is the weight quantification of the critical factors (α_f). Respondents are asked to give their judgement on a question *"To what extent did the absence of the critical factor (n) contribute to the failure?"*, depicted in 5-Point Likert Scale. The types of the critical factors absent are pre-described by the author based on the literature study (Section 3.4.3). The result is presented in Table 5.1. The finding of this section answers the Key Question 1: *"What are the organizational cause(s) of failure in the sample cases"*.

Table 5.1: Summary of weighting factors

Case	Contribution of factors (%)					
	F1	F2	F3	F4	F5	F6
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure
Berlin Congress Hall	32	35	-	34	-	-
Hyatt Regency	34	33	-	33	-	-
Ice Skating Hall Bad Reichenhall	-	32	-	34	-	34
Terminal 2E CDG Airport	25	25	-	25	-	25
Patio Sevilla	50	-	-	50	-	-
Hartford Civic Center	-	21	20	21	19	20
Kemper Arena	-	34	-	32	-	34
Ronan Point	-	21	20	21	18	21
Bos en Lommerplein	20	20	20	-	18	21
Amoco Tower	-	51	-	-	-	49

Figure 5.4 shows the average weight of critical factors for all ten cases, expressed in percentage of contribution. The detailed elaboration is presented in Appendix B.

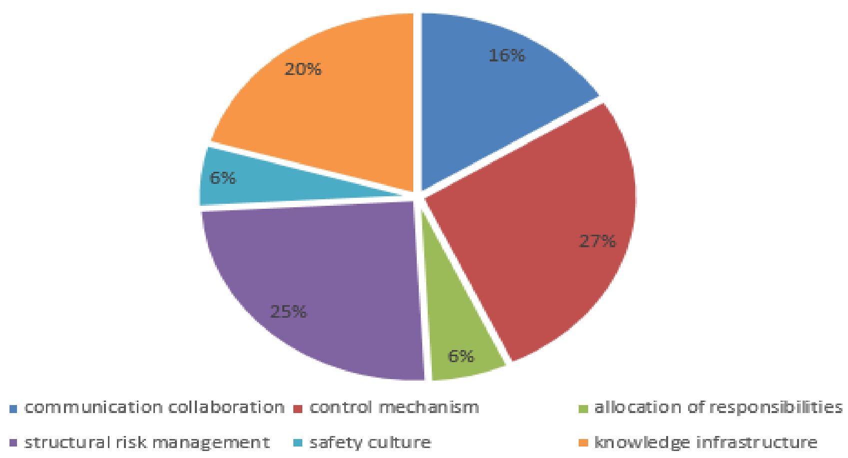

Figure 5.4: Weight of critical factors

5.2.2. Discussion

1. Communication and collaboration

   Five out of the ten cases had issues related to "Communication and collaboration". The problems regarding the informed consent principle became the highlight of this critical factor, especially when changes were made during construction. In projects with various stakeholders and subcontracts, this aspect occurred more often because the related parties worked individually rather than collaboratively.

2. Allocation of responsibilities

   Responsibility assignment and project planning are normally written in the contract. However, when the project is handled by multiple parties, a loophole of the agreement is likely to occur. The presence of a lead engineer or lead contractor is crucial regarding the legal aspect. These issues were suspected in three out of ten cases, making it the second least contributing factor.

3. Control mechanism

   The questionnaire result shows that the absence of ”Control mechanism” is the most dominant factor in building failure (27%). The absence of this factor observed in nine out of the ten cases (Table 4.1). Deviation from the approved design and the lack of reviewing activity were the forms of inadequate control mechanism within the failure cases. Activities related to ”control mechanism” is likely to consume time and money. Process like double-check was considered unnecessary by the stakeholders for the most of the cases.

4. Structural risk management

   Suspected in eight out of ten cases, ”Structural risk management” contributes 25% to the failure. Poor maintenance, inadequate design, and lack of adjustment as a response to design alteration or sign of failure were the forms of ”Structural risk management” in the study cases. The structural problems found were not unforeseen, some even recognized before the construction. Assuming the engineers were qualified, anticipation strategy should have been taken.

5. Safety culture

   The desire to save time and investment generated the contributing factor in three out of the ten samples. In one of the cases (Bos en Lommerplein, Section 4.9), the safety goal of the organization was questionable. The various cultural issues might also have occurred in other failure cases. However, there is no information found as such aspect is difficult to recognize and likely to be justified by the stakeholder to avoid the poor reputation [39].

6. Knowledge infrastructure

   The absence of sufficient ”Knowledge infrastructure” weigh 20% in overall, and observed in seven out of ten cases. The common issues were the application of unproven innovation or new technology. The engineers failed to recognize the effect of applying the concept to specific building design.

The six critical factors used in this study are taken from the research by Terwel (2014) [70]. Table 5.2 shows the ranking comparison between the questionnaire result of this study and the research by Terwel (2014) for *”less successful”* projects. In the *”less successful”* projects, the damage was either present or the structure was possibly unreliable without necessarily resulting in damage [70]. Meanwhile, the samples for this study are limited to collapse and near collapse incidents, the most severe form of failure.

Table 5.2: Comparison of the critical factors ranking

Ranking	Critical factors in less successful projects [70]	Critical factors in sample cases
1	Communication and collaboration	Control mechanism
2	Allocation of responsibilities	Structural risk management
3	Safety culture	Knowledge infrastructure
4	Knowledge infrastructure	Communication and collaboration
5	Control mechanism	Allocation of responsibilities
6	Structural risk management	Safety culture

From Table 5.2, it can be observed that the influence of the critical factors in less successful projects is not the same as their influence to the failure cases of this study. The top-ranked factors in the less successful projects such as ”Communication and collaboration” and ”Allocation of responsibilities” did not have a significant contribution to the building failure in the case study, with only 16% and 6% respectively. On the other hand, even though the impact of ”Control mechanism” and ”Structural risk management” are considered the lowest in less successful projects, the absence of these factors had a notable influence in the ten samples used for this research.

Three possible factors are suspected to cause the differences between the result of the two studies. First is the set-up of the questionnaire. In this research, the respondents only give their judgements to the pre-described factors. Meanwhile, in the previous study by Terwel (2014), the respondents were asked to rate the presence of all listed factors. Hence, the respondents had more freedom to give their judgement in the past study by Terwel. Second, the samples in this research are cases where the Ultimate Limit State was exceeded. There might be differences in the engineer’s perception of the factors influencing ULS failure and the factors influencing SLS failure. Third, the knowledge level of the respondents in the study by Terwel is arguably better than the respondents for this study. The respondents in the firstly-mentioned study were those who directly involved in the Dutch building industry, and the sample cases were taken from the Dutch building industry as well. Therefore, it can be expected that the respondents were able to provide a more accurate judgement than those of this study.

Among the six critical factors, the execution of ”Control mechanism” needs to be improved. Although it is recognized as a salient aspect of structural safety, the lack of control is still suspected in nine out of ten cases. Minimizing construction time or initial investment became the two main reasons why controlling activities were left out in the failure cases.

5.2.3. Result Limitation

The quantitative analysis of the weight of critical factor has the following limitations:

- Building failure is the result of cumulative defects and errors, both in construction and life service. There might be factors which are not recognized or identified within the six critical factors used for this research.

- This research relies on secondary data from investigations report. The limited knowledge of the cases and the bias in transfer information are possible to occur. The questionnaire respondents received at least the ”second-hand” information.

- The failure cases are taken from various countries and various era. The macro factors might have a more significant influence than the meso factors, while this aspect is not within the scope of the study.

- Subjectivity is inevitable. Firstly, the categorization of the critical factors is based on the author’s interpretation. Secondly, the respondents give their judgement using the limited information provided in the questionnaire. The questionnaire is containing essential information about failure cases, which is summarized by the author of this thesis. Nevertheless, since there is no statistical data related to the weight of factor, subjectivity is considered acceptable.

- The average results of the questionnaire do not show one dominant factor. This fact is the main shortcoming of a survey using the 5-Point Likert scale because respondents have the desire not be seen to give what they perceive as a socially unacceptable answer [26]. Intermediate scores (2, 3, and 4) appeared more often than absolute scores (1 and 5). The knowledge level of the respondents might also influence their decision to be on the safe side.

5.3. Financial Consequences of the Failure (C)

5.3.1. Summary

Four cost components due to the building failure are examined in this thesis. Those are ”material loss (C1)”, ”reconstruction cost (C2)”, ”loss of human life (C3)”, and ”compensation cost (C4)” (Section 3.3.3). The method and assumptions used to calculate the total financial consequences are presented in Section 3.4.2. The summary for the ten cases is shown in Table 5.3. The elaboration of the failure costs are presented in Appendix B. The finding of this section is answering the Key Question 2: *”How much is the cost incurred due to the building failure?”*.

Table 5.3: Comparison between the failure cost and investment

Case	Failure cost	Investment	Percentage
Case 1: Berlin Congreshall	€ 6,853,758	€ 6,379,710	107%
Case 2: Hyatt Regency	€ 790,777,772	€ 72,728,842	1087%
Case 3: Ice Hall Bad Reichenhall	€ 76,804,928	€ 9,672,432	794%
Case 4: Paris Airport	€ 400,698,484	€ 1,168,475,562	34%
Case 5: Patio Sevilla	€ 10,916,972	€ 1,226,781	890%
Case 6: Hartford Civic Centre	€ 15,504,543	€ 113,447,875	14%
Case 7: Kemper Arena	€ 23,175,341	€ 87,733,024	26%
Case 8: Ronan Point	€ 35,414,287	€ 13,432,317	264%
Case 9: Bos en Lommerplein	€ 12,773,371	€ 22,513,474	57%
Case 10: Amoco Tower	€ 262,791,426	€ 440,574,273	60%

The percentage of the failure cost relative to the initial investment, including the contribution of each component is depicted in Figure 5.5.

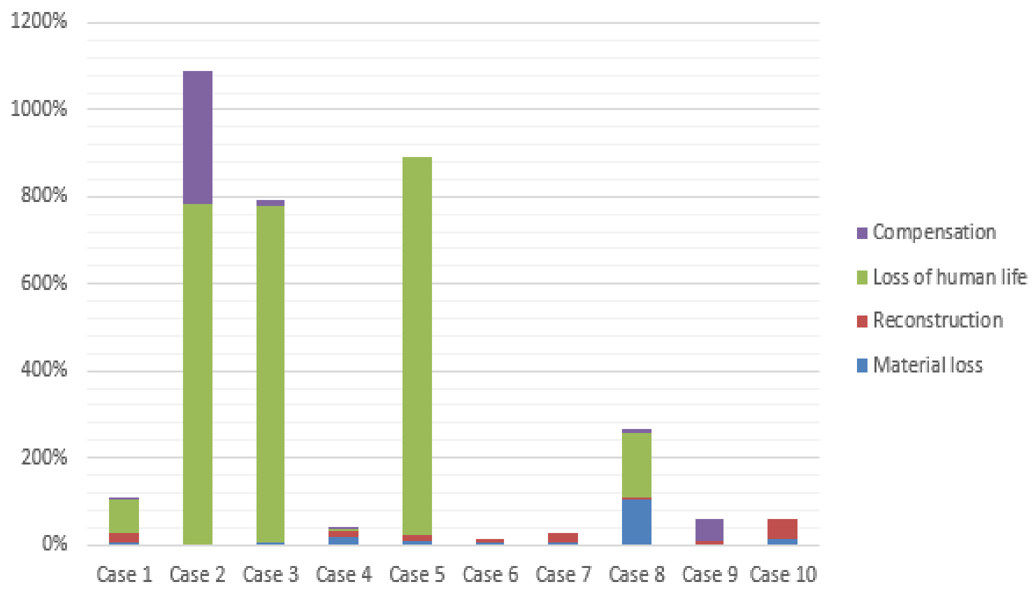

Figure 5.5: Contribution of the cost components to the overall loss

5.3.2. Discussion

On average, building failure incurred a cost of 333% of the investment. The extreme maximum value occurred in Case 2: Hyatt Regency, with the financial consequence of 1087% investment. Meanwhile, the failure in Case 6: Hartford Civic Centre resulted in the minimum failure cost of 14%.

The substantial difference between the two cases is the number of casualties. There were 114 people died in the case of Hyatt Regency, and a considerable amount of compensation was paid to the injured. On the other hand, the roof collapse in Hartford Civic Centre did not injure or kill anyone. To assess the distribution of the failure consequences, the percentage of each cost component (Section 3.3.3) making up the total cost for every failure case is calculated. The result is presented in Table 5.4.

Table 5.4: Contribution of the cost components to the case by case failure consequences

Case	Contribution of cost components (%)			
	C1	C2	C3	C4
	Material loss	Reconstruction	Loss of human life	Compensation
Berlin Congress Hall	5	18	73	4
Hyatt Regency	0	0	72	28
Ice Skating Hall Bad Reichenhall	0	-	98	2
Terminal 2E CDG Airport	58	37	5	0
Patio Sevilla	1	1	98	-
Hartford Civic Center	44	56	-	-
Kemper Arena	23	77	-	-
Ronan Point	40	2	56	2
Bos en Lommerplein	-	13	-	87
Amoco Tower	26	74	-	-

The value shown above is rounded into integers. The value of ”0” indicates that the contribution of the associated component is meagre, while ”-” means that the respective cost component did not present in the failure case. The average contribution of the four cost components to the failure consequences (C) is presented in Figure 5.6.

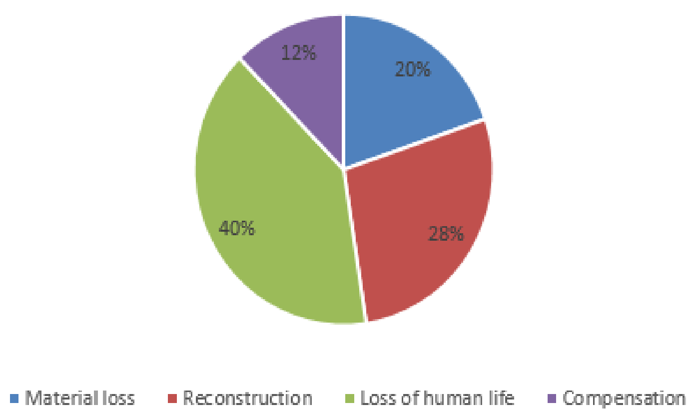

Figure 5.6: Distribution of the cost components to the financial consequences

From the data above, it is observed that ”Loss of human life” (C3) is the most determining factor. The unit cost of this component is much higher than the others and therefore gives a significant contribution. Figure 5.5 shows that when the failure resulted in fatalities, ”Loss of human life” (green coloured bar) always became the dominant contributor.

A notable finding is found within the value of ”Reconstruction” and ”Material loss”. Rebuilding activity (28%) costs more than the value of the building part which collapsed (12%). Saving in the initial investment could end up costly if the building had collapsed. Once the failure occurs, the repair work is also done to the other part of the building, and often redesign needs to be taken. These aspects might be the source of the spending in ”Reconstruction”.

5.3.3. Result Limitation

The calculation result of the ”Financial consequences” (C) has the following limitations:

- The cost unit is determined based on the assumptions derived from the various references. The assumed values are generalized and might not represent the real cash-flow incurred in the sample cases. Nevertheless, considering the Research scope (Section 1.5) and Research Limitations (Section 2.2), the shortcomings are acceptable.

- The assumptions for the cost of fatalities and compensation for the injured are questionable. There will be no certain monetary number able compensate a loss of human life. The value taken is only intended for the financial model.

- Non-safety related economic costs are not included in the calculation. Such loss might be more significant than the direct cost incurred in a failure case.

5.4. Impact of Safety Measures

5.4.1. Questionnaire Result

The impact of safety measures is quantitatively assessed using the engineering judgement given by respondents. In the questionnaire, the respondents are expected to provide their answer to the question *”To what extent does (safety measure N) might overcome the absence of (critical factor F)?”* using the 5-Point Likert Scale (Section 3.4.3).

The percentage of probability reduction impact (γ_n) is calculated using Formula 3.4. The value of γ_n becomes the input to calculate ”The Weighted Probability ($P_{w,n}$)” using Formula 3.5. Finally, ”The Weighted Risk ($R_{w,n}$)” is calculated using Formula 3.3. ”The Weighted Risk” is taken as an annual negative cash-flow in the Financial Model for the scenarios with measure (Formula 3.8).

Table 5.5 shows the impact of safety measure on the ten cases, presented in the percentage of failure probability reduction (γ_n). The detailed calculation is given in Appendix B.

Table 5.5: Summary of the failure probability reduction impact

Case	Safety measures					
	M1	M2	M3	M4	M5	M6
	Integrated coordination	Planning and responsibility	Supervision	Structural modeling	Survey and inspection	Employees competency
Berlin Congress Hall	-	73	-	74	74	-
Hyatt Regency	75	73	77	-	-	-
Ice Skating Hall Bad Reichenhall	-	-	-	75	78	-
Terminal 2E CDG Airport	-	-	75	73	-	-
Patio Sevilla	78	-	75	70	-	-
Hartford Civic Center	-	73	75	70	-	-
Kemper Arena	-	-	75	76	74	-
Ronan Point	-	76	77	75	-	-
Bos en Lommerplein	74	-	76	-	-	73
Amoco Tower	-	-	-	77	76	-

Figure 5.7 shows the overall result of the failure probability reduction for every safety measure. The value is obtained by averaging the result in Table 5.5. The finding of this section is answering the Key Question 3: *"How much is the impact of taking a certain safety measure regarding the failure probability?"*

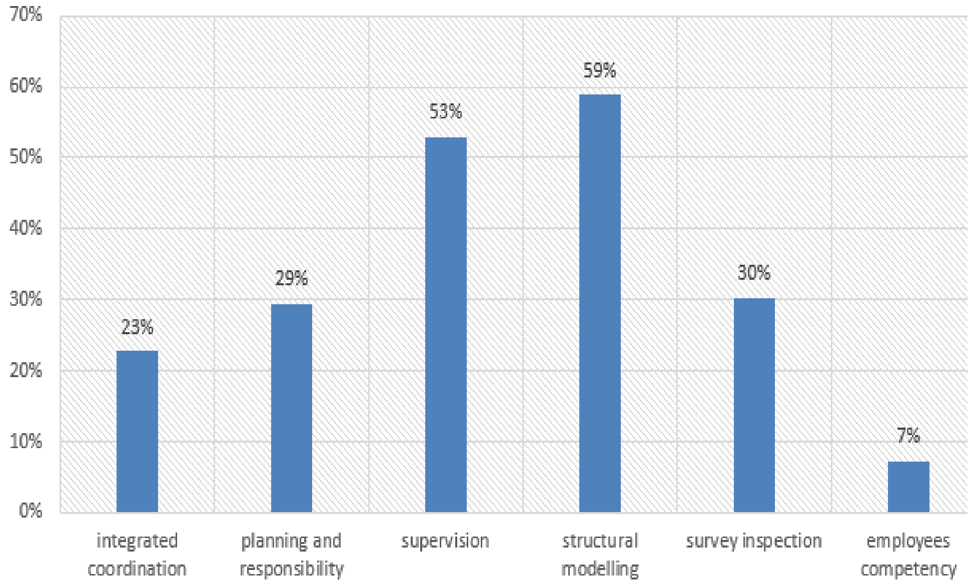

Figure 5.7: Risk reduction impact of safety measure

5.4.2. Discussion

1. Integrated coordination

There are five cases where ”Communication and collaboration” became the issue, but ”Integrated coordination” is only suggested for three of them. One hypothesis is because the failure might be prevented by taking more strategic measures, such as ”Structural modelling” or ”Supervision”.

2. Planning and responsibility

   The implementations of ”Planning and responsibility” for the four failure cases are varying, from the allocation of extra time to contract unification. Although the measure is specific, it underlines the importance of a reasonable task assignment in the project. Detailed project management is also helpful for the legal settlement in the case of failure.

3. Supervision

   Proposed for seven failure cases, ”Supervision” in the form of external checking, internal review, and the presence of superintendents are necessary to prevent intended and unintended errors during construction, to make sure the compliance of legal regulations, and to assess the reliability of the design. In five of the seven cases, ”Supervision” is rated as the most efficient measure by the respondents.

4. Structural modelling

   ”Structural modelling” in the form of physical or computational is suggested for eight out of the ten failure cases. By developing a model, structural behaviour can be evaluated, as well as minimizing failure probability due to the cumulative error in various factors. The multidimensional impact of performing ”Structural modelling” makes it arguably the most reliable safety measure. The current development of Building Information Modelling is supporting the application of this measure in the construction industry.

5. Survey-inspection

   ”Survey-inspection” becomes the relevant solution to prevent degradation related failure in the lifetime of the building. This sustainability aspect might not be the case for the four failure cases as the buildings are built before the 1980s, before the idea to implement safety measures was raised (Section 1.2). The current trend of ”Design-Build-Operation-Maintenance” in the construction contract is one of the distinct response to the problem in the past. The sample cases built in the later era might have implemented this type of contract, and therefore this measure is less relevant.

6. Employees competency

   It is assumed that building actors complied with qualification requirements for such big projects unless mentioned otherwise in the literature. However, it does not diminish the possibility that in other cases the competence of the employees was not flawless. ”Employees competency” is proposed only for the case of Bos en Lommerplein because the issue related to labour skill was raised (Section 4.9).

5.4.3. Result Limitation

The quantitative analysis of the safety measures impact has the following limitations:

- There is no statistical data regarding the effect of safety measures on the overall safety level because failure is an exceptional event.

- When there is no statistical data available, quantitative analysis of the safety measure impact should include calibration for the uncertainties. Conducting full probabilistic analysis is beyond the boundaries of this study. One alternative is by performing a qualitative analysis to assess the non-dimensional aspects.

- The calculation formula of the weighted failure probability ($P_{w,n}$) is not specific, as it uses a general assumption of ($P_{w,0}$)=10^{-4} per year in Formula 3.5. The value is taken due to the absence of statistical data. In reality, the occurrence probability of the incident which triggers the failure is varying.

- Similar to the limitation of the "Weight of Factors" (Section 5.2.3), subjectivity is inevitable. The phenomenon of social desirability bias is observed more clearly in this second part of the questionnaire. The risk reduction impact for all types of measures is around 70%. The absence of knowledge is considered more significant for the second part of the questionnaire. While the contributing factors are based on interpreted factual information, the impact of safety measure is hypothetical. Moreover, the type of safety measure assessed is pre-described by the author. Respondents prefer to give intermediate scores for the thing that is uncertain, or they are unsure about [26].

- One scenario represents the implementation of one safety measure. The interdependency and the possibility of overlapping between measures are not taken into account. In practice, it is possible that the best solution comes from the combination of various measures as one scenario.

5.5. Financial Analysis

5.5.1. Profitability Index of Safety Measures

The quantification of safety measures impact (Section 5.4) results in "The Weighted Risk ($R_{w,n}$)" for every scenario. The weighted risk is taken into account as an annual expenditure to compensate for the probability of failure during the service. The financial model is developed using the method in Section 3.5. The case by case analyses can be found in Appendix C.

The financial impact of safety measures is expressed as Profitability Index (Section 3.5.3). The findings are answering Key Question 4: *"How much is the benefit of applying the procedural safety measures?"*, and subsequently the Main Research Question *"What is the most financially beneficial procedural safety measure based on the case studies?"* can be solved. Figure 5.8 shows the average value of the Profitability Index of the ten sample cases.

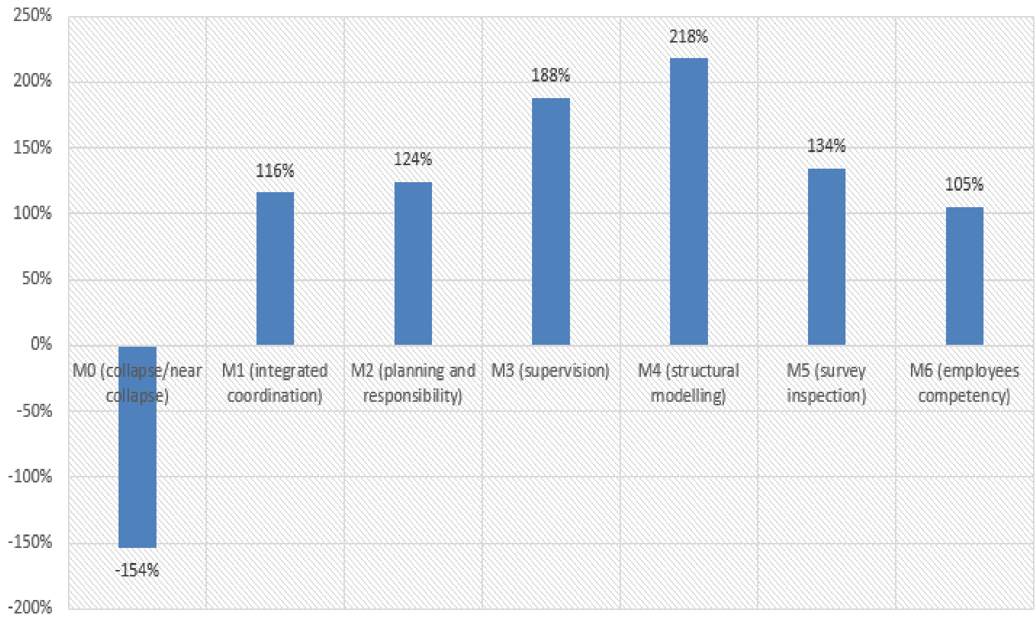

Figure 5.8: Overall Profitability Index of the safety measures

5.5.2. Discussion

According to the rule of Profitability Index (Section 2.1.3 and Section 3.5.3), the investment in all safety measures is acceptable because the Profitability Index is higher than 100%. Meanwhile, for the scenario without measure, the average deficit is more than 1.5 times of the investment.

The main contributor of the financial loss is the presence of fatalities. The case of Kemper Arena (where the roof collapsed, but no death was found) resulted in a loss of only 4% after 30 years (Appendix C.7). Meanwhile, in the case of Hyatt Regency (114 fatalities), the loss is estimated at 1130% by the end of the assessment period (Appendix C.2). The value is considered extreme compared to the project investment. As an additional comparison, if the 114 victims were injured instead of being killed in the Hyatt Regency walkways incident, the financial loss after 30 years is only 192% (Appendix C.11, Figure C.48). This additional scenario emphasises the significant influence of ”loss of human life” in the financial analysis.

For such a new project, it is not known whether the absence of safety measures will lead to failure or not. However, the project still has to bear the risk of failure. An additional scenario applied to the case of Hyatt Regency (Appendix C.11) gives the first insight regarding the benefit of safety measures, providing the failure did not occur. The yearly weighted risk (R_w) is taken as an expenditure to compensate for the probability of collapse. The result shows that the implementation of particular safety measures (”Integrated coordination” and ”Planning and responsibility”) gives slightly higher profit than the scenario when safety measure is left out in this additional analysis (Appendix C.11, Figure C.49). Meanwhile, the implementation of ”Supervision” gives a profit of 10% lower than the scenario without measure. The investment required to perform ”Supervision” is higher than the weighted risk for Additional Scenario 0 (without measure), resulting in a lower NPV after 30 years.

Finally, since this thesis is focused on learning from failure, the comparison of the safety measure scenarios with the successful project is not elaborated further.

1. Integrated coordination

   The implementation of ”Integrated coordination” requires investment in CIMS (Construction Information Management Systems) to purchase devices, software, and arrange training for the employees to operate the program [78]. The cost incurred before the construction and assumed not affected by the value of the project. Therefore, the benefit is higher when it is implemented in such big projects. In the small scale residential building Patio Sevilla ”Integrated Coordination” resulted in a profit of 11% (Appendix C.5). Meanwhile in the commercial hotel Hyatt Regency the same measure can generate a profit of 83% (Appendix C.2).

2. Planning and responsibility

   The implementations of ”Planning and responsibility” regarding choosing contract system and responsibility assignment are assumed costless. Meanwhile, the allocation of longer construction time incurred ”Time delay” cost (C2). However, those assumptions need to be proven. In reality, activities such as administration work and consultancy are likely to incurred direct and indirect cost.

3. Supervision

   Suggested for seven failure cases, ”Supervision” incurred additional budget to hire superintendents during the building process. For the fast-track projects, it is also assumed to generate ”Time delay” cost. Although it is ranked overall as the second most beneficial measure, ”Supervision” requires a significant amount of investment due to the extended project duration. In the six out of seven cases where ”Supervision” is implemented, the profits gained are the lowest compared to the other suggested measure for the respective case (Appendix C).

4. Structural modelling

   ”Structural modelling” is implemented in eight cases, and becomes the most beneficial measure in six of them. As the most efficient and beneficial safety measure, developing a structural model is a strategic decision in construction risk management. One thing to consider is that in practice, the cost to perform structural modelling (computational model, mock-up testing, or sample testing) depends on the type of test, scale, and specification. The deviation from the assumed value used in this research is likely to be significant.

5. Survey-inspection

   ”Survey-inspection” might incur cost prior to building life service, during life service, or even both, depending on the specific form of implementation (See Chapter 4). The accumulation of repetitive expenditure (such as extensive performance inspection) makes ”Survey-inspection” the least profitable measure in the four cases where it is proposed.

6. Employees competency

   ”Employees competency” is proposed only for Case 9: Bos en Lommerplein. In the case of Bos en Lommerplein, the labour quality for reinforcement work becomes the actual shortage within the project. The profit gained from this measure in Case 9 is 54%, ranked second out of the three proposed measures. The type of employment determines the investment required for this measure. The expenditure is directly proportional to the level of the job.

In comparison with the impact of measures in terms of risk reduction (Section 5.4), it can be observed that effectiveness of measure is in correlation with the overall financial benefit (Table 5.6).

Table 5.6: Comparison between the efficiency of safety measure and the benefit of safety measure

Ranking	Efficiency ranking of the safety measures	Benefit ranking of the safety measure
1	Structural modelling	Structural modelling
2	Supervision	Supervision
3	Survey inspection	Survey inspection
4	Planning responsibility	Planning responsibility
5	Integrated coordination	Integrated coordination
6	Employees competency	Employees competency

However, the correlation between efficiency and benefit is not always the case in every sample (See Appendix B and Appendix C). For example in Case 2: Hyatt Regency, ”Supervision” (M3) becomes the best measure in terms of failure probability reduction with γ_n of 77% (Appendix B.2), while the most beneficial measure is ”Integrated coordination” (M1) with a profit of 83% (Appendix C.2). This fact happened because the price of the additional investment (C_m) is not always proportional to the magnitude of the project. Several parameters of the additional investment are relative to the project value, while some others are assumed constant. The ”Supervision” in the case of Hyatt Regency incurred ”Time Delay” cost (I2) which accounts for 1% of total project value per month [36] (Section 3.5). Meanwhile, the implementation of ”Integrated Coordination” is not affected by the project value [78], and therefore the amount of additional investment (C_m) is considered very low compared to the initial investment (C_0) of the project.

Regarding the sensitivity analysis, the change of interest rate gives the largest impact on the result of the financial analysis for safety measure scenarios. All the project are analysed using the principle of Net Present Value in 2018 €(Section 2.2.3). The older the building, the project is exposed to the interest rate for a longer time. Subsequently, the change of value is more significant. Figure 5.9 shows the influence of the sensitivity parameters to the profit/loss analysis of the scenarios in Case 2: Hyatt Regency. The detailed elaboration for the ten sample cases is presented in Appendix C.

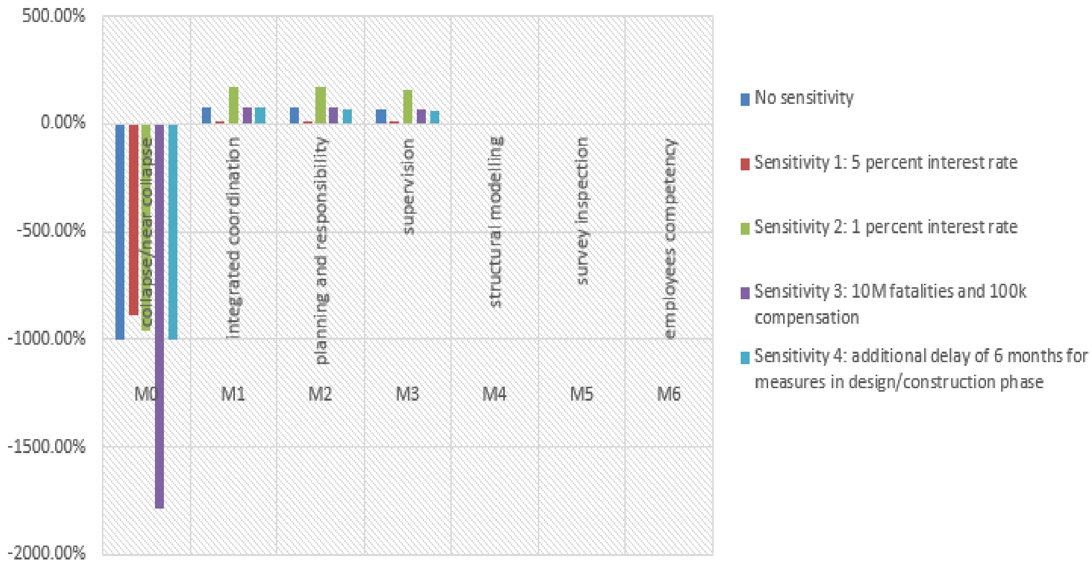

Figure 5.9: Impact of sensitivity to the profit/loss analysis in Case 2: Hyatt Regency

5.5.3. Result Limitation

The result of the cash flow analysis has the following limitation:

- The assessment is done by conducting an extended cash-flow analysis. Cash-flow analysis is the lowest level of project financial assessment. The intangible economic aspects which are excluded in the calculation might play a dominant role within the decision-making process, especially for the infrastructure buildings.
- Every aspect in this study is quantitatively expressed in monetary value, while in practice some of the components are not commonly valued in currency unit, if not injustice. For example, putting a price tag on the statistical value of human life is debatable.
- The cost unit used in the financial model is generalized for all of the cases. The revenue is assumed constant throughout the life service. In practice, the cash flow of a building as an asset fluctuates over time and influenced by the macroeconomic factors.
- The inclusion of ”The Weighted Risk ($R_{w,n}$)” into the model as negative cash flow is questionable because ”Risk” is an imaginary expenditure. In principle, the cash-flow analysis should only include the factual and expected financial elements. However, if the risk is excluded, the financial model assumes that the chance of failure is 0. This fact is not the case in this study, and the determination regarding the benefit of safety measure will be solely based on the additional investment (C_m) rather than the impact of the investment in the long-term period.

6

Conclusions and Recommendations

The goal of this research is to determine the most financially beneficial safety measure to prevent building failure. The findings of the four Key Questions are summarized in Section 6.1.1, after which the conclusion of the Main Research Question is presented in Section 6.1.2. Finally, the recommendation for building industry is listed in Section 6.2.1 and suggestions for future research are given in Section 6.2.2.

6.1. Conclusions

6.1.1. Findings of Key Questions

Key Question 1: What are the organizational cause(s) of failure in the sample cases?
Among the six critical factors assessed in this research, ”Control mechanism” is considered the most contributing factor based on the questionnaire result. Issues related to ”Structural risk management”, ”Knowledge Infrastructure”, and ”Communication and Collaboration” are also substantial. Meanwhile, the shortcomings in ”Allocation of Responsibilities” and ”Safety culture” are relatively insignificant in the failure cases.

Key Question 2: How much is the cost incurred due to the building failure?
The failure of sample buildings incurred an average financial consequence of more than three times the investment (333%). The main contributor is the presence of fatalities, making up 40% of the cost. In the case of the Hyatt Regency, the failure cost is more than ten times the investment, with more than 90% of the cost is due to the fatalities. However, the amount of the loss depends on the assumptions taken in the model. It is important to note that in practice not every loss can be expressed as an exact monetary value.

Key Question 3: How much is the impact of taking a certain safety measure regarding the failure probability?
Among the six types of safety measure proposed in this research, in average ”Structural modelling” is the most efficient as it might reduce the failure probability by up to 59%. ”Supervision” also has a significant impact by reduction of 53%. ”Survey inspection” (30%), ”Planning and responsibility” (30%), and ”Integrated coordination” (23%) are following at number three, four, and five respectively. Meanwhile ”Employees competency” has the least influence among the others.

Key Question 4: How much is the benefit of applying the procedural safety measures?
The financial benefit is correlated with the impact of safety measure, with ”Structural modelling” as the most beneficial and ”Supervision” as the second-most beneficial. In average, implementing procedural safety measures results in the Profitability Index of 147%. As a comparison, the Profitability Index of the actual collapse scenario is -154%.

6.1.2. Conclusion of The Main Research Question

From the findings of the four Key Questions, a general conclusion to the Main Research Question *”What is the most financially beneficial procedural safety measure based on the case studies?”* can be derived:

Overall, ”Structural modelling” is the most beneficial type of safety measure regarding the organizational issues within the construction project. By performing ”Structural modelling”, the errors of various aspects can be recognized, and the probability of failure can economically be reduced.

In this study, ”Structural modelling” is referred to two types of developing a model: construct and test to the physical model, and analysis of the computational model. The unit cost of each type of model is specified in Section 3.5. However, the implementation of ”Structural modelling” does not always give the highest profit in every sample case where it is proposed. The investment to implement ”Structural modelling” is relative to the project value, while for some other measures the investment is assumed constant regardless of the project value (Section 5.5.2).

6.2. Recommendations

6.2.1. Recommendations for Building Industry

The lessons learned from the building failure cases become valuable parameters regarding financial consideration when it comes to decision-making. The models in this study are developed using real examples of building failure and reasonable estimations of the cost components based on scientific studies. The point of interest lies in the difference between the actual and the safety scenarios instead of the exact value of the result.

The similar analysis procedure, but in a more sophisticated way, is also commonly performed for the assessment of a new project. The financial analysis is generated using the combination of estimation from experience, economic forecast, and estimated future risk. Therefore, it can be expected that the findings of this study might help building actors in the decision-making process. Derived from the outcome of this study, the recommendations are listed as follows:

1. Pay more attention to the control mechanism

   The lack of control is the most critical factor within organizational issues. Even though it is recognized as an important aspect within a project, deficiencies still found. Independent external control is one of the reliable solutions, and internal peer review becomes the alternative.

2. Avoid the application of unproven innovation

   The presence of the factor ”Knowledge infrastructure” in building failure is mainly caused by the use of new techniques without recognizing the consequence of the implementation. The design of one structure does not always appropriate for the other project. Differences in the complexity level, size, hazard, and available resources should be recognized beforehand. Adjustment and testing are necessary. Based on this study, additional investment to perform structural modelling prior to the construction is considered the most beneficial and efficient to reduce the risk of failure.

3. Focus on the life cycle cost

   The saving in the initial investment does not guarantee the project will gain benefit after the specific life service. With the current trend of Design-Built-Operation-Maintenance contract, it is wise for the structural engineers to consider the long-term effect of the design. Field of building technology already implement the life cycle costing concept in the design of building envelope proved with sustainability certification.

4. Consider investing in procedural safety measures

   The financial consequence due to building collapse is enormous. However, the probability of failure can be reduced by taking procedural safety measures. The safety measures might overcome the organizational problems within the project, and therefore minimizing the accumulated human error. The model shows that the investment of safety measures is only adding a little bit of the total project cost, but the impact is positive. For a successful project, the implementation of particular safety measures is still expected to give a financial benefit, based on the additional assessment performed in this thesis.

5. Structural modelling as the definite option

   There are two kinds of "Structural modelling" suggested in this study. Those are computational and physical modelling. The aim of developing a model is to assess the performance of the design or building materials.

   Computational modelling is commonly applied in the modern building using the structural analysis programs such as *"Etabs"* or "SAP2000". Nevertheless, such program is focused on the structural calculation only. Nowadays, the demand for structural design is increasing as the building requirements for sustainability, building physics, aesthetics, and building functions are getting more complex. Various specialists are involved in the project, each with his/her own tasks, interest, and knowledge. The main challenge for civil engineers is to integrate all those aspects to produce a structurally safe building which fulfils the required functional performance.

   One of the strategic solutions is to apply *"Building Information Modelling"* (BIM) in the project. In this context, BIM is a tool to produce a comprehensive model of architectural, building services, building physics, and structural analysis. With a program such as *"Rhino-Grasshopper"*, various aspects can be combined and analysed in a single parametric virtual model using plug-ins. For civil engineers, *"Oasys GSA"* is one of the useful structural analysis plug-ins that can be added to the model in *"Rhino-Grasshopper"*. The main advantage of a parametric model is the automatic adjustment of the optimum solution to maintain a previously established relationship between components [5]. The application of BIM is not limited to new projects. Model for existing building can also be developed as an investment to the future repair or maintenance.

   The sophisticated BIM is currently under intensive research and development by the time this report was made (2018). Therefore, the conventional physical model is still relevant to the current building industry. Either test of mock-up model or full-scale building component is expected to be a reliable proof regarding the behaviour of the structure. One main drawback of physical modelling is the cost to create the specimens, as it requires investment in material, human resources, equipment, and time. However, this study shows that the investment to perform "Structural modelling" gives the most benefit than the other safety measures, and more importantly, it is expected to reduce the failure probability due to human/organizational error in the project.

6.2.2. Recommendations for Future Research

This research is one of the initial integrative studies of forensic engineering, construction management, and financial engineering. The results are obtained from the simple financial model and contain limitations as mentioned in Chapter 5. The result might not exactly represent a specific project. There are rooms for improvement in this study. Recommendations for the future research of the similar field are listed as follows:

1. Focus on one type of building

   The sample cases in this research are of various kinds of building, from dwellings to an airport terminal. With the principle of generalization in cost unit, the preciseness of some monetary values are questionable. For example, the supervisor's fee for Paris Airport should be much higher than in the apartment project in Maastricht. Analysing the similar type of building gives a more fair comparison.

2. Learn from successful projects

   Collapse does not occur frequently. On the other hand, minor failure in a building will not gain public interest. Therefore, the available references are limited. However, actors in the unsuccessful projects tend to conceal the mistakes, on contrary to those involved in a successful project. Primary data regarding the organizational factors within a project is more likely to be obtained. By analysing the first-hand information, the drawbacks of this research such as the bias in information transfer and the limited knowledge of the respondents can be minimized.

3. Study the cost variables to develop a structural model

   In this thesis, it is concluded that "Structural modelling" is the most beneficial type of safety measure. However, the unit costs for the two kinds of implementation (computational and physical modelling) are generalized (Section 3.5.1). The price of a model highly depends on the level of detail, size, and the level of analysis. Considering the importance of "Structural modelling", it is suggested to improve the unit cost into a more specific value. One of the methods to determine the rate of developing particular structural model is by conducting interview with professionals in this field. If possible, analysing the database of previous modelling project will provide a better estimation.

4. Extend the scope of financial analysis

   Cash flow analysis is the narrowest level of financial analysis. To perform a thorough cost-benefit analysis, the assessment should not be restricted to the safety-related expenditure. Broader economic aspects such as social value, ethics, aesthetics, and environmental impact of the project are the examples of the additional consideration for the cost-benefit analysis. As some aspects cannot be expressed in monetary value, a qualitative study of the safety measure impact becomes the alternative assessment method. Finally, it is suggested to separate the report of quantitative and qualitative analysis [21].

   When analysing multi-dimensional construction project, especially public infrastructure, indirect effects of a project and financial risks are the essential factors of the cost-benefit analysis. In this thesis, the importance of financial risks is shown by the impact of the interest rate. However, in practice, the value of the interest rate is never constant. A detailed forecast is required to produce a more accurate result. Meanwhile, the indirect effects are not taken into account for this study. Eijgenraam et al. (2000) suggested four common approaches to analyse the indirect effects of a construction project [21]:

   - Macro-production: effects of a country's infrastructure investments on the national economy
   - Case studies: learn from the past similar projects
   - Focused field work: surveys and interviews of the ongoing projects
   - Models: creates a tailored economic model using the global estimation of the indirect welfare effects

5. Perform a full-probabilistic approach

   In case there is no statistical data available, the uncertainties of the questionnaire result should be calibrated. One of the methods is using a program called *"Excalibur"*. The open source program allows parametric model in weighing expert's judgement as well as shows the sensitivity of the final result regarding the variables and the scoring given by the different respondents. The scoring given by experts or other reliable personnel is valued more than those from laypeople and evaluated against the median score.

The calibrated result provides a more precise quantitative result to the calculation of the weighted probability ($P_{w,n}$). Hence, a deeper understanding of the failure causes and safety measure impact can be derived. Note that even using a sophisticated model, it is still not possible to deliver a forecast of the failure probability. Nevertheless, a better decision can be expected, since the model addresses more considerations in the weighting procedure.

Bibliography

[1] Adviesbureau ir. JG Hageman BV. Bezwijken Parkeergarage Eindhoven Airport, Analyse naar de Oorzak. *Rapport 9663-1-0: Analyse naar de oorzak*, 2017.

[2] Airports Council International. Amidst Market Uncertainties, Airport Industry Remains Resilient With Greater Reliance on Passenger-Related Revenues. *ACI Media Releases*, 2016.

[3] Al-Hajj, Assem. Modeling Running and Maintenance Costs for Life Cycle Costing Applications in Buildings. *Durability of Building Materials & Componentes*, 8:1699–1706, 1999.

[4] Arndt, Michael. Amoco Chucks All the Marble on Its Tower. Retrieved from: `http://articles.chicagotribune.com/1989-03-07/business/8903240963_1_marble-amoco-building-granite`, 1989. [Accessed: 03-02-2018].

[5] Azhar, S., Khalfan, M., and Maqsood, T. Building Information Modelling (BIM): Now and Beyond. *Construction Economics and Building*, 12(4):15–28, 2015.

[6] Azhar, Salman. Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, 11(3):241–252, 2011.

[7] Bos, Freek Paul. *Safety Concepts in Structural Glass Engineering: Towards an Integrated Approach*. PhD thesis, TU Delft, Delft University of Technology, 2009.

[8] Brealey, RA., Myers, SC., and Allen, F. *Principles of Corporate Finance 10th Edition*. McGraw-HillIrwin, 2011.

[9] Brown, Colin B. and Yin, Xiaochen. Errors in Structural Engineering. *Journal of Structural Engineering*, 114(11):2575–2593, 1988.

[10] Buildings: Smarter Facility Management. Office Building Expenses and Income Increased from 2015 to 2016. Retrieved from: `https://www.buildings.com/article-details/articleid/21314/title/office-building-expenses-and-income-increased-from-2015-to-2016`, 2017. [Accesed: 20-05-2018].

[11] Bussell, MN. and Jones, AEK. Robustness and the Relevance of Ronan Point Today. *Structural Engineer*, 88(23-24):20–25, 2010.

[12] Capital Region Development Authority. *2016-2017 Annual Report*. Connecticut Capital Region Development Authority, 2017.

[13] Centraal Planbureau. *Discontovoet Onderwijs, Uitgevoerd op Verzoek van het Ministerie van Onderwijs, Cultuur en Wetenschap*. Centraal Planbureau, 2017.

[14] Construction Labour Market Analyzer. CLMA Project Labor Cost Allocation. Retrieved from: `http://myclma.com/wp-content/uploads/2015/02/CLMA-Allocation-of-Project-Cost-2014Oct27.pdf`, 2015. [Accesed: 25-05-2018].

[15] de Graaf, Peter. Fouten bij Balkons Maastricht. Retrieved from: `https://www.volkskrant.nl/binnenland/fouten-bij-balkons-maastricht~a727332/`, 2003. [Accessed: 10-03-2018].

[16] de Jong, Peter and Wamelink, Hans. Building Cost and Eco-Cost Aspects of Tall Buildings. In *CTBUH 8th World Congress*, pages 3–5, 2008.

[17] De Martino, G., Di Ludovico, M., Prota, A., Moroni, C., Manfredi, G., and Dolce, M. Estimation of Repair Costs for RC and Masonry Residential Buildings Based on Damage Data Collected by Post-Earthquake Visual Inspection. *Bulletin of Earthquake Engineering*, 15(4):1681–1706, 2017.

[18] Delatte Jr, Norbert J. Beyond Failure: Forensic Case Studies for Civil Engineers. American Society of Civil Engineers, 2008.

[19] Diekmann, James E. and Girard, Matthew J. Are Contract Disputes Predictable? *Journal of construction engineering and management*, 121(4):355–363, 1995.

[20] Duckett, Will. Risk Analysis and the Acceptable Probability of Failure. *Structural Engineer*, 83(15):25–26, 2005.

[21] Eigenraam, CJJ., Koopmans, C., Tang, Paul JG., and Verster, ACP. *Evaluatie van Infrastructuurprojecten: Leidraad voor Kosten-Baten Analyse*. Centraal Planbureau, 2000.

[22] Ellirtgwood, Bruce. Design and Construction Error Effects on Structural Reliability. *Journal of structural engineering*, 113(2):409–422, 1987.

[23] Emporis. Sheraton Kansas City Hotel at Crown Center. Retrieved from: `https://www.emporis.com/buildings/121804/sheraton-kansas-city-hotel-at-crown-center-kansas-city-mo-usa`, 2018. [Accesed: 22-05-2018].

[24] Feld, Jacob and Carper, Kenneth L. *Construction Failure*, volume 78. John Wiley & Sons, 1997.

[25] Frye, William D. What Are Your True Variable Costs per Occupied Room? Retrieved from: `http://lodgingmagazine.com/what-are-your-true-variable-costs-per-occupied-room/`, 2014. [Accessed: 15-05-2018].

[26] Garland, Ron. The Mid-Point on a Rating Scale: Is It Desirable. *Marketing bulletin*, 2(1):66–70, 1991.

[27] Gijsbers, FBJ., Vervuurt, AHJM., and Borsje, H. Parkeergarage Bos en Lommerplein Amsterdam. *TNO-Rapport*.

[28] GLA Economics. The Value of Land and Housing in London. *GLA Economics: Economic Evidence Base for London 2016*, 40(5):136–183, 2016.

[29] Grant Thornton Vietnam. Report Overview Hotel Survey 2016, Executive Summary. *Vietnam Upscale Lodging Industry – Hotel Survey 2016*, 2016.

[30] Hébert, R., Beouch, L., Fichet, O., Bigas, JP., Teyssié, D., Berthier, B., and Prichystal, JB. Cracks and Stains on Façade-Cladding Made of Carbonate Rock Thin Panels. *Structural Survey*, 30(2):130–144, 2012.

[31] Helmerich, Rosemarie and Zunkel, Astrid. Partial Collapse of the Berlin Congress Hall on May 21st, 1980. *Engineering Failure Analysis*, 43:107–119, 2014.

[32] Hollnagel, Erik. *Cognitive Reliability and Error Analysis Method (CREAM)*. Elsevier, 1998.

[33] Hornby, AS., Wehmeier, S., and Ashby, M. *Oxford Advanced Learner's Dictionary*. Oxford University Press, 2000.

[34] Insurance Journal. Paris Airport Roof Structure to be Replaced. Retrieved from: https://www.insurancejournal.com/news/international/2005/03/18/52698.htm, 2005. [Accessed: 20-05-2018].

[35] Jensen, Tim. Hartford Civic Center Roof Collapsed 40 Years Ago. Retrieved from: https://patch.com/connecticut/hartford/hartford-civic-center-roof-collapsed-40-years-ago, 2018. [Accessed: 11-03-2018].

[36] Koushki, PA., Al-Rashid, K., and Kartam, N. Delays and Cost Increases in the Construction of Private Residential Projects in Kuwait. *Construction Management and Economics*, 23(3):285–294, 2005.

[37] Lane, Barbara Miller. The Berlin Congress Hall 1955-1957. *Perspectives in American History*, 1:131, 1984.

[38] Lebeau, M., Duguay, P., and Boucher, A. Costs of Occupational Injuries and Diseases in Québec. *Journal of safety research*, 50:89–98, 2014.

[39] Levy, Matthys and Salvadori, Mario. *Why Buildings Fall Down: How Structures Fail*. WW Norton & Company, 2002.

[40] Loughran, Patrick. *Failed Stone: Problems and Solutions with Concrete and Masonry*. Walter de Gruyter, 2007.

[41] Luth, Gregory P. Chronology and Context of the Hyatt Regency Collapse. *Journal of Performance of Constructed Facilities*, 14(2):51–61, 2000.

[42] Martin, Rachel and Delatte, Norbert J. Another Look at Hartford Civic Center Coliseum Collapse. *Journal of Performance of Constructed Facilities*, 15(1):31–36, 2001.

[43] McCarthy, Niall. The Countries Working the Most Hours Every Year [Infographic]. Retrieved from: https://www.forbes.com/sites/niallmccarthy/2018/01/08/the-countries-working-the-most-hours-every-year-infographic/#5ac0514f2fbc, 2018. [Accessed: 27-05-2018].

[44] Means Engineering. *RSMeans Cost Data*. Hoboken: R. S. Means Company, Incorporated, 2012.

[45] Ministerie van VROM. *Kasteel of Kaartenhuis? Een Discussiestuk Over Constructieve (On)veiligheid*. Ministerie van VROM, 2007.

[46] Morin, Charles R. and Fischer, Chad R. Kansas City Hyatt Hotel Skyway Collapse. *Journal of Failure Analysis and Prevention*, 6(2):5–11, 2006.

[47] Nature Publishing Group. Ronan Point: Who is to blame? *Nature*, 220, 1968.

[48] NRC Handelsblad. Esthetische Correctie was Oorzaak Ramp. Retrieved from: https://www.nrc.nl/nieuws/2003/07/05/esthetische-correctie-was-oorzaak-ramp-7645568-a69466, 2003. [Accessed: 10-03-2018].

[49] Occupational Safety and Health Administration. Workers' Compensation Costs of Falls in Construction. Retrieved from: https://www.osha.gov/doc/topics/residentialprotection/2012_fall_costs/index.html, 2018. [Accessed: 13-05-2018].

[50] Oregon Department of Transportation. Construction Material Testing Services. Retrieved from: http://www.oregon.gov/ODOT/Construction/Documents/construction_materials_testing_fees.pdf, 2018. [Accessed: 27-05-2018].

[51] Pan, Yifan. Probability Analysis of Life Cycle Cost of Bridges With Different Preventive Measures and Repair Methods. Master's thesis, TU Delft, 2012.

[52] Paret, Terrence F., Moncarz, Piotr D., and Taylor, Robert K. Engineering Process Failure—Hyatt Walkway Collapse. *Journal of Performance of Constructed Facilities*, 15(4):154–154, 2001.

[53] Partners for Lawrence Athletics and Youth. Annual Operating and Maintenance Costs. *P.L.A.Y. Feasibility Study Report*, 2007.

[54] Peansupap, Vachara and Ly, Rothmony. Evaluating the Impact Level of Design Errors in Structural and Other Building Components in Building Construction Projects in Cambodia. *Procedia Engineering*, 123:370–378, 2015.

[55] Pearson, Cynthia and Delatte, Norbert. Ronan Point Apartment Tower Collapse and Its Effect on Building Codes. *Journal of Performance of Constructed Facilities*, 19(2):172–177, 2005.

[56] Pfatteicher, Sarah KA. The Hyatt Horror: Failure and Responsibility in American Engineering. *Journal of Performance of Constructed Facilities*, 14(2):62–66, 2000.

[57] Priemus, Hugo. Lessen van het Bos en Lommerplein. *Rooilijn*, 40(5):326–331, 2007.

[58] Priemus, Hugo and Ale, Ben. Construction Safety: An Analysis of Systems Failure: The Case of the Multifunctional Bos & Lommerplein Estate, Amsterdam. *Safety Science*, 48(2):111–122, 2010.

[59] ProMatcher Home Construction. Kansas City Home Construction Costs & Prices - ProMatcher Cost Report. Retrieved from: `https://home-builders.promatcher.com/cost/kansas-city-mo-home-builders-costs-prices.aspx`, 2018. [Accessed: 22-05-2018].

[60] Raphael, W., Faddoul, R., Feghaly, R., and Chateauneuf, A. Analysis of Roissy Airport Terminal 2E Collapse Using Deterministic and Reliability Assessments. *Engineering Failure Analysis*, 20:1–8, 2012.

[61] Rechtien, Matthew R. The Hyatt Regency Disaster Revisited. Retrieved from: `http://www.structuremag.org/?p=1751`, 2014. [Accessed: 01-02-2018].

[62] Rubin, Robert A. and Banick, Lisa A. The Hyatt Regency Decision: One View. *Journal of Performance of Constructed Facilities*, 1(3):161–167, 1987.

[63] Smith, Erling A. and Epstein, Howard I. Hartford Coliseum Roof Collapse: Structural Collapse Sequence and Lessons Learned. *Civil Engineering—ASCE*, 50(4):59–62, 1980.

[64] Stratta, James L. *Report of the Kemper Arena Roof Collapse of June 4, 1979, Kansas City, Missouri*. Stratta, 1979.

[65] Suddle, Shahid. *Physical Safety in Multiple Use of Space*. PhD thesis, 2004.

[66] Suddle, Shahid. The Weighted Risk Analysis Applied for Bos and Lommer. *International Journal of Performability Engineering*, 3(4):481–497, 2007.

[67] Suddle, Shahid. The Weighted Risk Analysis. *Safety Science*, 47(5):668–679, 2009.

[68] Swift, Mike. A Quiet Hartford Civic Center Turns 20 Today. Retrieved from: `http://articles.courant.com/1995-01-09/news/9501090021_1_civic-pride-main-street-hartford-civic-center`, 1995. [Accessed 01-05-2018].

[69] Terwel, Karel. Contributing Human and Organizational Factors for Damage of Bos & Lommer Plaza in Amsterdam. In *IABSE Symposium Report*, volume 109, pages 3262–3269. International Association for Bridge and Structural Engineering, 2017.

[70] Terwel, Karel C. Structural Safety: Study Into Critical Factors in the Design and Construction Process. 2014.

[71] Terwel, Karel C. and Jansen, Sylvia JT. Critical Factors for Structural Safety in the Design and Construction Phase. *Journal of performance of constructed facilities*, 29(3):04014068, 2014.

[72] The Government of the Hong Kong Special Administrative Region of The People's Republic Of China, Development Bureau. Site Safety Personnel. Retrieved from: `https://www.devb.gov.hk/filemanager/en/content_191/chapter7.pdf`, 1999. [Accessed: 23-05-2018].

[73] Thompson, Paul. Inside the Kemper Arena Renovation Being Undertaken by the Foutch Brothers. Retrieved from: `http://northeastnews.net/pages/inside-kemper-arena-renovation-undertaken-foutch-brothers/`, 2018. [Accessed: 25-05-2018].

[74] Toriizuka, Takashi. Application of Performance Shaping Factor (PSF) for Work Improvement in Industrial Plant Maintenance Tasks. *International Journal of Industrial Ergonomics*, 28(3-4):225–236, 2001.

[75] Torres, Pablo. Case Study: The New Terminal 2E at Paris-Charles De Gaulle Airport. *Rapport technique, Airport Systems Planning, Design & Management, Massachusetts Institute of Technology*, 2004.

[76] van Herwijnen, F. Leren van Instortingen. *Bouwen met staal, Zoetermeer, The*, 2009.

[77] van Well-Stam, D., van Kinderen, S., and van den Bunt, BP. *Risicomanagement voor Projecten*. Spectrum, 2013.

[78] Vaughan, Joshua L., Leming, Michael L., Liu, M., and Jaselskis, E. Cost-Benefit Analysis of Construction Information Management System Implementation: Case Study. *Journal of Construction Engineering and Management*, 139(4):445–455, 2012.

[79] Vrijling, JK. and Verlaan, JG. Financial Engineering, Reader CME2300. *Faculty of Civil Engineering and Geosciences, Delft University of Technology*, 2015.

[80] VROM-inspectie et al. Plan van Aanpak Constructieve Veiligheid. *VROM-inspectie*, 2006.

[81] Wearne, Phillip. *Collapse: When Buildings Fall Down*. TV Books Incorporated, 2000.

[82] Winter, Stefan and Kreuzinger, Heinrich. The Bad Reichenhall Ice-Arena Collapse and the Necessary Consequences for Wide Span Timber Structures. In *Proceedings WCTE 2008 Conference*, 2008.

[83] Wood, JG. Paris Airport Terminal Collapse: Lessons for the Future. *Structural Engineer*, 83(5), 2005.

A

Appendix A: Sample Case Analysis

A.1. Case Selection

Filter questions:

1. Does the case candidate have multiple investigation literatures?
2. Is the investigation already settled?

Result of initial sample case selection is presented in Table A.1

Table A.1: Case selection step 1

Case	Various literatures	Investigation status
Berlin Congress Hall	Yes	Settled
Hyatt regency	Yes	Settled
Ice skating hall, Bad Reichenhall	Yes	Settled
Terminal 2E CDG Airport	Yes	Settled
Patio Sevilla	Yes	Settled
Hartford Civic Center	Yes	Settled
Kemper Arena	Yes	Settled
Parking Garage Hotel van der Valk	No	Settled
Ronan Point	Yes	Settled
Bos en Lommerplein	Yes	Settled
Amoco Tower	Yes	Settled
Parking Garage Eindhoven Airport	Yes	Ongoing

A.2. Relevance Check

Key points of research framework:

1. Only analyze safety related failure in building construction
2. Design measures can be taken to prevent or minimize the cause of failure
3. Financially accountable; loss and income can be estimated

Questions to check the relevance of the cases with research framework

- Safety related questions:
    1. Which part of the building had failed?
    2. Is the failure caused/might have caused fatalities?
- Causal and measures related questions:
    1. What are the unique characteristics/challenges of the project that requires more attention?
    2. What are the cause(s) of the failure?
    3. What safety measures proposed in the investigation report(s)?
- Financial related questions:
    1. What are the cost components of direct/indirect loss presented in the investigation report(s)?
    2. what are the cost components of the income cash flow?
    3. What are the cost components of the safety measures?

Congreshall Berlin, Germany: 1957-1980 (23 years)

1. Which part of the building had failed?
    - *Full collapse of the southern external roof overhang* [31]
2. Is the failure caused/might have caused fatalities?
    - *Yes, 1 death, several injuries* [76]
3. What are the unique characteristics/challenges of the project that requires more attention?
    - *Hypar shell as a roof erected on only two bearings with a wide brim has never been built in such manner before* [31]
    - *Prestressed concrete structures with complicated detailing is not really common at that time* [31]
    - *Curves lie on a slender, vertical disks, sensitive to fulfill stability requirements under extreme load* [31]
4. What are the cause(s) of the failure?
    - *Unclear load path* [31]
    - *Lack of concrete cover causing corrosion of pre-stress bar* [31]
    - *Requirements for advancing components, as chlorides or carbonation, in the concrete mass did not exist at that time* [31]
    - *Imperfection in execution, tendons were not in the middle axis* [31]
5. What safety measures proposed in the investigation report(s)?
    - *Avoid complicated load transfer as it might cause unjustified simplification* [76]
    - *Time management; short construction time might lead to unsupervised task* [76]
    - *Chloride content should be taken into account up to max level* [76]
    - *Inspection during service lifetime* [76]
    - *Use new simple reinforced concrete shell with a thickness of 11 cm instead of only 7 cm in the former complicated prestressed roof* [31]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
    - *Material cost*
    - *Compensation cost for victims*
    - *Idle time during reconstruction*
    - *Reconstruction cost*
    - *Monetary value of human being*
7. what are the cost components of the income cash flow?
    - *Rent price of the hall*
    - *Commercial income*
8. What are the cost components of the safety measures?
    - *Additional material cost (higher quality steel, increase of concrete cover)*
    - *Routine inspection cost*
    - *Modeling cost for complex structure using physical/ computer program*
    - *Supervision cost on both design and execution*

Hyatt regency, Kansas City 1980-1981 (1 year)

1. Which part of the building had failed?
   - *Full collapse of sky bridges connecting two tower* [46]
2. Is the failure caused/might have caused fatalities?
   - *Yes, 114 deaths and 186 injuries* [76]
3. What are the unique characteristics/challenges of the project that requires more attention?
   - *Design of hanging walkways* [76]
   - *Fast-track construction project (the construction team had begun to build the hotel while the design team was still finalizing the plans)* [56]
   - *Each of approximately 10 associate engineers was supervising six or seven other projects at a time* [56]
4. What are the cause(s) of the failure?
   - *Alteration of suspension detail of sky bridge* [39]
   - *The built construction can only carry 30% of the Kansas standard (5kn/m2), and the original design can even only carry 60%* [39] [76]
   - *Extra load by cement topping not accounted in the design* [39]
   - *Lack of redundancy*[39]
   - *No original design calculations were found for the box beam that failed* [62]
   - *Responsible engineer personally only looked at the shop drawing but did not really "review" the box-beam connection* [62] [61]
5. What safety measures proposed in the investigation report(s)?
   - *Do not modify connection detail without consent and review from original designer* [76]
   - *Important role of head constructor as supervisor*[76]
   - *a fast track project requires extra diligence in its execution* [52]
   - *Limit the project handled by 1 engineer at the same time*[56]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
   - *Material cost*
   - *Compensation cost for victims*
   - *Engineering fee to review the entire structural design in the atrium* [62]
   - *Reconstruction cost*
   - *Monetary value of human being*
7. What are the components of the income cash flow?
   - *Rent price of the hotel rooms*
   - *Rent price for commercial area*
8. What are the cost components of the safety measures?
   - *Engineering cost for more focused engineer* [56]
   - *Supervision cost*
   - *Time related cost due to longer process through supervising*

Ice skating hall, Bad Reichenhall, Germany 1973-2006 (33 year)

1. Which part of the building had failed?
   - *Chain collapse of the roof structure leads to full collapse* [76]
2. Is the failure caused/might have caused fatalities?
   - *Yes, 15 deaths and 34 injuries* [76]
3. What are the unique characteristics/challenges of the project that requires more attention?
   - *Wide span of glue laminated box girder, was new technique at that time. Codes were only suitable for limited girder height* [82]
4. What are the cause(s) of the failure?
   - *The use of urea-formaldehyde glue under moist conditions* [76]
   - *Mistakes in the structure calculation – and no (mandatory in Germany) evaluation of the calculations by a check engineer* [82]
   - *Divergence from the technical approval for this type of construction* [82]
   - *Non robust construction*
   - *No of maintenance during the service life* [82]
5. What safety measures proposed in the investigation report(s)?
   - *For long span structure, use RF glue for laminated timber* [76]
   - *Exposure to humidity should be taken into account* [76]
   - *Not using hollow girder for humid environment, as there are non accessible area for investigation* [82]
   - *New technique should be physically tested beforehand* [76]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
   - *Material cost*
   - *Compensation cost for victims*
   - *Monetary value of human being*
7. What are the components of the income cash flow?
   - *Admission fee for the ice skating hall*
   - *Commercial income*
8. What are the cost components of the safety measures?
   - *Modelling cost (physical and computational) of new structure*
   - *Material cost for using different kind of glue+additional nail/dowels*
   - *Routine inspection cost*

Terminal 2E CDG Airport, Paris, France, 2003-2004 (1 year)

1. Which part of the building had failed?
    - *One segment of terminal totally collapsed* [76]
2. Is the failure caused/might have caused fatalities?
    - *Yes, 4 deaths, 3 injures* [76]
3. What are the unique characteristics/challenges of the project that requires more attention?
    - *The distribution and flow of forces is hard to visualize due to its unusual structure and design complexity* [83]
    - *Paul Andreu (the architect) had problems with the realization of his design. Hall 2F of CDG also had some structural problems during the construction phase* [75]
4. What are the cause(s) of the failure?
    - *Lack of robustness and redundancy* [83]
    - *Inadequate model for the complex structure* [60]
    - *Not taking into account the concrete deformations at the long term, effect of temperature to the connection* [76]
    - *Non symmetric cross section, causing concentrated stress* [60]
    - *Aéroports de Paris (ADP) acted as judge and jury when it comes to the design and construction, no external control* [75]
    - *Conflict of interest between huge amount of stakeholder (400 parties involved)* [75]
5. What safety measures proposed in the investigation report(s)?
    - *Fair supervision from independent third party*[75]
    - *Make rigorous 3D model, where behavior of the building parts can be analyzed* [34]
    - *Never neglect temperature load for high stiffness construction* [76]
    - *Prepare secondary load path* [76]
    - *Assess the reliability approach of constructions* [60]
    - *If original design still used: add tensional members that link the end of the arcs at the bottom level, use concrete of 55 MPa instead of 40 MPa* [60]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
    - *Material cost*
    - *Replacement cost*
    - *Insurance claim on multiple companies* [34]
    - *Investigation cost*
    - *Compensation cost for victims*
    - *Compensation cost for the airlines due to operation with a low level of service* [75]
    - *Monetary value of human being*
7. What are the components of the income cash flow?
    - *Airlines tax*
    - *Passengers tax*
    - *Commercial income*
8. What are the cost components of the safety measures?
    - *Supervision cost*
    - *Modeling cost*
    - *Engineering design cost*
    - *Extra material cost by using better concrete and adding structural members*

Patio Sevilla, Maastricht, 2003 (less than 1 year)

1. Which part of the building had failed?
    - *Balconies collapsed, facade ripped off* [45]
2. Is the failure caused/might have caused fatalities?
    - *Yes, 2 deaths* [76]
3. What are the unique characteristics/challenges of the project that requires more attention?
    - *Multiple vendors involved for balcony construction* [76]
    - *Column is not in the edge of the balcony* [45] [76]
    - *Column is then not directly supported by wall, but the contractor made steel console under the nock to function as the wall* [76]
4. What are the cause(s) of the failure?
    - *Failure of the nock of the ground floor balcony or 1st floor balcony* [45]
    - *Calculation of the steel console is based on the original drawing, where the column is at the edge* [45]
5. What safety measures proposed in the investigation report(s)?
    - *Independent investigation during and before construction phase (In this case investigation reports are opposing each other, because investigators hired by different subcontractor/ supplier involved* [76]
    - *Change of drawings in the construction phase should be avoided. If it is really necessary, all parties involved should be informed* [76]
    - *Load transfer should be made clear, including secondary load path, and all connection should be tested* [76]
    - *Coordination between design (architectural), construction (structural), and building service* [76]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
    - *Investigation cost*
    - *Reconstruction cost*
    - *Compensation cost for victims*
    - *Monetary value of human being*
7. What are the components of the income cash flow?
    - *Apartment rent*
8. What are the cost components of the safety measures?
    - *Supervising cost*
    - *Project management cost*
    - *Physical testing cost*
    - *Engineering cost for design revision*
    - *Additional material for secondary load path*

Hartford Civic Center, Connecticut, USA (1975-1978)

1. Which part of the building had failed?
   - *The whole roof collapsed* [76]
2. Is the failure caused/might have caused fatalities?
   - *Yes, but no fatalities or injures reported*
3. What are the unique characteristics/challenges of the project that requires more attention?
   - *Non standard solution for space frame roof to reduce $0.5M cost* [39]
   - *The use of early year computer modeling program* [81]
4. What are the cause(s) of the failure?
   - *Design underestimation* [76]
   - *False design assumption for the computer program* [76]
   - *Negligence by the project manager to the sign of failure found during construction and building lifetime* [39] [18]
   - *No physical test performed, only relied on computer program* [81]
   - *Too many variations in roof design, while there were not enough statistical data about the performance* [81]
   - *Absence of a full-time registered structural engineer experienced with the design. Project manager refuse the supervising idea for cost-cutting reason* [18] [42]
   - *Hartford Department of Licenses and Inspection did not require the project peer review that it usually required for projects of this magnitude* [18]
5. What safety measures proposed in the investigation report(s)?
   - *Perform physical test* [76]
   - *Hire experienced structural engineer as daily supervisor* [18] [42]
   - *Perform internal peer review* [42]
   - *Unified contract and clear assigned responsibility* [42]
   - *If original design maintained: Addition of less than 50 bars to the bracing could have saved the roof from collapsed* [39]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
   - *Material cost*
   - *Reconstruction cost*
7. What are the components of the income cash flow?
   - *Rent fee of the arena*
   - *Spectators admission fee*
   - *Commercial income*
8. What are the cost components of the safety measures?
   - *Design supervision cost*
   - *Construction supervision cost(both in design and construction)*
   - *Project management cost*
   - *Modeling cost (computational and physical)*
   - *Additional peer reviewers fee*

Kemper Arena, Kansas City, USA (1973-1979)

1. Which part of the building had failed?
    - *Part of the roof collapsed* [81]
2. Is the failure caused/might have caused fatalities?
    - *Yes, but no fatalities or injures reported*
3. What are the unique characteristics/challenges of the project that requires more attention?
    - *Large flat reinforced concrete roof supported by steel truss is unusual* [39] [18]
    - *Roof designed as rain reservoir* [39]
4. What are the cause(s) of the failure?
    - *Water ponding due to lack of drainage combined with strong wind* [39] [18]
    - *Fatigue failure of the connecting bolts on the hangers. A490 high-strength bolts used is not recommended for variable or fatigue loads* [18]
    - *No redundancy due to the framing scheme* [64]
    - *Stiffly welded structure, not allowing much deflection* [39]
5. What safety measures proposed in the investigation report(s)?
    - *Analyze the roof in three dimensions, not just two, to determine the actual flexibility and ponding susceptibility* [18]
    - *Use ductile welded steel bars* [39]
    - *Revise hanger detail, replace all hangers* [39]
    - *Perform sufficient wind analysis* [64]
    - *Raise the roof position* [64]
    - *Add more drainage* [64] [18]
    - *Make topographical survey of the roof structure before installation* [64]
    - *Attach roof membrane to metal deck to prevent separation and fluttering* [64]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
    - *Material loss*
    - *Investigation cost*
    - *Idle time cost of 2 years during restoration* [39]
    - *Reconstruction cost*
7. What are the components of the income cash flow?
    - *Admission fee for spectators*
    - *Rent fee of the arena*
    - *Commercial income*
8. What are the cost components of the safety measures?
    - *Engineering cost for redesigning*
    - *Material cost*

Ronan Point, East London, England, 1968 (less than 1 year)

1. Which part of the building had failed?
    - *Failure of load bearing walls in one apartment leads to partial collapse of the structure* [18]
2. Is the failure caused/might have caused fatalities?
    - *Yes, 4 people dead and 17 injured* [39]
    - *Furthermore, later findings stated the building is not safe, leads to fully demolition* [39]
3. What are the unique characteristics/challenges of the project that requires more attention?
    - *Stacked prefabricated wall panels as load bearing structure; while at that time the building code had not yet prepared for such innovation* [55]
4. What are the cause(s) of the failure?
    - *Progressive collapse; initiated by small explosion* [39] [18] [47]
    - *Lack of structural integrity, no structural frame, no secondary load path* [18]
    - *Poor workmanship* [18]
    - *Original concept of the system only meant for 6 storey building* [18]
    - *Ronan Point was underdesigned to take wind pressure, because of its height. The old codes was invalid for new building height* [47] [55]
5. What safety measures proposed in the investigation report(s)?
    - *Provide structural redundancy* [11] [39]
    - *Apply safety factor for unexpected load* [11]
    - *Ensuring interaction between components* [18]
    - *Presence of skilled supervisors who understand the design intent and can communicate it clearly to the field workers are needed full-time at the construction site* [18]
    - *Comprehensive structural modelling and wholebuilding test in case of fire load* [11]
    - *Having one party responsible for the overall structure, especially for such a hybrid structure* [11]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
    - *Compensation cost for victims*
    - *Monetary value of human being*
    - *Engineering cost for the reconstruction*
    - *Reconstruction cost*
    - *Material cost*
    - *Investigation cost*
    - *Demolition cost*
    - *Indirect cost for the assessment/reconstruction/demolition of other similar buildings*[39]
7. What are the components of the income cash flow?
    - *Rent of the apartments*
8. What are the cost components of the safety measures?
    - *Engineering cost (physical or computational modeling, reassessment of the system, redesigning)*
    - *Supervision cost*
    - *Additional material cost*

Bos en Lommerplein, Amsterdam, 2004-2006 (2 years)

1. Which part of the building had failed?
   - *Part of the load bearing structure had failed significantly, near collapse situation* [69] [27]
2. Is the failure caused/might have caused fatalities?
   - *Yes, but no fatalities or injures reported*
   - *Whole complex were evacuated due to safety emergency* [58] [27]
3. What are the unique characteristics/challenges of the project that requires more attention?
   - *Dynamic preparation, functional program changed constantly* [58] [69]
   - *Labor issue(language barrier, technical competency)* [58] [69]
   - *Too much fragmentation and no clear all-encompassing final responsibility* [58]
   - *Cost cutting oriented project* [58]
4. What are the cause(s) of the failure?
   - *Design error for the reinforcement of the concrete floor between apartments and shops* [27] [69]
   - *Errors in the calculations of the detailing of reinforcement of concrete half-joints* [69]
   - *Reinforcement deviated from drawings* [69]
   - *The board was unwilling to appoint a coordinating consultant engineer, while during construction over 50 subcontractors were involved* [69]
   - *Price oriented, leads to poor construction quality (tend to avoid duplicate work such as checking; simplification in modeling)* [57] [58]
   - *Cheating action by the certified contractor* [57] [58]
   - *Mandatory report which the plan assessors (mostly municipality) have at their disposal is usually incomplete, design safety not guaranteed* [57]
5. What safety measures proposed in the investigation report(s)?
   - *External supervision by experienced company* [69]
   - *Hire properly trained, experienced, and certified employees* [57]
   - *Avoid owner-less task* [58]
   - *Mandatory presence of coordinating structural engineer* [58]
   - *Internal peer review* [58]
   - *Improve building construction control by municipality* [58]
   - *Interface management (quality of the components + how they fit together)* [58]
   - *Unified building permit of the complex project* [58] [57]
   - *Any changes during the actual building activities should relate only to the non-structural components* [58]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
   - *Evacuation cost*
   - *Vacancy of apartments and other area in the complex*
   - *Repair cost* [58]
7. What are the components of the income cash flow?
   - *Commercial income*
   - *Parking fee*
   - *Apartment rent*
   - *Office rent*
   - *Shops and other business rent*
8. What are the cost components of the safety measures?
   - *Engineering cost (review/supervision/management)*
   - *Cost of hiring more competent employees*
   - *Cost of possible delay due to multiple supervision*

Amoco Tower, Chicago 1974-1988 (14 years)

1. Which part of the building had failed?
   - *Facade skin panels* [39]
2. Is the failure caused/might have caused fatalities?
   - *Yes, but no fatalities or injures reported*
   - *Preventive action to avoid fatalities were taken by installing stainless-steel straps once the deformation considered to be dangerous* [4]
3. What are the unique characteristics/challenges of the project that requires more attention?
   - *Thin tube structure and thin facade stone panels to minimize structural cost* [40]
4. What are the cause(s) of the failure?
   - *Type of stone used on the facade is susceptible to thermal changes* [30]
   - *Thin facade panels, sensitive to creep/shrinkage* [39]
   - *The use of bolt connection prevents thermal movement* [39] [4]
   - *Based on test, on average, the installed panels were much weaker than the preliminary sample* [40]
5. What safety measures proposed in the investigation report(s)?
   - *Replace all the skin using thicker facade panels* [4]
   - *Use less thermal sensitive stone cladding* [39] [40]
   - *Testing of samples throughout the whole project to anticipate variation in material* [40]
6. What are the cost components of direct/indirect loss presented in the investigation report(s)?
   - *Waste material cost*
   - *Investigation cost*
   - *Temporary safety response cost*
   - *Financial loss from interrupted office activities during3 years of restoration*
   - *Facade replacement cost*
7. What are the components of the income cash flow?
   - *Office rent*
   - *Indirect income from office activities*
8. What are the cost components of the safety measures?
   - *Material cost*
   - *Sample testing cost*
   - *Engineering cost*

A.3. Classification Filter

Table A.2: Case selection step 3

Begin of Table

Case	Causes	Factor classification	Measure	Measure type
Berlin Congress Hall	Collaboration between architectural and structural design	Communication and collaboration	Use simple load transfer system	Technical
	Lack of concrete cover	Macro factor	Adjust time allocation	Procedural
	Corrosion sensitive pre-stress bar	Macro factor	Take chloride content to the max level	Technical
	Code is lagging behind	Macro factor	Inspection during lifetime	Procedural
	Execution imperfection	Control mechanism	Modify design of the shell	Technical
	Neglecting cracked condition	Structural risk management	Mandatory physical model	Procedural
Hyatt Regency	Alteration on the detailed design	Communication and collaboration	No modification allowed without consent	Procedural
	Under-designed capacity	Structural risk management	Head constructor as supervisor	Procedural
	Unaccounted as built load due to deviation with design	Communication and collaboration	Extra diligence for fast track project	Procedural
	Lack of redundancy	Structural risk management	Limit amount of project handled by 1 engineer at the same time	Procedural
	Original design calculations for the box beam is missing	Communication and collaboration		
	Accepting modification without reviewing	Control mechanism		
Bad Reichenhall	Incorrect type of glue	Knowledge infrastructure	Use RF glue	Technical
	No maintenance during the service life	Structural risk management	Physically test new technique	Procedural
	Divergence from the technical approval	Control mechanism	Take humidity effect into account	Technical
	No mandatory evaluation performed by check engineer	Control mechanism	Not using hollow girder for humid environment	Technical
			Routine inspection during lifetime	Procedural
Terminal 2E CDG Airport	Unclear flow of forces	Structural risk management	Independent supervision	Procedural
	Inadequate model	Knowledge infrastructure	Mandatory 3D modelling	Procedural
	Neglecting temperature effect	Structural risk management	Add tensional members	Technical
	Too many stakeholders involved	Communication and collaboration	Prepare secondary load path	Technical
	No external control	Control mechanism	Perform assessment of constructions reliability	Procedural
	Idealist architect	Micro factor	Use 55 MPa concrete	Technical

Continuation of Table A.2

Patio Sevilla	Lack of design adjustment	Structural risk management	Supervision during construction	Procedural
	Change of detail without consent	Communication and collaboration	Avoid change of drawing in construction phase	Procedural
	Contractor was unaware of isokorven properties	Communication and collaboration	Provide clear load path	Technical
			Mandatory test to all connection	Procedural
Hartford Civic Center	Design underestimation	Knowledge infrastructure	Perform physical test	Procedural
	False assumption for the computer program	Knowledge infrastructure	Hire experienced structural engineer as daily supervisor	Procedural
	Negligence by to the sign of failure	Structural risk management	Internal peer review	Procedural
	No control during construction	Control mechanism	Unified contract	Procedural
	Lack of control from local authority	Macro factor	Add more 50 bracing	Technical
	Profit oriented organization	Safety culture		
	Misunderstanding between contracts	Allocation of responsibilities		
Kemper Arena	Poor workmanship	Control mechanism	Analyse the roof in 3D	Procedural
	No maintenance during lifetime	Structural risk management	Use ductile welded steel bars	Technical
	Non redundant structural scheme	Knowledge infrastructure	Attach roof membrane to metal deck	Technical
			Perform wind analysis	Procedural
			Make sloped roof	Technical
			Add more drainage	Technical
			Make topographical survey of the roof structure before installation	Procedural
			Peer review	Procedural
			Routine inspection	Procedural
Ronan Point	Profit oriented project	Safety culture	Provide structural redundancy	Technical
	Lack of structural integrity and redundancy	Structural risk management	Safety factor for unexpected load	Technical
	Poor workmanship	Control mechanism	Mandatory test to connections	Procedural
	Original concept of the system only meant for 6 storey building	Knowledge infrastructure	Hire full time supervisor	Procedural
	The old codes was invalid for new building height	Macro factor	Comprehensive structural modelling	Procedural
	No lead engineer	Allocation of responsibility	Single responsibility for hybrid structure	Procedural

Continuation of Table A.2				
Bos en Lommerplein	Language problem on site	Communication and collaboration	External supervision	Procedural
	Too many stakeholders involved	Communication and collaboration	Hire certified employees	Procedural
	Installed reinforcement deviated from drawings	Control mechanism	Apply interface management	Procedural
	No coordinating consultant engineer	Control mechanism	Mandatory presence of coordinating structural engineer	Procedural
	Price oriented, leads to poor construction quality	Safety culture	Internal peer review	Procedural
	Cheating action by contractor	Micro factor		
	Poor control from municipality	Macro factor		
	No safety goal set	Safety culture		
	Incompetent labour	Knowledge infrastructure		
Amoco Tower	Inappropriate material and dimension	Knowledge infrastructure	Replace all the skin with thicker panel	Technical
	Installed panels were much weaker than the preliminary sample	Control mechanism	Use less thermal sensitive stone cladding	Technical
			Testing of samples throughout the whole project	Procedural
			Perform modelling of long-term load	Procedural
End of Table				

B

Appendix B: Safety Measures Simulation

The measures simulation aims to evaluate the impact of safety measures. The principles mentioned in Section 3.4.2 are applied.

B.1. Case 1: Berlin Congress Hall

Financial Consequences

- Material loss

  The project value of the roof is estimated using RS Means database [44]. The parameters used are:

  - Roof dimension: 3,500 m^2, 70mm thickness
  - Pre-stressing cost: €0.66/ft^2 (RS Means p.64, value in 2011)
  - Forming cost: €6.23/ft^2 (RS Means p.61, value in 2011)
  - Concrete cost: €99.5/$yard^3$ (RS Means p.65, value in 2011)

  The present value roof cost is €342,008

- Reconstruction cost

  The total reconstruction cost is approximately €1,261,750, calculated using the roof area (3,500 m^2) and general repair cost presented in Section 3.4.2 (€361/m^2).

- Monetary value of human life

  The incident caused one fatalities [76]. The total monetary value for the loss of human life is €5,000,000.

- Compensation cost

  Five people were injured due to the incident [76]. The total monetary value for the compensation is €250,000.

The financial consequences (C) due to the failure is €6,853,758

Impact of safety measure

- The weighting factors (α_f)

  Three factors became the issue in the case of Berlin Congress Hall: Communication and collaboration (F1); Control mechanism (F2); and Structural risk management (F4). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

Figure B.1: Weight of factor in Case 1: Berlin Congress Hall

- Weighted risk analysis (γ_n)

  Three measures are proposed in Berlin Congress Hall case study: Planning and responsibility (M2); Structural modelling (M4); and Survey and inspection (M5). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.1: The weighted risk analysis for Case 1: Berlin Congress Hall

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability (year^{-1})	Weighted risk (€/year)
Weight	32%	35%	-	34%	-	-			
1: Integrated coordination	-	-	-	-	-	-	-	-	-
2: Planning and responsibility	3.58	3.71	-	3.61	-	-	73	$2.73 \cdot 10^{-5}$	187
3: Supervision	-	-	-	-	-	-	-	-	-
4: Structural modelling	3.61	3.61	-	3.90	-	-	74	$2.58 \cdot 10^{-5}$	177
5: Survey and Inspection	3.39	3.90	-	3.84	-	-	74	$2.56 \cdot 10^{-5}$	176
6: Employees competency	-	-	-	-	-	-	-	-	-

B.2. Case 2: Hyatt Regency, Kansas City

Financial Consequences

- Material loss

  The contract value of the hanging bridge was reported $ 390,000 in 1980 [41], or equivalent to present value €1,199,166.

- Reconstruction cost

  The total area of the bridge was 270 m^2. Using the general repair cost presented in Section 3.4.2 (€361/m^2, the estimated cost to renovate the bridge to a standard design is €97,335.

- Monetary value of human life

  The incident caused 114 fatalities [76]. The total monetary value for the loss of human life is €570,000,000.

- Compensation cost The number of wounded was unknown. However, it was reported that $78,000,000 was paid to the family of the victims in 1983 [56], equivalent to present value 219,481,271.

The total financial consequences (C) due to the failure is €790,777,772.

Impact of safety measure

- The weighting factors (α_f)

  Three factors became the issue in the case of Hyatt Regency: Communication and collaboration (F1); Control mechanism (F2); and Structural risk management (F4). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

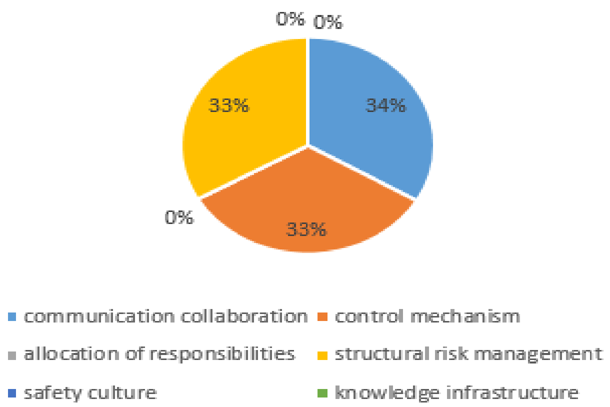

Figure B.2: Weight of factor in Case 2: Hyatt Regency

- Weighted risk analysis (γ_n)

  Three measures are proposed in Hyatt Regency case study: Integrated Coordination (M1); Planning and Responsibility (M2); and Supervision (M3). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.2: The weighted risk analysis for Case 2: Hyatt Regency

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability ($year^{-1}$)	Weighted risk (€/year)
Weight	34%	33%	-	33 %	-	-			
1: Integrated coordination	3.87	3.73	-	3.70	-	-	75	$2.47 \cdot 10^{-5}$	19,501
2: Planning and responsibility	3.57	3.93	-	3.47	-	-	73	$2.69 \cdot 10^{-5}$	21,267
3: Supervision	3.67	3.90	-	3.93	-	-	77	$2.33 \cdot 10^{-5}$	18,459
4: Structural modelling	-	-	-	-	-	-	-	-	-
5: Survey and Inspection	-	-	-	-	-	-	-	-	-
6: Employees competency	-	-	-	-	-	-	-	-	-

B.3. Case 3: Ice Skating Arena, Bad Reichenhall

Financial Consequences

- Material loss

  The project value of the roof is estimated using RS Means database [44]. The parameters used are:

  - Roof dimension: 3,600 m^2, circumference: 210m
  - Framing cost: €1.3/ft (RS Means p.124, value in 2011)
  - Decking cost: €6.9/ft^2 (RS Means p.61, value in 2011)

  The present value of the roof cost is €250,928.

- Reconstruction cost

  The building was not reconstructed after the incident.

- Monetary value of human life

  The incident caused 15 fatalities [76]. The total monetary value for the loss of human life is €75,000,000.

- Compensation cost

  Thirty people were heavily injured due to the collapse. There was also an expenses of €54,000 for legal settlement [76]. The total compensation is €1,554,000

The financial consequences (C) due to the failure is €76,804,928.

Impact of safety measure

- The weighting factors (α_f)

  Three factors became the issue in the case of ice arena in Bad Reichenhall: Control mechanism (F2); Structural risk management (F4); and Knowledge Infrastructure (F6). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

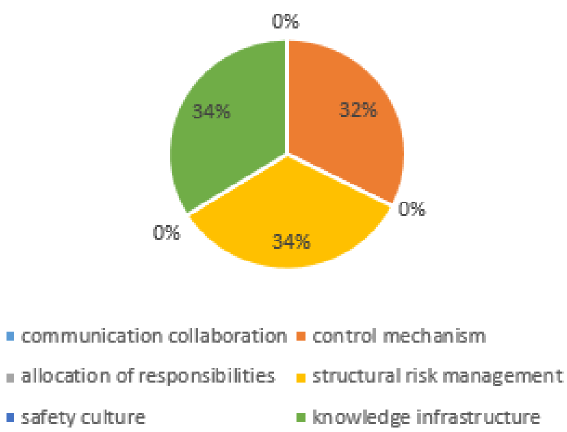

Figure B.3: Weight of factor in Case 3: Ice Skating Arena

- Weighted risk analysis (γ_n)

  Two measures are proposed in Bad Reichenhall Ice Skating Arena case study: Structural modelling (M4) and Survey and inspection (M5). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.3: The weighted risk analysis for Case 3: Ice Skating Arena

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability ($year^{-1}$)	Weighted risk (€/year)
Weight	-	33%	-	34%	-	34%			
1: Integrated coordination	-	-	-	-	-	-	-	-	-
2: Planning and responsibility	-	-	-	-	-	-	-	-	-
3: Supervision	-	-	-	-	-	-	-	-	-
4: Structural modelling	-	3.67	-	3.83	-	3.73	75%	$2.51 \cdot 10^{-5}$	1,927
5: Survey and Inspection	-	3.63	-	4.10	-	3.90	78%	$2.24 \cdot 10^{-5}$	1,720
6: Employees competency	-	-	-	-	-	-	-	-	-

B.4. Case 4: Terminal 2E, Charles de Gaulle Airport, Paris

Financial Consequences

- Material loss

  The project value of the whole Terminal 2E was approximately €750,000,000, with €150,000,000 was invested to the collapsed part [75]. The value of collapsed part is equivalent to present value €233,695,112.

- Reconstruction cost

  The reconstruction cost was reported to be around €100,000,000 in 2005 [34], equivalent to present value €146,853,371.

- Monetary value of human life

  The incident caused four fatalities [76]. The total monetary value for the loss of human life is €20,000,000.

- Compensation cost

  Three people were injured due to the incident [76]. The total monetary value for the compensation is €150,000.

The total financial consequences (C) due to the failure is €400,698,483.

Impact of safety measure

- The weighting factors (α_f)

  Four factors became the issue in the case of Paris Airport: Communication and collaboration (F1); Control mechanism (F2); Structural risk management (F4); and Knowledge Infrastructure (F6). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

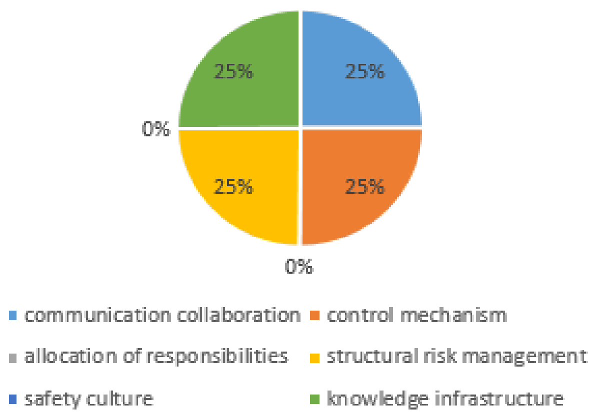

Figure B.4: Weight of factor in Case 4: CDG Airport

- Weighted risk analysis (γ_n)

  Two measures are proposed in Paris Airport case study: Supervision (M3) and Structural Modelling (M4). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.4: The weighted risk analysis for Case 4: Paris Airport

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability ($year^{-1}$)	Weighted risk (€/year)
Weight	25%	25%	-	25%	-	25 %			
1: Integrated coordination	-	-	-	-	-	-	-	-	-
2: Planning and responsibility	-	-	-	-	-	-	-	-	-
3: Supervision	3.67	4.00	-	3.63	-	3.66	75	$2.52 \cdot 10^{-5}$	10,102
4: Structural modelling	3.43	3.47	-	3.70	-	4.00	73	$2.70 \cdot 10^{-5}$	10,819
5: Survey and Inspection	-	-	-	-	-	-	-	-	-
6: Employees competency	-	-	-	-	-	-	-	-	-

B.5. Case 5: Patio Sevilla, Maastricht

Financial Consequences

- Material loss

  The project value of Patio Sevilla is estimated using "height charge principle" in [16]. Only part of complex which collapsed is analysed. Patio Sevilla is a six-story building, with the height per level of 2.55m (www.huurwoningen.nl). The GFA per one unit is 100m^2 (www.huurwoningen.nl), and there is one unit per story.

  The height charge of structural cost for this building is €110/m^3, and height charge of completion is €150/m^3. The land cost in Maastricht is approximately €250.16/m^2 (www.woningmarktcijfers.nl).

  The total building value is €1,226,781.

  Supposed that the balcony is 12.5/m^2 and there were 5 balconies, the estimated material loss is €127,790.

- Reconstruction cost

  For the case of Patio Sevilla, it is assumed that the material loss is equal to the cost to repair the balconies = €127,790.

- Monetary value of human life

  The incident caused two fatalities [15]. The total monetary value for the loss of human life is €10,000,000.

- Compensation cost

  There was no injury reported in the collapse incident.

The total financial consequences (C) is €10,255,579.

Impact of safety measure

- The weighting factors (α_f)

  Two factors became the issue in the case of Patio Sevilla: Communication and collaboration (F1); and Structural risk management (F4). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

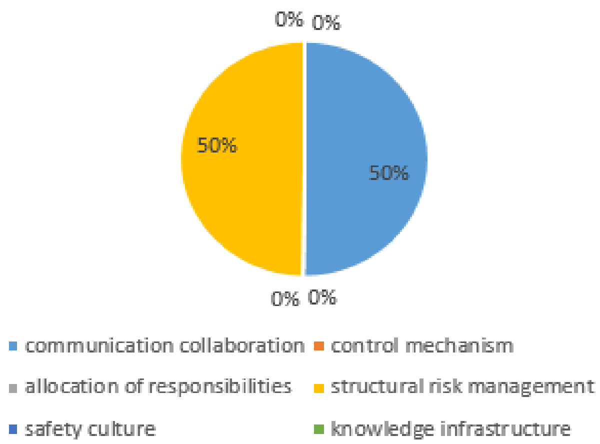

Figure B.5: Weight of factor in Case 5: Patio Sevilla

- Weighted risk analysis (γ_n) Three measures are proposed in Patio Sevilla case study: Integrated Coordination (M1), Supervision (M3), and Structural Modelling (M4). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.5: The weighted risk analysis for Case 5: Patio Sevilla

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability (year^{-1})	Weighted risk (€/year)
Weight	50 %	-	-	50%	-	-			
1: Integrated coordination	3.93	-	-	3.87	-	-	78%	$2.20 \cdot 10^{-5}$	226
2: Planning and responsibility	-	-	-	-	-	-	-	-	-
3: Supervision	3.67	-	-	3.83	-	-	75%	$2.50 \cdot 10^{-5}$	256
4: Structural modelling	3.50	-	-	3.50	-	-	70 %	$3.00 \cdot 10^{-5}$	308
5: Survey and Inspection	-	-	-	-	-	-	-	-	-
6: Employees competency	-	-	-	-	-	-	-	-	-

B.6. Case 6: Hartford Civic Centre, Connecticut

Financial Consequences

- Material loss

  The project value of Hartford Civic Centre was $30,000,000 in 1973 [68]. The roof cost was approximately 6% of the total investment [81], or about $1,800,000. The present value of the collapsed roof is €6,806,873.

- Reconstruction cost

  The roof was reconstructed using a standard design which costs approximately $ 500,000 (in the construction year) more than the original design [39]. The present value to rebuilt the standard roof is estimated €8,697,670.

- Monetary value of human life

  There was no fatalities reported in the incident.

- Compensation cost

  There was no fatalities reported in the incident.

The total financial consequences (C) due to the failure is €15,504,543

Impact of safety measure

- The weighting factors (α_f)

  Five factors became the issue in the case of Hartford Civic Centre: Control mechanism (F2); Allocation of responsibilities (F3); Structural risk management (F4); Safety Culture (F5); and Knowledge Infrastructure (F6). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

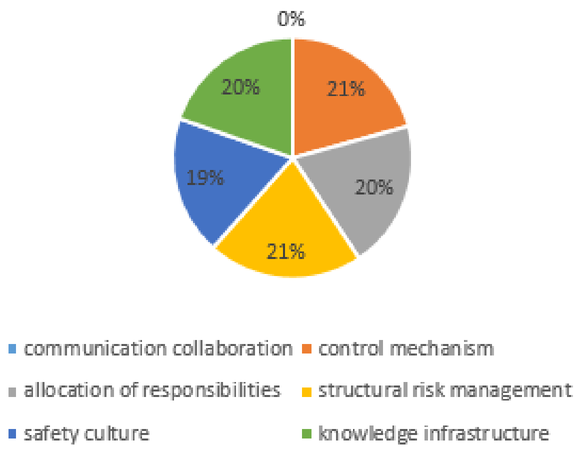

Figure B.6: Weight of factor in Case 6: Hartford Civic Centre

- Weighted risk analysis (γ_n)

  Three measures are proposed in Hartford Civic Centre case study: Planning and Responsibility (M2), Supervision (M3), and Structural Modelling (M4). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.6: The weighted risk analysis for Case 6: Hartford Civic Centre

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability ($year^{-1}$)	Weighted risk (€/year)
Weight	-	21%	20%	21%	19%	20%			
1: Integrated coordination	-	-	-	-	-	-	-	-	-
2: Planning and responsibility	-	3.60	3.87	3.57	3.63	3.60	73%	$2.70 \cdot 10^{-5}$	418
3: Supervision	-	3.90	3.70	3.80	3.63	3.73	75%	$2.49 \cdot 10^{-5}$	386
4: Structural modelling	-	3.40	3.30	3.40	3.27	4.03	70%	$3.04 \cdot 10^{-5}$	471
5: Survey and inspection	-	-	-	-	-	-	-	-	-
6: Employees competency	-	-	-	-	-	-	-	-	-

B.7. Case 7: Kemper Arena, Kansas City

Financial Consequences

- Material loss

  The project value of Kemper Arena was $23,200,000 in 1973 [81]. The roof cost for such sport arena was approximately 6% of the total investment [81], or about $ 1,392,000 (in 1973). The present value of the roof (2018) is €5,263,981.

- Reconstruction cost

  The reconstruction incurred cost of $ 6,000,000 [81], equal to present value of €17,911,360.

- Monetary value of human life

  There was no fatalities reported in the incident.

- Compensation cost

  There was no fatalities reported in the incident.

The total financial consequences (C) due to the failure is €23,175,341

Impact of safety measure

- The weighting factors (α_f)

  Three factors became the issue in the case of Kemper Arena: Control mechanism (F2); Structural risk management (F4); and Knowledge Infrastructure (F6). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

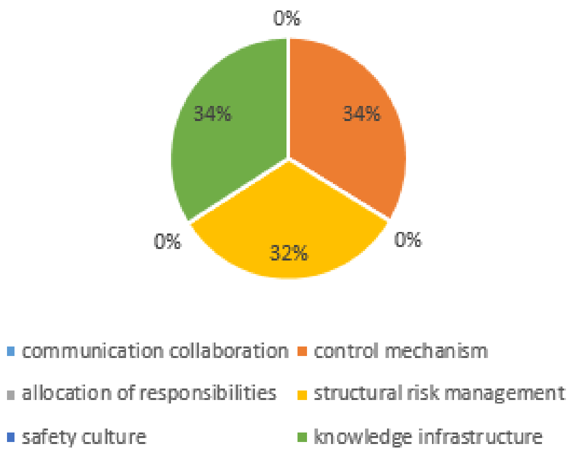

Figure B.7: Weight of factor in Case 7: Kemper Arena

- Weighted risk analysis (γ_n)

  Three measures are proposed in Kemper Arena case study: Supervision (M3); Structural modelling (M4); and Survey and inspection (M5). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.7: The weighted risk analysis for Case 7: Kemper Arena

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability (year^{-1})	Weighted risk (€/year)
Weight	-	34%	-	32%	-	34%			
1: Integrated coordination	-	-	-	-	-	-	-	-	-
2: Planning and responsibility	-	-	-	-	-	-	-	-	-
3: Supervision	-	3.83	-	3.70	-	3.67	75%	$2.53 \cdot 10^{-5}$	587
4: Structural modelling	-	3.67	-	3.70	-	3.97	76%	$2.44 \cdot 10^{-5}$	566
5: Survey and inspection	-	3.53	-	3.77	-	3.80	74%	$2.60 \cdot 10^{-5}$	603
6: Employees competency	-	-	-	-	-	-	-	-	-

B.8. Case 8: Ronan Point, East London

Financial Consequences

- Material loss

  The project value of Ronan Point is estimated using "height charge principle" in [16].

  The building consisted of 22 levels [18] and with assumption of 4m per level, the total height is 88m. Suppose that two-bedroom apartment is $75m^2$ and one-bedroom apartment is $30m^2$, the total GFA is $6{,}280m^2$.

  The height charge of structural cost for this building is €120/m^3, and height charge of completion is €150/m^3. The land cost in East London is approximately €1750/m^2 [28]. The total building value is €13,432,317.

  However, because the building was totally demolished in 1986, the reconstruction cost in 1968-1969 also become material loss.

  The total material loss is €13,998,302.

- Reconstruction cost

  The total reconstruction cost is approximately €565,985, assuming the reconstructed area is 25% of the building GFA and the repair cost is €361/m^2 (Section 3.4.2).

- Monetary value of human life

  The incident caused four fatalities [76]. The total monetary value for the loss of human life is €20,000,000.

- Compensation cost

  Seventeen people were injured due to the incident [76]. The total monetary value is €850,000.

The total financial consequences (C) is €35,414,287

Impact of safety measure

- The weighting factors (α_f)

  Five factors became the issue in the case of Ronan Point: Control mechanism (F2); Allocation of responsibilities (F3); Structural risk management (F4); Safety Culture (F5); and Knowledge Infrastructure (F6). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

Figure B.8: Weight of factor in Case 8: Ronan Point

- Weighted risk analysis (γ_n)

  Three measures are proposed in Ronan Point case study: Planning and Responsibility (M2), Supervision (M3), and Structural Modelling (M4). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.8: The weighted risk analysis for Case 8: Ronan Point

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability (year^{-1})	Weighted risk (€/year)
Weight	-	21%	20%	21%	18%	21%			
1: Integrated coordination	-	-	-	-	-	-	-	-	-
2: Planning and responsibility	-	3.77	4.03	3.70	3.53	3.87	76	$2.43 \cdot 10^{-5}$	861
3: Supervision	-	4.03	4.00	3.60	3.73	3.90	77	$2.29 \cdot 10^{-5}$	811
4: Structural modelling	-	3.67	3.47	4.10	3.37	3.97	75	$2.55 \cdot 10^{-5}$	902
5: Survey and Inspection	-	-	-	-	-	-	-	-	-
6: Employees competency	-	-	-	-	-	-	-	-	-

B.9. Case 9: Bos en Lommerplein, Amsterdam

Financial Consequences

- Material loss

  It is assumed that there was no material loss incurred in the incident. Only repair cost is incurred. The value is calculated in the next point.

- Reconstruction cost

  Refurbishment was done to the whole building [58]. The building GFA is €11,000 m^2, and the building is classified as low rise building with repair cost of 2018 €155/m^2 (Section 3.4.2). The total repair cost is €1,699,500.

- Monetary value of human life

  There was no fatalities in the near collapse incident.

- Compensation cost

  Nobody injured in the incident. However, the evacuation incurred cost of €8,000,000 in 2007, equivalent to present value of €11,073,871.

The total financial consequences (C) due to the failure is €12,773,371.

Impact of safety measure

- The weighting factors (α_f)

  Five factors became the issue in the case of Bos en Lommerplein: Communication and collaboration (F1); Control mechanism (F2); Allocation of responsibilities (F3); Safety Culture (F5); and Knowledge Infrastructure (F6). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

Figure B.9: Weight of factor in Case 9: Bos en Lommerplein

- Weighted risk analysis (γ_n)

  Three measures are proposed in Ronan Point case study: Integrated coordination (M1), Supervision (M3), and Employees competency (M6). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.9: The weighted risk analysis for Case 9: Bos en Lommer

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability (year^{-1})	Weighted risk (€/year)
Weight	20%	20%	20 %	-	18%	21 %			
1: Integrated coordination	3.63	3.93	3.77	0	3.40	3.67	74%	$2.63 \cdot 10^{-5}$	336
2: Planning and responsibility	-	-	-	-	-	-	-	-	-
3: Supervision	3.87	3.80	3.70	0	3.43	4.07	76%	$2.43 \cdot 10^{-5}$	311
4: Structural modelling	-	-	-	-	-	-	-	-	-
5: Survey and inspection	-	-	-	-	-	-	-	-	-
6: Employees competency	3.73	3.63	3.47	0	3.20	4.13	73%	$2.71 \cdot 10^{-5}$	346

B.10. Case 10: Amoco Tower, Chicago

Financial Consequences

- Material loss

  The cost of marble façade is estimated using the database from RS Means [44]. The unit cost of marble panel is $ 64 per square feet (in 2011), equal to present value €66.49 per square feet. The façade area which taken down is 77,976 m^2 [39]. The total present value is €68,610,428.

- Reconstruction cost

  The façade replacement cost was reported as much as $ 80,000,000 in 1988, equal to present value €194,180,998.

- Monetary value of human life

  There was no fatalities in the case of Amoco Tower.

- Compensation cost

  Nobody injured in the case of Amoco Tower.

The total financial consequences (C) due to the failure is €262,791,426.

Impact of safety measure

- The weighting factors (α_f)

  Two factors became the issue in the case of Amoco Tower: Control mechanism (F2); and Knowledge Infrastructure (F6). The contribution of the critical factors (α_f) is calculated using Equation 3.6.

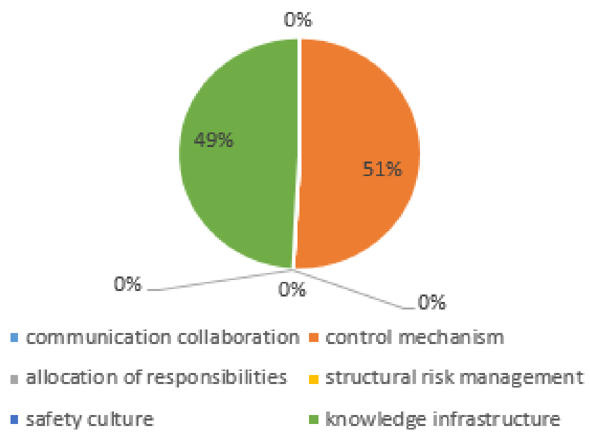

Figure B.10: Weight of factor in Case 10: Amoco Tower

- Weighted risk analysis (γ_n)

  Two measures are proposed in Amoco Tower case study: Structural modelling (M4); and Survey and inspection (M5). The calculation procedure is elaborated in Section 3.4.2. The result is presented as follows:

Table B.10: The weighted risk analysis for Case 10: Amoco Tower

	Impact on critical factors						Weighted risk analysis		
	F1	F2	F3	F4	F5	F6	γ_n	$P_{w,n}$	$R_{w,n}$
	Communication & collaboration	Control mechanism	Allocation of responsibilities	Structural risk management	Safety culture	Knowledge infrastructure	Probability reduction (%)	Weighted probability ($year^{-1}$)	Weighted risk (€/year)
Weight	0%	51%	0%	0%	0%	49%			
1: Integrated coordination	-	-	-	-	-	-	-	-	-
2: Planning and responsibility	-	-	-	-	-	-	-	-	-
3: Supervision	0	3.80	0	0	0	3.93	77%	$2.27 \cdot 10^{-5}$	5,963
4: Structural modelling	0	3.77	0	0	0	3.87	76%	$2.37 \cdot 10^{-5}$	6,224
5: Survey and inspection	-	-	-	-	-	-	-	-	-
6: Employees competency	-	-	-	-	-	-	-	-	-

C

Appendix C: Financial Model

The financial model is developed to facilitate decision maker instead of actual forecast. The principles mentioned in Section 3.4.2 and Section 3.5 are applied. All values are presented in 2018 Euro unless stated otherwise. The calculation of the NPV is following Equation 3.7 (Scenario without safety measure) and 3.8 (Scenario with safety measure). The assumptions and parameters elaborated in Section 3.4.2 and Section 3.5.1 are applied for the models unless specific information is mentioned. The summary for each case is presented as profit/loss analysis (Formula 3.10).

C.1. Case 1: Berlin Congress Hall

Scenario 0 (without measure)

- Initial investment (C_0)

  The initial investment for the whole terminal is estimated using the database from RSmeans (p. 478) [44]. The input data used are type of building (auditorium) and total area (3,500 m^2 or 37,660 ft^2). The unit cost is 2011 \$ 5,187,288/ft^2. The present value of building cost is equal to €6,379,710.

- Operation-maintenance (C_{om})

  The unit cost of operation maintenance is €87.82 per m^2 per year (Section 3.5.1). With total area of 3,500 m^2, the total annual operation-maintenance cost is €307,358.

- Revenue (C_{ref})

  The average annual revenue for such hall is assumed \$ 450,000 [53], equivalent to present value €622,905.

- Financial consequences (C)

  The failure occurred in 1980 incurred cost of €6,853,758 (Appendix B.1). The hall was in major restoration up to for two years, assumed no cash flow in 1981-1982.

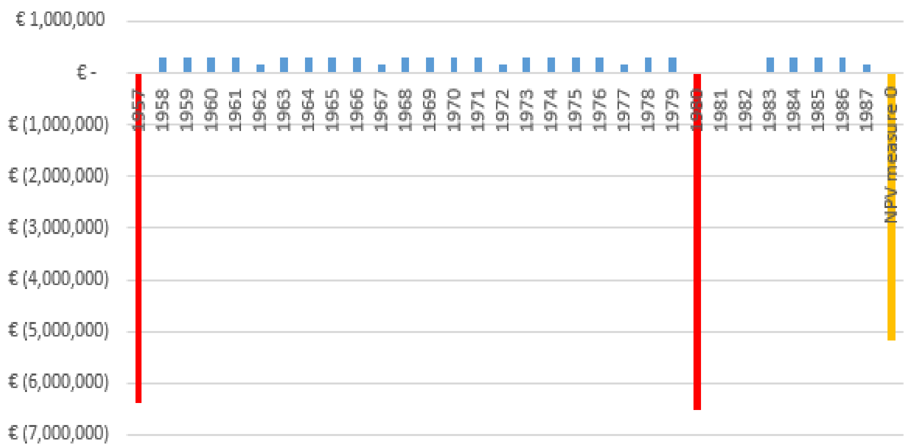

Figure C.1: Cash flow analysis for Case 1: Berlin Congress Hall, Scenario 0

Scenario 2 (with Planning and responsibility)
The safety measure incurred an additional cost due to the allocation of extra time. Other parameters remain the same.

- Measure Investment (C_m)

  Using the assumptions in Section 3.5.1, the additional six months of construction time will cost €382,783.

- Weighted risk (R_w)

  The annual risk for Scenario 2 is €187 (Appendix B.1).

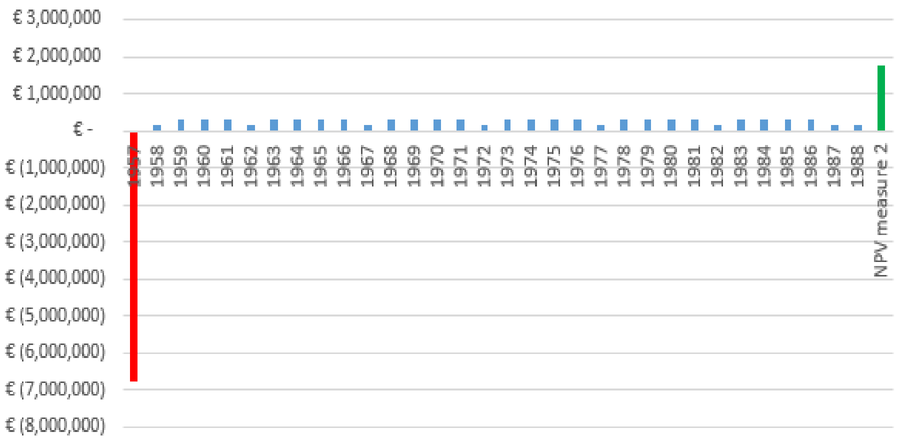

Figure C.2: Cash flow analysis for Case 1: Berlin Congress Hall, Scenario 2

Scenario 4 (with structural modelling)
The implementation of safety measure incurred an additional cost to make physical model. Other parameters remain the same.

- Measure Investment (C_m)

  The modelling cost is assumed 1% of investment (Section 3.5.1). The total additional investment is €63,797.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €177 (Appendix B.1).

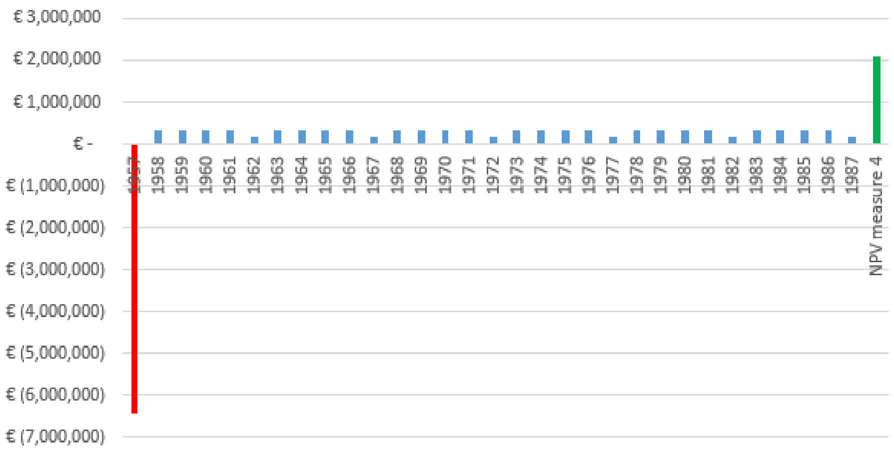

Figure C.3: Cash flow analysis for Case 1: Berlin Congress Hall, Scenario 4

Scenario 5 (with survey and inspection)

- Measure Investment (C_m)

  Routine survey and inspection cost €13.66 per m^2 per year [3]. Using the total area, the total additional cost is €47,811 per year or €1,434,340 for the whole assessment time.

- Weighted risk (R_w)

  The annual risk for Scenario 5 is €176 (Appendix B.1).

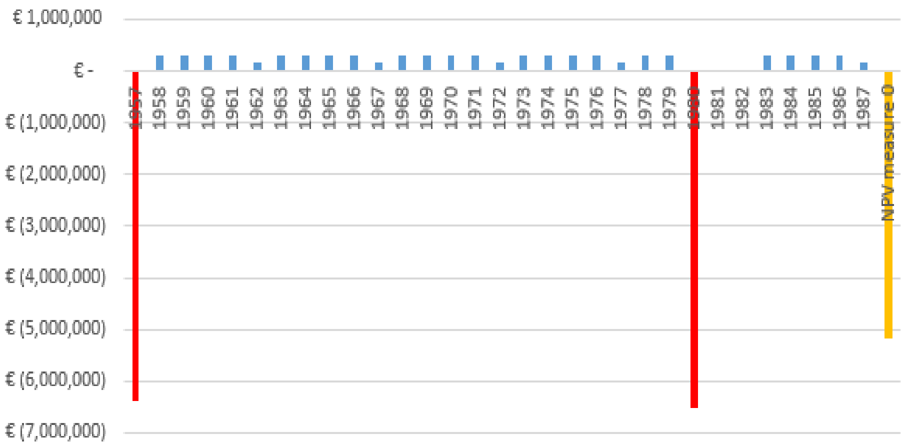

Figure C.4: Cash flow analysis for Case 1: Berlin Congress Hall, Scenario 5

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 1: Berlin Congress Hall:

Table C.1: Summary: Case 1, Berlin Congress Hall (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €6,379,710	- €5,166,555	19%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €6,762,493	€1,776,039	26%
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €6,443,508	€2,095,521	33%
Scenario 5	Survey and inspection	- €7,814,050	€725,008	9%
Scenario 6	Employees competency	-	-	-

Table C.2: Summary: Case 1, Berlin Congress Hall (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €7,299,036	- €7,549,173	-103%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €7,736,978	- €745,213	-10%
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €7,372,026	- €379,760	-5%
Scenario 5	Survey and inspection	- €9,574,666	- €2,582,370	-27%
Scenario 6	Employees competency	-	-	-

Table C.3: Summary: Case 1, Berlin Congress Hall (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €5,561,475	- €4,213,321	-76%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €5,895,164	€2,825,153	48%
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €5,617,090	€3,103,718	55%
Scenario 5	Survey and inspection	- €5,561,475	€2,263,437	41%
Scenario 6	Employees competency	-	-	-

Table C.4: Summary: Case 1, Berlin Congress Hall (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €6,379,710	- €10,416,555	-163%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €6,762,493	€1,771,600	26%
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €6,443,508	€2,091,462	32%
Scenario 5	Survey and inspection	- €7,814,050	€1,274,216	16%
Scenario 6	Employees competency	-	-	-

Table C.5: Summary: Case 1, Berlin Congress Hall (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €6,379,710	- €5,166,555	-81%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €7,145,276	€1,368,879	19%
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €6,826,290	€1,712,562	25%
Scenario 5	Survey and inspection	- €7,814,050	€725,008	9%
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 1: Berlin Congress Hall is presented in Figure C.5

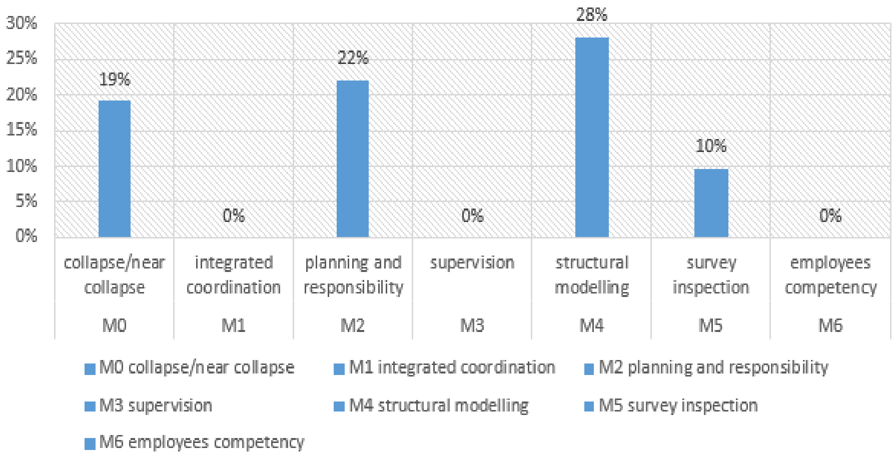

Figure C.5: Average profit/loss for Case 1: Berlin Congress Hall

C.2. Case 2: Hyatt Regency, Kansas City

Scenario 0 (without measure)

- Initial investment (C_0)

  The initial investment for the hotel is estimated using the principle of "Building cost and eco-cost aspects of tall buildings" [16]. The height of Hyatt Regency is 154m, and the GFA is estimated as 32,170 m^2 based on the number of rooms and functional areas [23].

  The structural cost is €140 per m^3 and the completion cost is €160 per m^3 according to the "façade height charge" [16]. The land cost in Kansas is assumed €100 per m^2 [59].

  The total building value is €72,728,842

- Operation-maintenance (C_{om})

  The unit cost of operation maintenance is €48.62 per room per night [25]. With total 775 rooms, the total annual operation-maintenance cost is €13,753,943.

- Revenue (C_{ref})

  The average rent price for Hyatt Regency per May 2018 is estimated around €115 per room per night (www.hotels.com). The average occupancy for such 3-star hotel is 60% [29]. The annual revenue is €19,518,375.

- Financial consequences (C)

  The failure occurred in 1981 incurred cost of €790,777,772 (Appendix B.2).

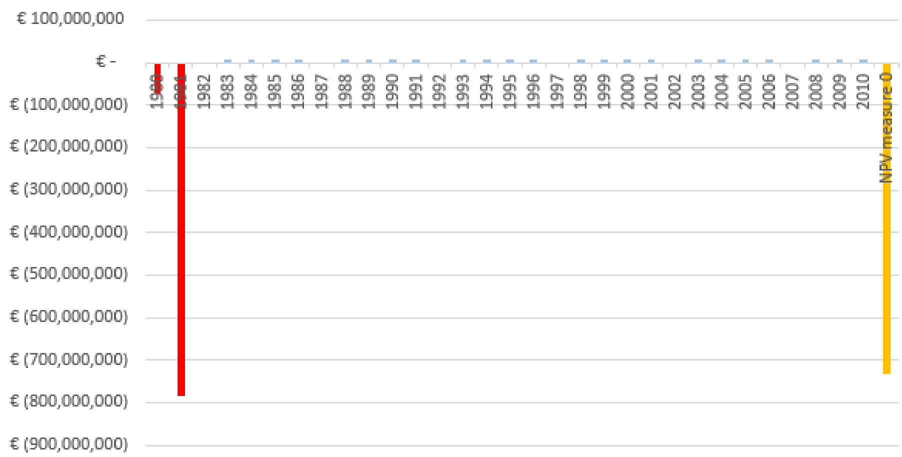

Figure C.6: Cash flow analysis for Case 2: Hyatt Regency, Scenario 0

Scenario 1 (with Integrated coordination)

- Measure investment (C_m)

  Using the assumptions in Section 3.5.1, the cost of CIMS implementation is €90,000 (in 2011) [78], equivalent to present value €104,335.

- Weighted risk (R_w)

  The annual risk for Scenario 1 is €19,501 (Appendix B.2).

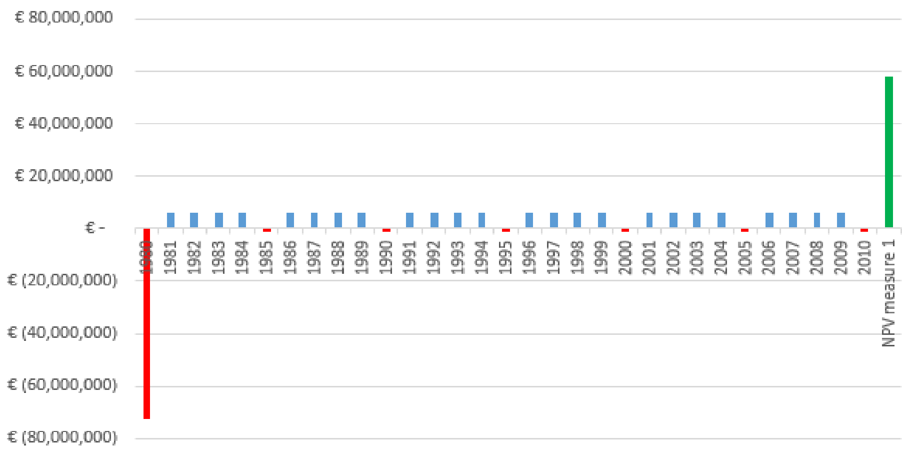

Figure C.7: Cash flow analysis for Case 2: Hyatt Regency, Scenario 1

Scenario 2 (with Planning and responsibility

- Measure Investment (C_m)

  ”Planning and responsibility” in form of hiring project engineers who are supervising less project at the same time is assumed costless

- Weighted risk (R_w)

  The annual risk for Scenario 2 is €21,267 (Appendix B.2).

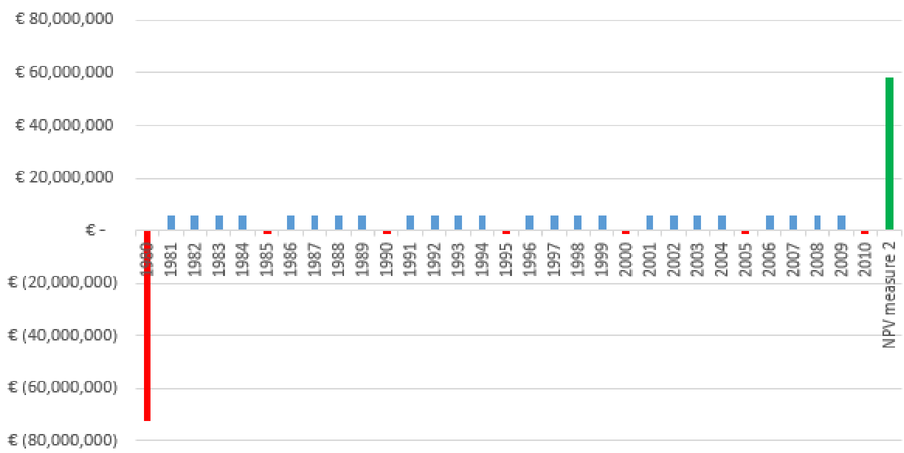

Figure C.8: Cash flow analysis for Case 2: Hyatt Regency, Scenario 2

Scenario 3 (with Supervision)

The implementation of safety measure will incur additional costs to employ supervisors and delay cost due to the extra activity in a fast-track project.

- Measure Investment (C_m)

  The contractor size for the bridge is estimated 95 persons based on its project value [36]. The number of supervisors required on site is assumed 1 personnel [72], with annual salary $ 75,000. The delay costs for extra six months construction is approximately €4,363,731 (Section 3.5.1). The total additional investment is €4,438,731.

- Weighted risk (R_w)

  The annual risk for Scenario 3 is €18,459 (Appendix B.2).

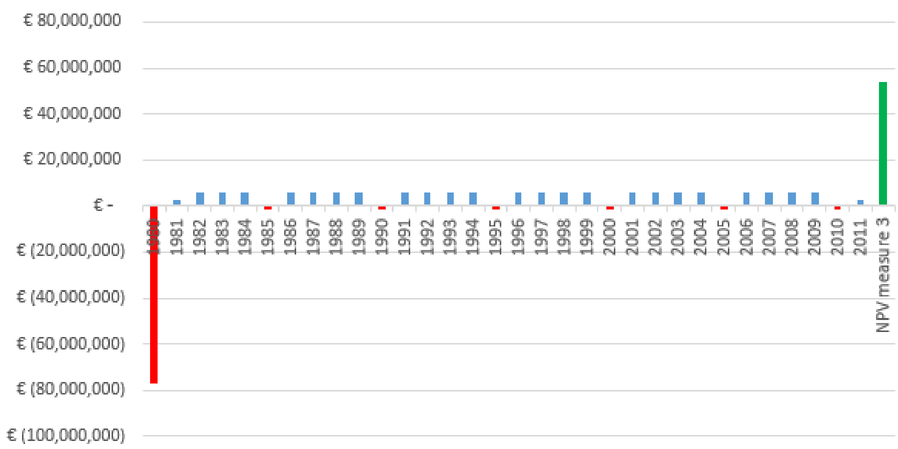

Figure C.9: Cash flow analysis for Case 2: Hyatt Regency, Scenario 3

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 2: Hyatt Regency:

Table C.6: Summary: Case 2, Hyatt Regency (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	- €730,722,936	-1005%
Scenario 1	Integrated coordination	- €72,833,177	- €58,252,925	80%
Scenario 2	Planning and responsibility	- €72,728,842	€58,304,280	80%
Scenario 3	Supervision	- €77,167,573	€53,931,335	70%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.7: Summary: Case 2, Hyatt Regency (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €88,151,035	- €782,081,471	-887%
Scenario 1	Integrated coordination	- €88,265,901	€6,242,421	7%
Scenario 2	Planning and responsibility	- €88,151,035	€6,588,082	7%
Scenario 3	Supervision	- €93,515,097	€1,289,910	1%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.8: Summary: Case 2, Hyatt Regency (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €59,778,934	- €575,471,992	-963%
Scenario 1	Integrated coordination	- €59,873,525	€105,532,945	176%
Scenario 2	Planning and responsibility	- €59,778,934	€105,581,900	177%
Scenario 3	Supervision	- €63,440,670	€101,976,828	161%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.9: Summary: Case 2, Hyatt Regency (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	- €1,300,722,936	-1788%
Scenario 1	Integrated coordination	- €72,833,177	€57,831,225	79%
Scenario 2	Planning and responsibility	- €72,728,842	€57,844,391	80%
Scenario 3	Supervision	- €77,167,573	€53,518,860	69%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.10: Summary: Case 2, Hyatt Regency (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	- €730,722,936	-1005%
Scenario 1	Integrated coordination	- €75,695,892	€55,370,709	73%
Scenario 2	Planning and responsibility	- €77,092,573	€53,919,282	70%
Scenario 3	Supervision	- €81,568,803	€49,548,561	61%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 2: Hyatt Regency is presented in Figure C.10.

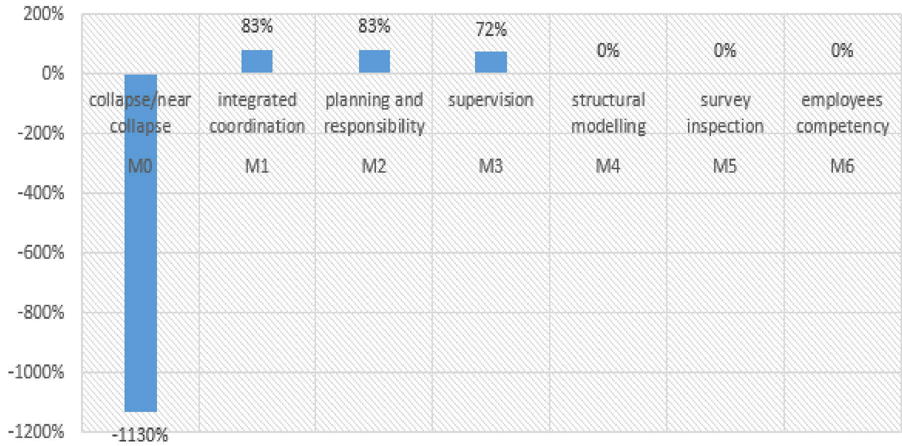

Figure C.10: Average profit/loss for Case 2: Hyatt Regency

C.3. Case 3: Ice Skating Arena, Bad Reichenhall

Scenario 0 (without measure)

- Initial investment (C_0)

  The initial investment for the whole terminal is estimated using the database from RSmeans (p. 481) [44]. The input data used are type of building (ice rink) and total area (3,600 m^2 or 38,736 ft^2). The unit cost for such building is 2011 $ 203 per ft^2. The present value of building cost is equal to €9,672,432.

- Operation-maintenance (C_{om})

  There was no maintenance activity reported during the whole lifetime of the arena. The operational cost is €74.40 per m^2 per year [3]. The annual operational cost is €267,841.

- Revenue (C_{ref})

  The average annual revenue for such hall is assumed $ 450,000 or equivalent to present value €622,905 [53].

- Financial consequences (C)

  The failure occurred in 2006 incurred monetary consequences of €76,804,928 (Appendix B.3). The hall was not reconstructed. The assessment period for Case 3: Ice Skating Arena, Bad Reichenhall is 34 year instead of 30 years, from its opening up to the collapse.

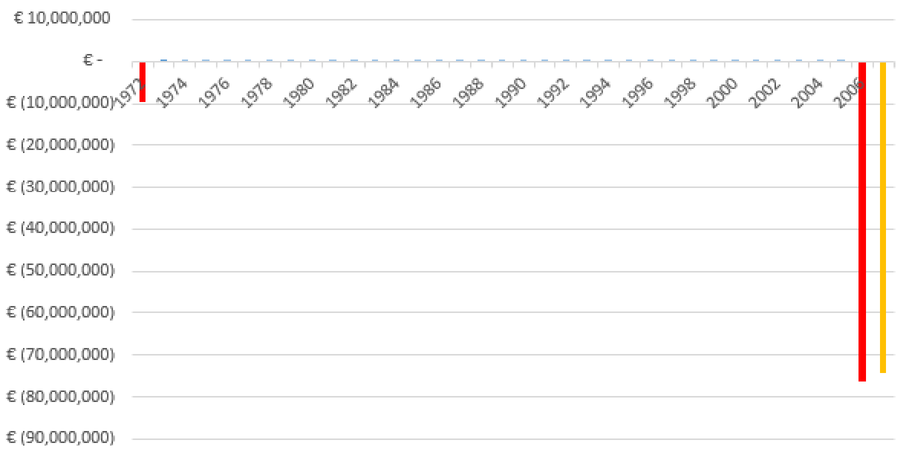

Figure C.11: Cash flow analysis for Case 3: Bad Reichenhall, Scenario 0

Scenario 4 (with structural modelling)

The implementation of safety measure incurred an additional cost to make physical and/or computational model.

- Measure Investment (C_m)

  The cost of mock up model is assumed 1% of investment (Section 3.5.1), or €96,724. The cost of computational model is approximately 0.25% of building value, or €24,181. The total additional investment is €120,905.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €1,927 (Appendix B.3).

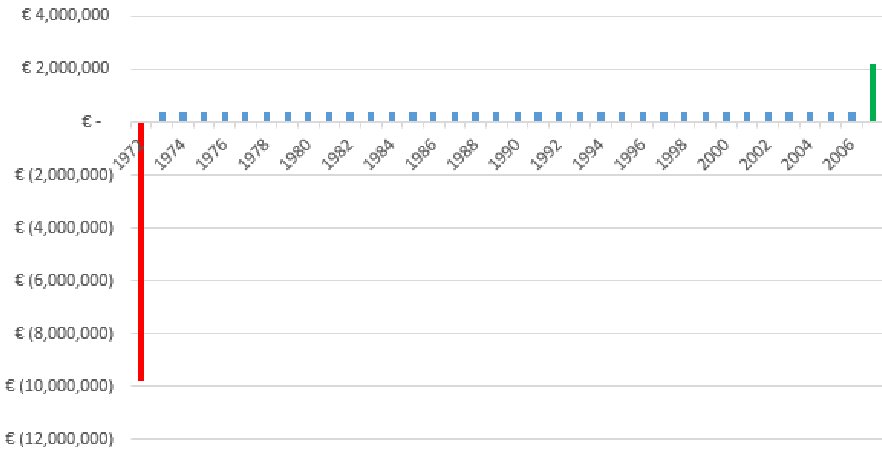

Figure C.12: Cash flow analysis for Case 3: Bad Reichenhall, Scenario 4

Scenario 5 (with survey and inspection)

- Measure Investment (C_m)

  Routine inspection costs €6.72 per m^2 per year [3]. The total additional cost is €24,192 per year or €822,528 for the whole assessment time.

- Weighted risk (R_w)

  The annual risk for Scenario 5 is €1,720 (Appendix B.3).

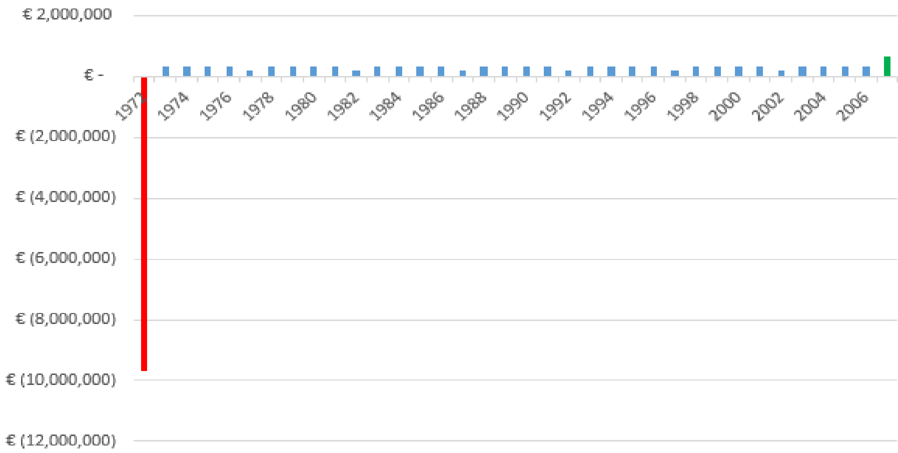

Figure C.13: Cash flow analysis for Case 3: Bad Reichenhall, Scenario 5

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 3: Ice Skating Arena Bad Reichenhall:

Table C.11: Summary: Case 3, Ice Skating Arena Bad Reichenhall (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €9,672,432	- €74,405,174	- 769%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €9,793,338	€2,213,318	23%
Scenario 5	Survey and inspection	- €10,494,960	€642,663	6%
Scenario 6	Employees competency	-	-	-

Table C.12: Summary: Case 3, Ice Skating Arena Bad Reichenhall (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €11,066,244	- €76,277,331	-689%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €11,204,572	€450,051	4%
Scenario 5	Survey and inspection	- €11,888,772	€1,574,464	-13%
Scenario 6	Employees competency	-	-	-

Table C.13: Summary: Case 3, Ice Skating Arena Bad Reichenhall (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €8,431,886	- €73,891,887	-876%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €8,537,285	€2,778,671	33%
Scenario 5	Survey and inspection	- €8,431,886	€1,494,135	18%
Scenario 6	Employees competency	-	-	-

Table C.14: Summary: Case 3, Ice Skating Arena Bad Reichenhall (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €9,672,432	- €150,925,923	- 1560%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €9,793,338	€2,148,030	22%
Scenario 5	Survey and inspection	- €11,888,772	€584,417	5%
Scenario 6	Employees competency	-	-	-

Table C.15: Summary: Case 3, Ice Skating Arena Bad Reichenhall (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €9,672,432	- €74,405,174	-769%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €10,373,684	€1,631,045	16%
Scenario 5	Survey and inspection	- €10,494,960	€642,663	6%
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 1: Berlin Congress Hall is presented in Figure C.14.

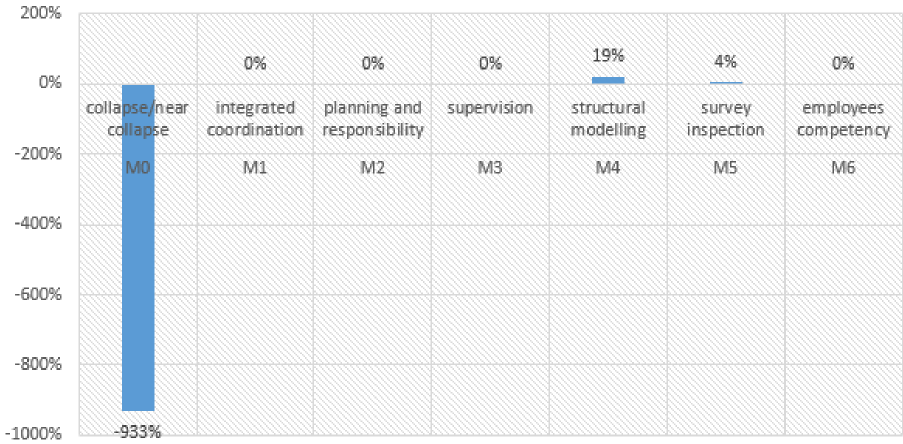

Figure C.14: Average profit/loss for Case 3: Ice Skating Arena Bad Reichenhall

C.4. Case 4: Terminal 2E, Charles de Gaulle Airport, Paris

Scenario 0 (without measure)

- Initial investment (C_0)

  The initial investment for the whole terminal was approximately 750 million Euro in 2003 [75], equivalent to present value 2018 €1,168,475,562.

- Operation-maintenance (C_{om})

  The average operational cost for airport is 2014 $ 16.82, equivalent to €18,93 per passenger per year [2]. With a capacity of 11 million passengers per year [75], the total annual operation-maintenance cost is €208,241,640.

- Revenue (C_{ref})

  The average annual revenue for airport is 2014 $ 41.58, equivalent to €46,80 per passenger per year [2]. With capacity of 11 million passengers per year [75], the annual revenue is €514,785,219 per year.

- Financial consequences (C)

  The failure occurred in May 2004 costs the project €400,698,483 (Appendix B.4). The terminal was in major restoration up to 2007, assumed no cash flow from 2005-2007.

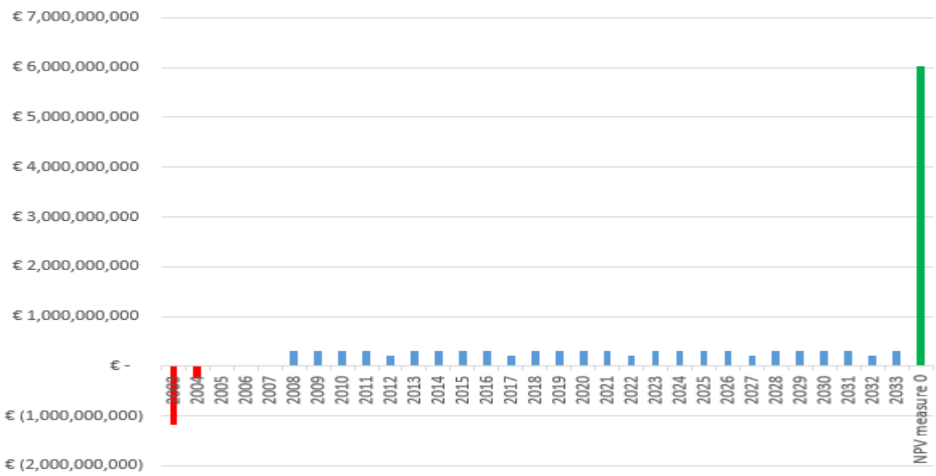

Figure C.15: Cash flow analysis for Case 4: Paris Airport, Scenario 0

Scenario 3 (with supervision)

- Measure Investment (C_m)

  The contractor size for the collapsed part is estimated 18,433 persons, based on its project value [36]. The number of supervisors required on site is assumed 60 personnel [72]. The duration of construction is 6 years [75]. With annual salary of $ 75,000 per person, the total cost of supervision is €27,000,000.

- Weighted risk (R_w)

  The annual risk for Scenario 3 is €10,102 (Appendix B.4)

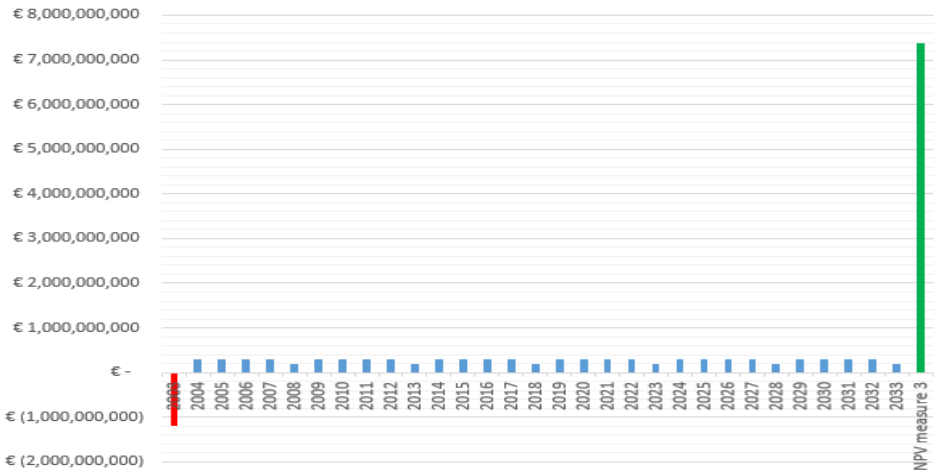

Figure C.16: Cash flow analysis for Case 4: Paris Airport, Scenario 3

Scenario 4 (with structural modelling)

The implementation of safety measure will incur an additional cost to perform three dimensional modelling. Other parameters remain the same.

- Measure Investment (C_m)

  The modelling cost is approximately 0.25% of investment [6] (Section 3.5.1). The total additional investment is €2,921,189.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €10,819 (Appendix B.4)

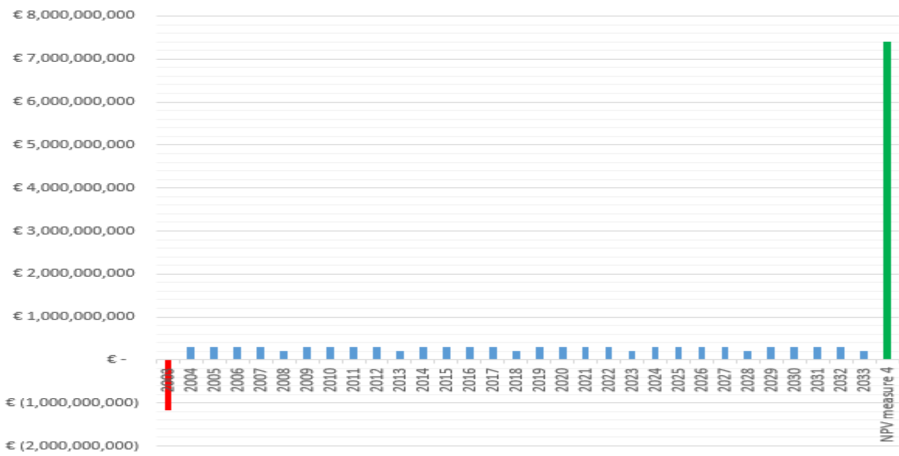

Figure C.17: Cash flow analysis for Case 4: Paris Airport, Scenario 4

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 4: Charles de Gaulle Airport:

Table C.16: Summary: Case 4, CDG Airport (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,168,475,562	€6,033,626,710	516%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,195,475,562	€7,375,803,853	617%
Scenario 4	Structural modelling	- €1,171,396,751	€7,399,861,130	632%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.17: Summary: Case 4, CDG Airport (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,559,196,135	€6,130,982,288	393%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,595,378,717	€7,661,207,156	480%
Scenario 4	Structural modelling	- €1,563,094,125	€7,693,463,772	492%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.18: Summary: Case 4, CDG Airport (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €870,726,717	€5,850,438,294	672%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €899,387,761	€7,025,348,803	781%
Scenario 4	Structural modelling	- €872,903,533	€7,051,816,471	808%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.19: Summary: Case 4, CDG Airport (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,168,475,562	€6,013,476,710	515%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,195,475,562	€7,375,803,853	617%
Scenario 4	Structural modelling	- €1,171,396,751	€7,399,844,807	632%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.20: Summary: Case 4, CDG Airport (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,168,475,562	€6,033,626,710	516%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,267,834,096	€7,303,435,218	576%
Scenario 4	Structural modelling	- €1,241,505,285	€7,329,741,777	590%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 4: Charles de Gaulle Airport is presented in the Figure C.18.

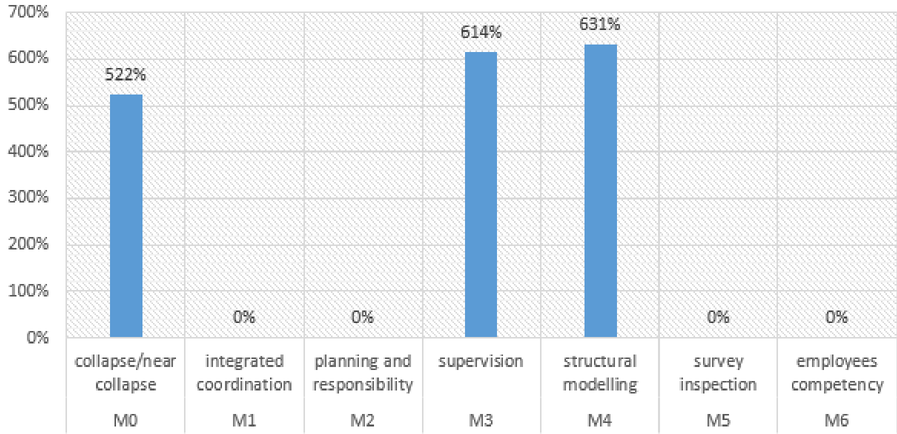

Figure C.18: Average profit/loss for Case 4: CDG Airport

C.5. Case 5: Patio Sevilla, Maastricht

Scenario 0 (without measure)

- Initial investment (C_0)

  The construction cost of Patio Sevilla is estimated using "height charge principle" in [16]. The estimated project value is €1,226,781 (See Appendix B.5).

- Operation-maintenance (C_{om})

  The total GFA of the assessed part of the building is assumed 600m^2 (Section B.5). The unit cost is €87.82 per m^2 per year (Section 3.5.1). The total annual operation-maintenance cost is €52,690. The building was restored after the incident, and for the model it is assumed there is no cash flow in 2004 due to the repair.

- Revenue (C_{ref})

  The average apartment price in Maastricht is approximately €1,500 per unit per month, based on the market price (www.huurwoningen.nl). The occupancy rate is assumed 100%. With total 6 apartment units in the assessed part of the building, the annual revenue is estimated €108,000. The building was restored after the incident, and for the model it is assumed there is no cash flow in 2004 due to the repair.

- Financial consequences (C)

  The total financial consequences (C) due to the failure is €10,916,972 (Appendix B.5).

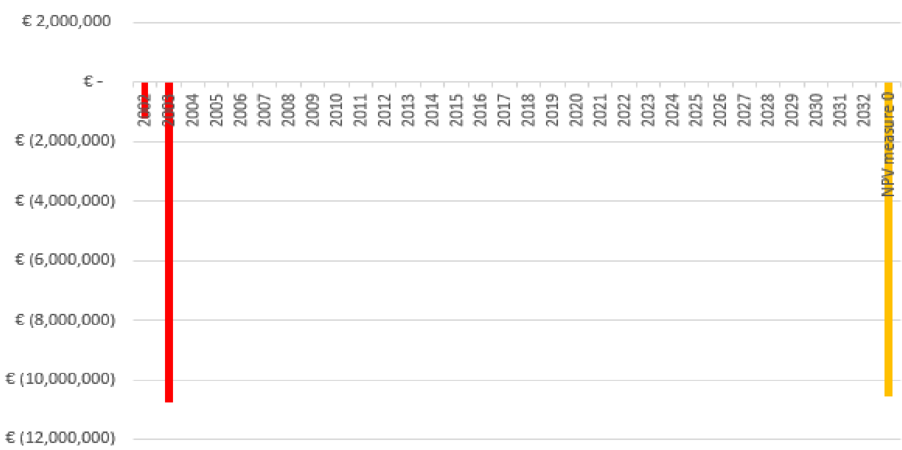

Figure C.19: Cash flow analysis for Case 5: Patio Sevilla, Scenario 0

Scenario 1 (with Integrated coordination)

- Measure Investment (C_m)

  Using the assumptions in Section 3.5.1, the cost of CIMS implementation is €90,000 (in 2011) [78], equivalent to present value €104,335.

- Weighted risk (R_w)

  The annual risk for Scenario 1 is €226 (Appendix B.5).

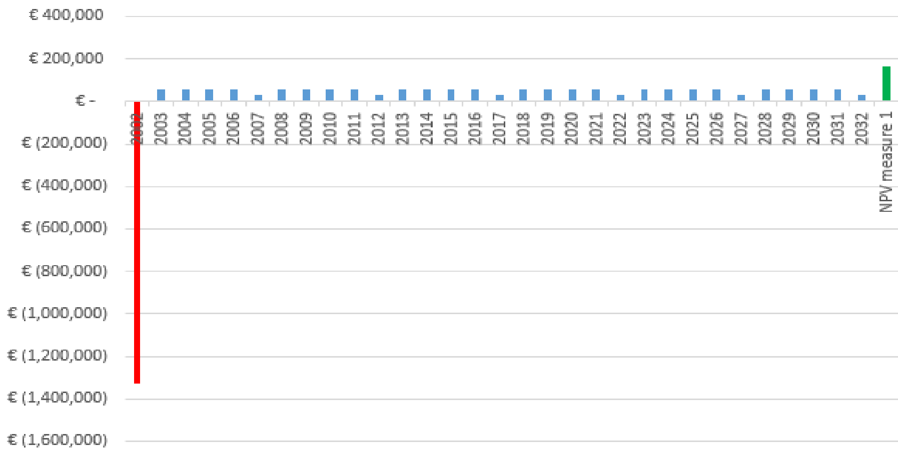

Figure C.20: Cash flow analysis for Case 5: Patio Sevilla, Scenario 1

Scenario 3 (with supervision)

- Measure investment (C_m)

  The contractor size for the collapsed part is estimated 10 persons, based on its project value [36]. The number of supervisors required on site is assumed 1 person [72]. The construction took three years to complete [76]. The total additional investment is estimated €225,000.

- Weighted risk (R_w)

  The annual risk for Scenario 3 is €256 (Appendix B.5).

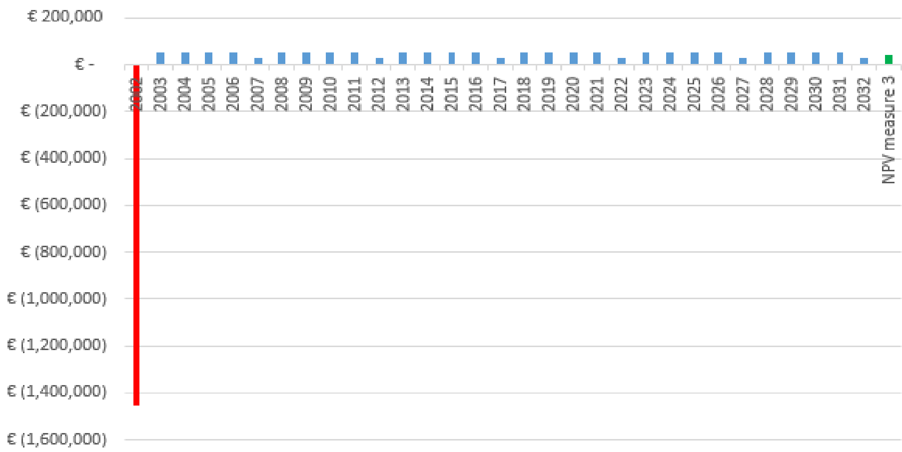

Figure C.21: Cash flow analysis for Case 5: Patio Sevilla, Scenario 3

Scenario 4 (with structural modelling)

The implementation of safety measure incurred an additional cost to develop physical model.

- Measure Investment (C_m)

  The physical modelling cost is assumed 1% of investment (Section 3.5.1). The total additional investment is €12,268.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €308 (Appendix B.5).

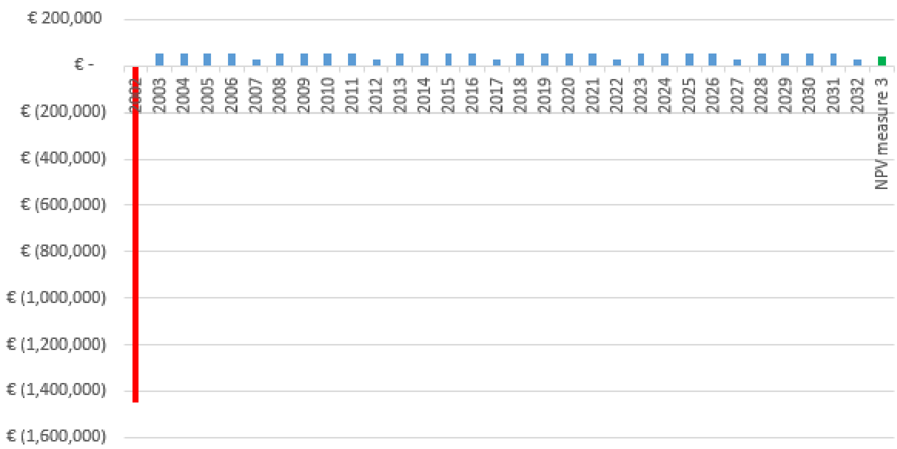

Figure C.22: Cash flow analysis for Case 5: Patio Sevilla, Scenario 4

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 5: Patio Sevilla.

Table C.21: Summary: Case 5, Patio Sevilla (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,226,781	- €10,566,108	-861%
Scenario 1	Integrated coordination	- €1,331,116	€163,346	12%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,451,781	€41,754	3%
Scenario 4	Structural modelling	- €1,239,049	€252,950	20%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.22: Summary: Case 5, Patio Sevilla (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,486,921	- €11,130,736	-749%
Scenario 1	Integrated coordination	- €1,601,786	- €1,127,211	-70%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,747,386	- €1,273,742	-73%
Scenario 4	Structural modelling	- €1,501,790	- €1,029,690	-69%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.23: Summary: Case 5, Patio Sevilla (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,008,344	- €9,057,305	-898%
Scenario 1	Integrated coordination	- €1,102,934	€1,044,248	95%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,240,161	€906,099	73%
Scenario 4	Structural modelling	- €1,018,427	€1,126,304	111%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.24: Summary: Case 5, Patio Sevilla (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,226,781	- €19,904,716	-1623%
Scenario 1	Integrated coordination	- €1,331,116	€156,747	12%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,451,781	€34,252	2%
Scenario 4	Structural modelling	- €1,239,049	€243,950	20%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.25: Summary: Case 5, Patio Sevilla (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,226,781	- €10,566,108	-861%
Scenario 1	Integrated coordination	- €1,404,722	€89,513	6%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €1,562,888	- €69,609	-4%
Scenario 4	Structural modelling	- €1,312,656	€179,036	14%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 5: Patio Sevilla is presented in the Figure C.23.

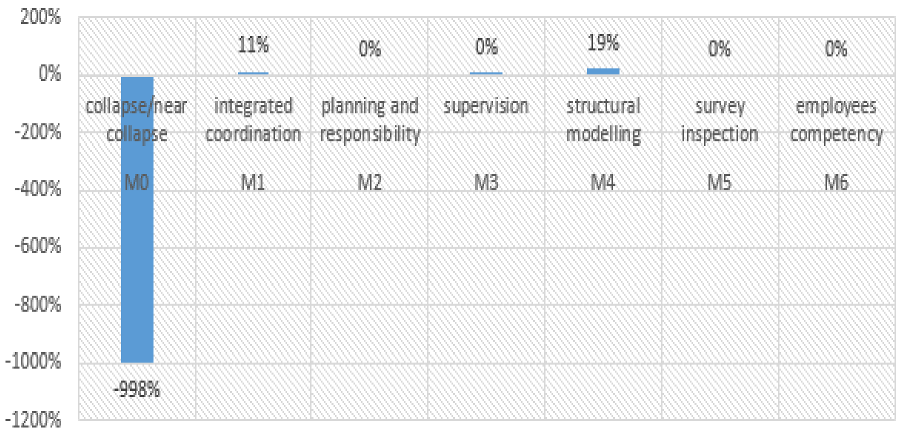

Figure C.23: Average profit/loss for Case 5: Patio Sevilla

C.6. Case 6: Hartford Civic Centre, Connecticut

Scenario 0 (without measure)

- Initial investment (C_0)

  The construction cost of Hartford Civic Centre was reported to be around $ 30,000,000 in 1972 [68] or equal to present value €113,447,875.

- Operation-maintenance (C_{om})

  In 2017, The Capital Region Annual Report of Connecticut released a report, mentioning the operation-maintenance cost of the arena for about $ 1,000,000, equal to present value €1,030,000 [12].

- Revenue (C_{ref})

  In 2017, The Capital Region Annual Report of Connecticut released a report, mentioning the annual revenue cost of the arena for about $ 3,600,000, equal to present value €3,708,000 [12].

- Financial consequences (C)

  The total financial consequences (C) due to the failure is €15,504,543 (Appendix B.6).

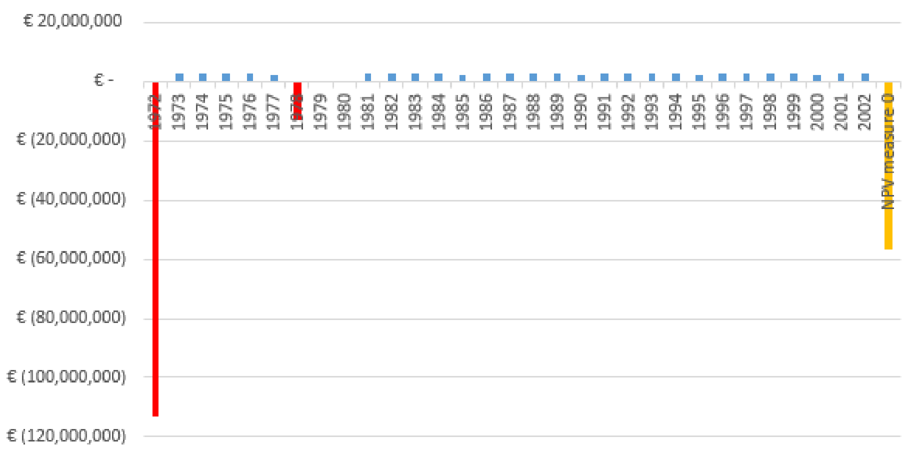

Figure C.24: Cash flow analysis for Case 6: Hartford Civic Centre, Scenario 0

Scenario 2 (with Planning and Responsibility)

- Measure Investment (C_m)

  The measure related to responsibility assignment is assumed costless.

- Weighted risk (R_w)

  The annual risk for Scenario 2 is €418 (Appendix B.6).

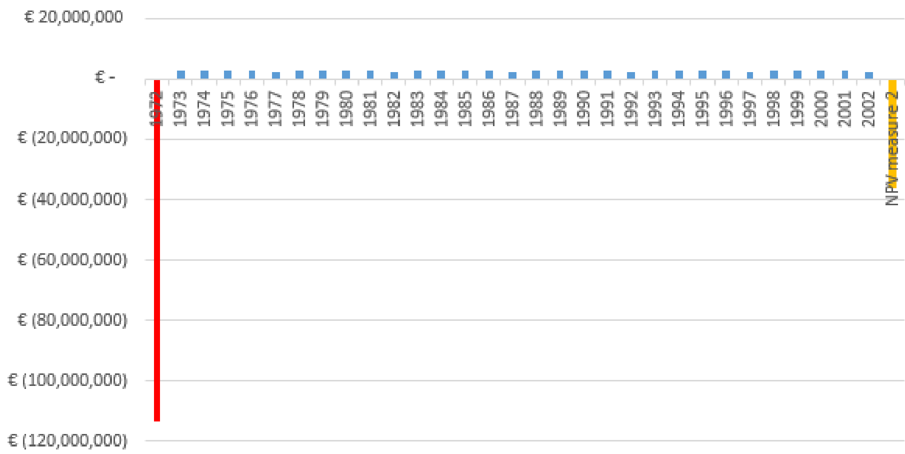

Figure C.25: Cash flow analysis for Case 6: Hartford Civic Centre, Scenario 2

Scenario 3 (with supervision)
The implementation of safety measure will incur additional costs to employ supervisors and delay cost due to the extra activity in such a fast-track project.

- Measure Investment (C_m)

  The contractor size for the collapsed part is estimated 95 persons, based on its project value [36]. The number of supervisors required on site is assumed one person [72] with salary of €75,000 per year. The duration of construction was 1 year [63]. The delay costs for extra six months is approximately €6,806,873 (Section 3.5.1) . The total additional investment is €6,881,873.

- Weighted risk (R_w)

  The annual risk for Scenario 3 is €386 (Appendix B.5).

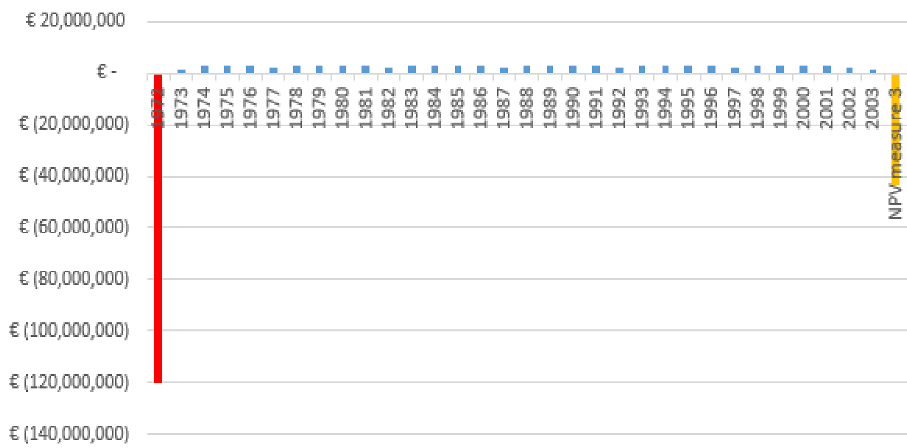

Figure C.26: Cash flow analysis for Case 6: Hartford Civic Centre, Scenario 3

Scenario 4 (with structural modelling)
The implementation of safety measure will incur an additional cost to develop physical model.

- Measure Investment (C_m)

  The physical modelling cost is assumed 1% of investment (Section 3.5.1). The total additional investment is €1,134,479.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €471 (Appendix B.5).

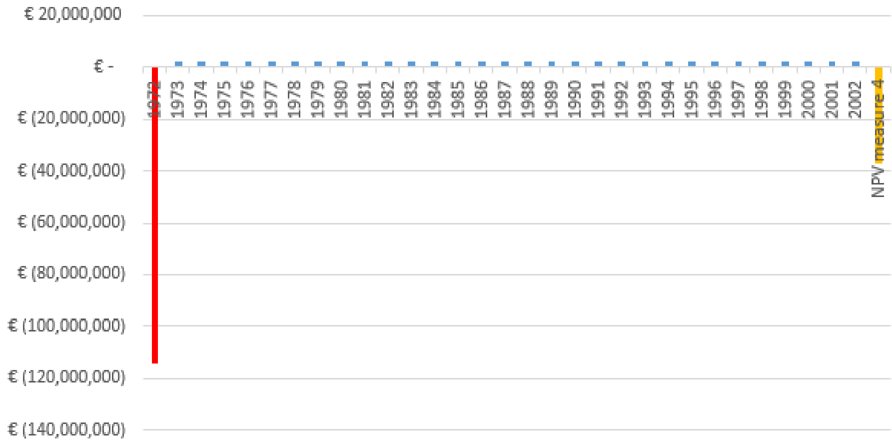

Figure C.27: Cash flow analysis for Case 6: Hartford Civic Centre, Scenario 4

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 6: Hartford Civic Centre.

Table C.26: Summary: Case 6, Hartford Civic Centre (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €113,447,875	- €56,543,418	-50%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €113,447,875	- €36,210,412	-32%
Scenario 3	Supervision	- €120,329,748	- €43,091,701	-36%
Scenario 4	Structural modelling	- €114,582,354	- €37,346,495	-33%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.27: Summary: Case 6, Hartford Civic Centre (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €269,550,234	- €232,573,766	- 86%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €269,550,234	- €190,830,022	-71%
Scenario 3	Supervision	- €285,798,248	- €207,076,648	-72%
Scenario 4	Structural modelling	- €272,245,736	- €193,529,334	-71%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.28: Summary: Case 6, Hartford Civic Centre (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €46,944,322	€17,642,954	38%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €46,944,322	€28,800,490	61%
Scenario 3	Supervision	- €49,835,982	€25,909,072	52%
Scenario 4	Structural modelling	- €47,413,766	€28,330,383	60%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.29: Summary: Case 6, Hartford Civic Centre (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €113,447,875	- €56,543,418	-50%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €113,447,875	- €36,210,412	-32%
Scenario 3	Supervision	- €120,329,748	- €43,091,701	-36%
Scenario 4	Structural modelling	- €114,582,354	- €37,346,495	-33%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.30: Summary: Case 6, Hartford Civic Centre (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €113,447,875	- €56,543,418	-50%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €120,254,748	- €43,017,703	-36%
Scenario 3	Supervision	- €127,174,120	- €49,935,688	-39%
Scenario 4	Structural modelling	- €121,389,227	- €44,153,839	-36%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 6: Hartford Civic Centre is presented in the Figure C.28.

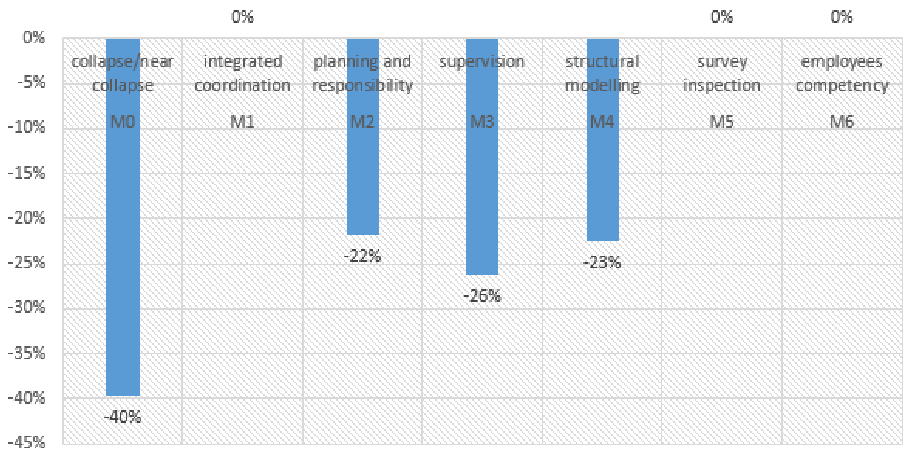

Figure C.28: Average profit/loss for Case 6, Hartford Civic Centre

C.7. Case 7: Kemper Arena, Kansas City

Scenario 0 (without measure)

- Initial investment (C_0)

  The construction cost of Kemper Arena Centre was reported to be around $ 23,200,000 in 1973 [39] or equal to present value €87,733,024.

- Operation-maintenance (C_{om})

  Kemper Arena requires an annual budget of around €1,000,000 for operation-maintenance activity [73].

- Revenue (C_{ref})

  The revenue of Kemper Arena is estimated based in the capacity comparison against Hartford Civic Centre. The 18,000 spectators arena approximately receives income of €4,449,600 per year.

- Financial consequences (C)

  The total financial consequences (C) due to the failure is €23,175,341 (Appendix B.7). After the collapse, building was reconstructed within 2 years. During the reconstruction (1980-1981), it is assumed that there are no income orandperation-maintenance cost.

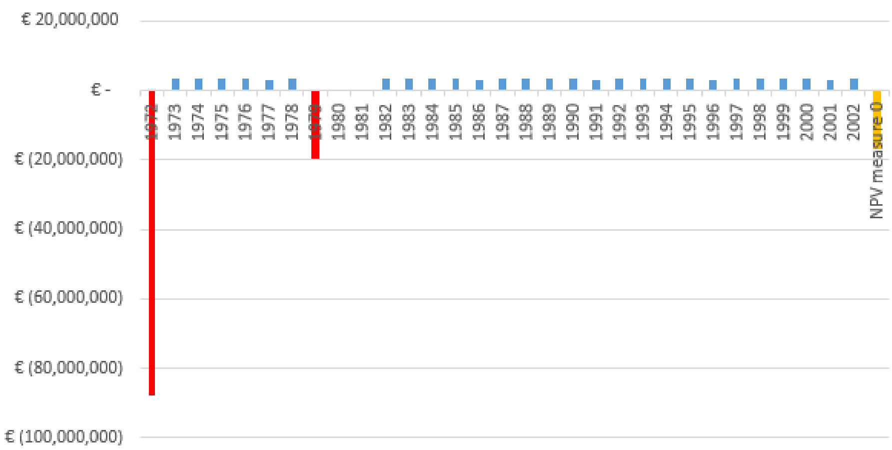

Figure C.29: Cash flow analysis for Case 7: Kemper Arena, Scenario 0

Scenario 3 (with supervision)

- Measure Investment (C_m)

  The contractor size for the collapsed part is estimated 671 persons, based on its project value [36]. The number of supervisors required on site is two person [72] with the annual salary of €75,000. The duration of construction was 1.5 year [63]. The total additional investment is €225,000.

- Weighted risk (R_w)

  The annual risk for Scenario 3 is €587 (Appendix B.5).

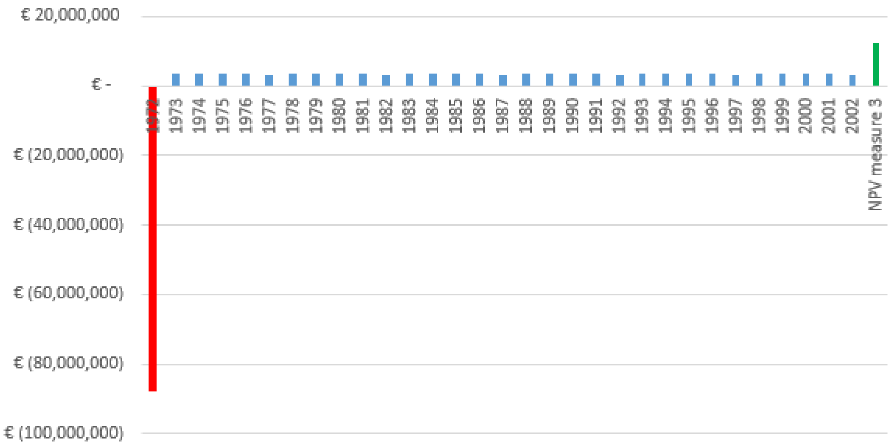

Figure C.30: Cash flow analysis for Case 7: Kemper Arena, Scenario 3

Scenario 4 (with structural modelling)
The implementation of safety measure will incur an additional cost to perform computational wind analysis.

- Measure Investment (C_m)

  The computational modelling cost is assumed 0.25% of investment (Section 3.5.1). The total additional investment is €219,333.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €566 (Appendix B.5).

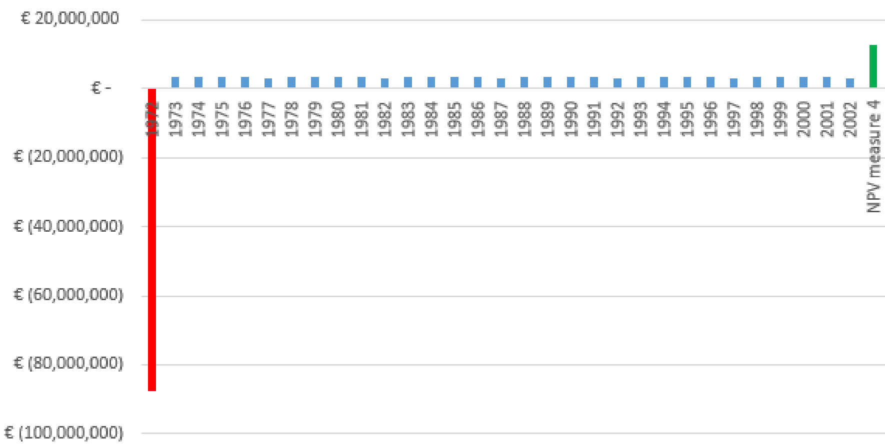

Figure C.31: Cash flow analysis for Case 7: Kemper Arena, Scenario 4

Scenario 5 (with survey and inspection)
The implementation of safety measure requires investment in topographical survey, extra time due to extra engineering activity prior to the erection, and routine inspection.

- Measure Investment (C_m)

  The average annual salary for a professional topographical surveyor is €69,000 per person. For the project, it is assumed two surveyors required during the construction for approximately six months of survey. Subsequently, it is assumed there will be delay for six months. Routine inspection costs €6.72 per m^2 per year [3]. The total additional cost is €8,558,581.

- Weighted risk (R_w)

  The annual risk for Scenario 5 is €603 (Appendix B.1).

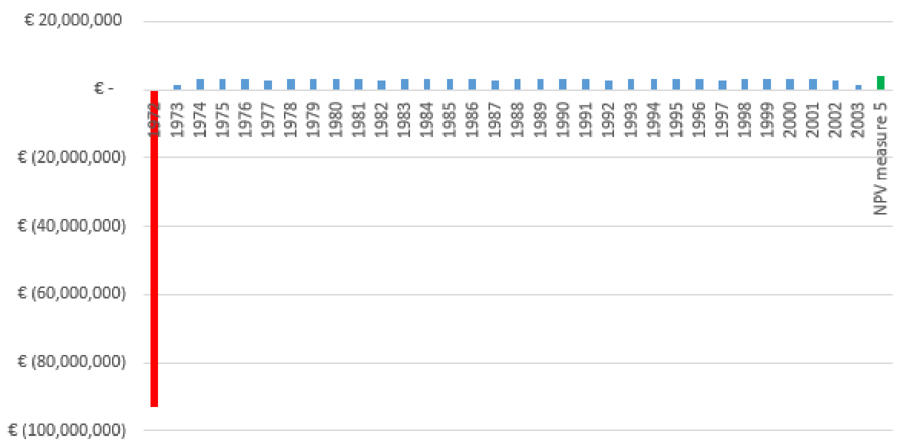

Figure C.32: Cash flow analysis for Case 7: Kemper Arena, Scenario 5

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 7: Kemper Arena.

Table C.31: Summary: Case 7, Kemper Arena (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €87,733,024	- €16,884,456	-19%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €87,958,024	€12,512,366	14%
Scenario 4	Structural modelling	- €87,952,356	€12,518,669	14%
Scenario 5	Survey and inspection	- €96,291,605	€4,070,189	4%
Scenario 6	Employees competency	-	-	-

Table C.32: Summary: Case 7, Kemper Arena (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €208,452,181	- €160,939,753	-77%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €208,694,265	- €105,651,496	51%
Scenario 4	Structural modelling	- €208,973,311	- €105,930,542	-51%
Scenario 5	Survey and inspection	- €221,028,312	- €121,320,937	-55%
Scenario 6	Employees competency	-	-	-

Table C.33: Summary: Case 7, Kemper Arena (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €36,303,609	€44,517,315	123%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €36,531,993	€61,355,763	168%
Scenario 4	Structural modelling	- €36,394,368	€61,493,388	169%
Scenario 5	Survey and inspection	- €38,550,826	€56,003,307	145%
Scenario 6	Employees competency	-	-	-

Table C.34: Summary: Case 7, Kemper Arena (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €87,733,024	- €16,819,565	-19%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €87,958,024	€12,512,366	14%
Scenario 4	Structural modelling	- €87,952,356	€12,518,033	14%
Scenario 5	Survey and inspection	- €96,291,605	€4,070,189	4%
Scenario 6	Employees competency	-	-	-

Table C.35: Summary: Case 7, Kemper Arena (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €87,733,024	- €16,819,565	-19%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €93,297,005	€7,172,797	8%
Scenario 4	Structural modelling	- €93,216,337	€7,254,121	8%
Scenario 5	Survey and inspection	- €98,329,986	- €1,085,670	-1%
Scenario 6	Employees competency	-	-	-

The overall result of the cash-flow analysis for Case 7: Kemper Arena is presented in the Figure C.33.

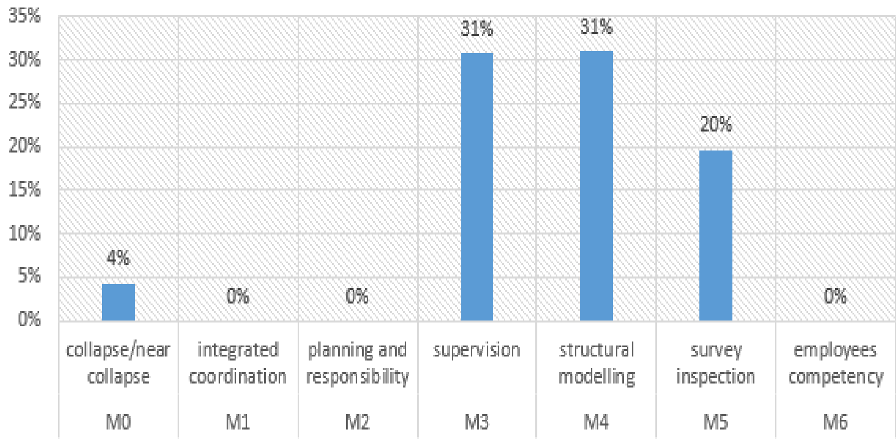

Figure C.33: Average profit/loss for Case 7, Kemper Arena

C.8. Case 8: Ronan Point, East London

Scenario 0 (without measure)

- Initial investment (C_0)

  The construction cost of Ronan Point is estimated using ”height charge principle” in [16]. The project value is approximately €13,432,317 (Appendix B.8).

- Operation-maintenance (C_{om})

  The total GFA of Ronan Point is 6,280m^2 (Appendix B.8). The unit cost is €87.82 per m^2 per year (Section 3.5.1). The total annual operation-maintenance cost is €551,488.

  It is assumed that there was no operational cost in 1969 as the building was under major restoration, and there is no operational cost after the demolition in 1986.

- Revenue (C_{ref})

  The average apartment price in London is approximately €1,500 per unit per month, based on the market price (www.rightmove.co.uk). The occupancy rate is assumed 90%. With total 110 apartment units, the annual revenue is estimated €1,782,000 per year.

  It is assumed that there was no income in 1969 as the building was under major restoration, and there is no income after 1986 up to the end of assessment period.

- Financial consequences (C)

  The total financial consequences (C) due to the failure is €35,414,287 (Appendix B.8). This value is divided at two occasion, in 1968 and in 1986.

  The gas explosion in 1968 incurred a cost of (C_1) €21,415,985 due to the collapse, fatalities, and reconstruction. Meanwhile, the demolition in 1986 incurred cost of (C_2) €13,998,302.

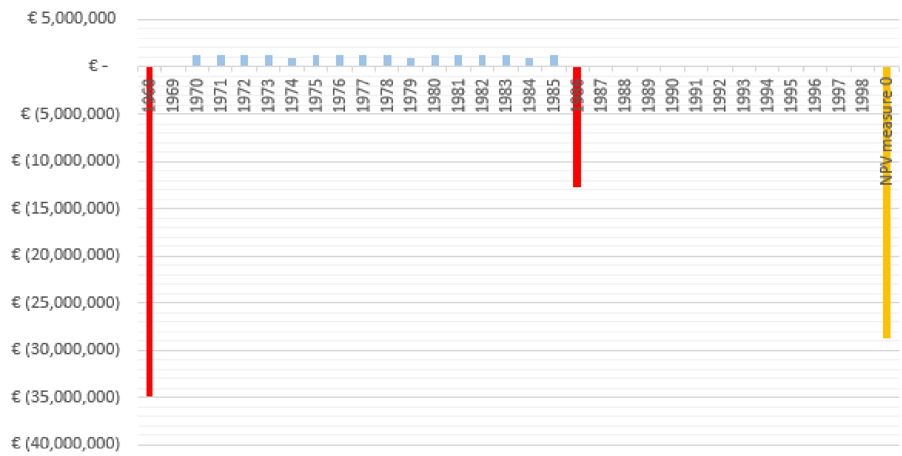

Figure C.34: Cash flow analysis for Case 8: Ronan Point, Scenario 0

Scenario 2 (with planning and responsibility)

The implementation of responsibility assignment is assumed at zero cost. Other parameters remain the same.

- Measure Investment (C_m)

  ”Planning and responsibility” for this case is assumed at no cost, therefore C_m=0.

- Weighted risk (R_w)

  The annual risk for Scenario 2 is €861 (Appendix B.8).

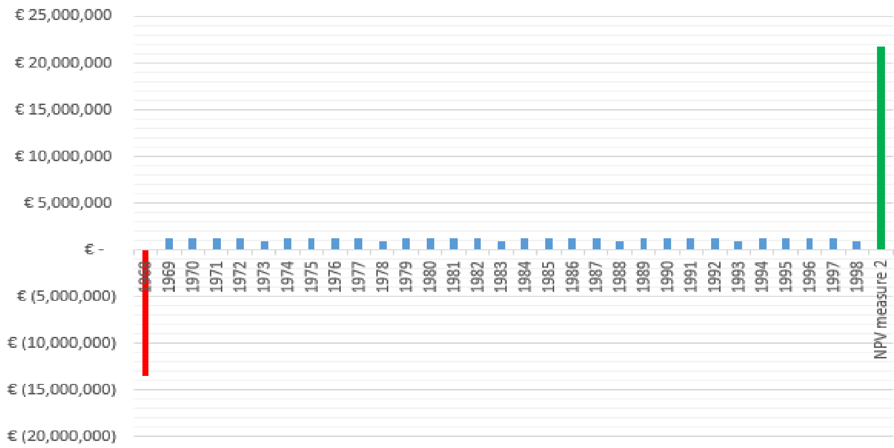

Figure C.35: Cash flow analysis for Case 8: Ronan Point, Scenario 2

Scenario 3 (with supervision)
The implementation of safety measure will incur additional costs to employ supervisors and delay cost due to the extra activity in a fast-track project. Other parameters remain the same.

- Measure Investment (C_m)

  The contractor size for the collapsed part is estimated 1,059 persons, based on its project value [36]. The number of supervisors required on site is assumed 3 personnel [72]. The actual duration of construction was 1 year [18]. The delay costs for extra six months is approximately €805,939 (Section 3.5.1) . The total additional investment is €1,143,439.

- Weighted risk (R_w)

  The annual risk for Scenario 3 is €811 (Appendix B.8).

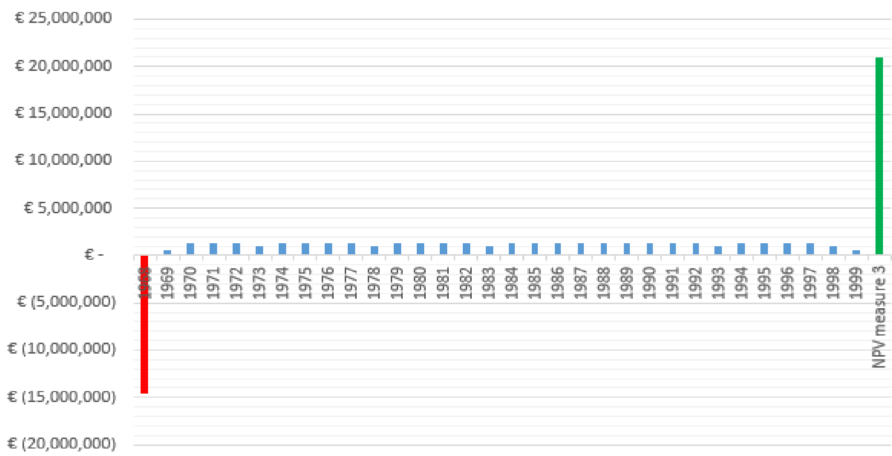

Figure C.36: Cash flow analysis for Case 8: Ronan Point, Scenario 3

Scenario 4 (with structural modelling)

The implementation of safety measure will incur costs to develop computational model and physical verification of building elements. Other parameters remain the same.

- Measure Investment (C_m)

  The computational modelling cost is approximately 0.25% of investment [6] or €33,581 (Section 3.5.1). The cost of physical model is assumed 1% of investment or €134,323. The total additional investment is €167,904.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €902 (Appendix B.8).

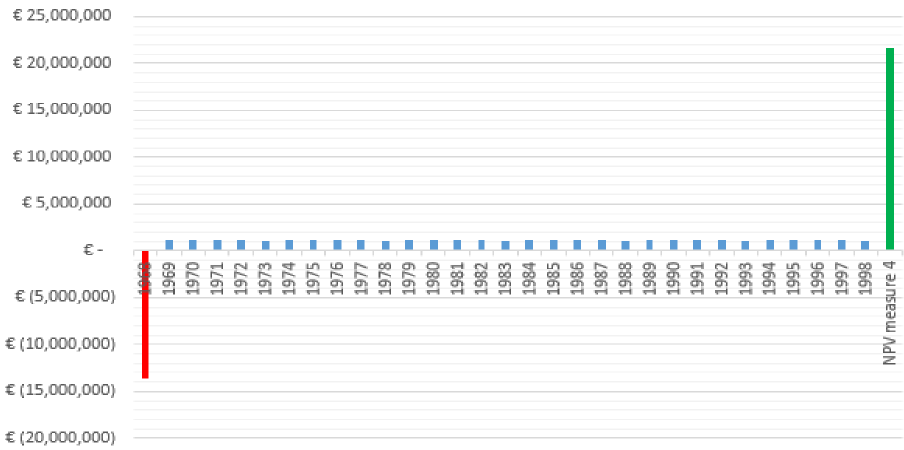

Figure C.37: Cash flow analysis for Case 8: Ronan Point, Scenario 4

Summary and sensitivity analysis

Presented below are the summary of all the scenarios before and after sensitivity analyses for Case 8: Ronan Point.

Table C.36: Summary: Case 8, Ronan Point (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €13,432,317	- €28,755,149	-214%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €13,432,317	€21,802,709	162%
Scenario 3	Supervision	- €14,575,756	€20,935,706	144%
Scenario 4	Structural modelling	- €13,571,095	€21,633,582	159%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.37: Summary: Case 8, Ronan Point (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €16,280,648	- €40,457,945	-249%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €16,280,648	€8,277,846	51%
Scenario 3	Supervision	- €17,594,987	€7,401,733	42%
Scenario 4	Structural modelling	- €16,447,909	€8,109,262	49%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.38: Summary: Case 8, Ronan Point (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €11,040,594	- €20,119,945	-182%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €11,040,594	€31,027,687	281%
Scenario 3	Supervision	- €12,040,529	€30,200,633	251%
Scenario 4	Structural modelling	- €11,155,455	€30,911,687	277%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.39: Summary: Case 8, Ronan Point (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €13,432,317	- €49,605,149	-369%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €13,432,317	€21,787,495	162%
Scenario 3	Supervision	- €14,575,756	€20,920,900	144%
Scenario 4	Structural modelling	- €13,571,095	€21,646,774	160%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.40: Summary: Case 8, Ronan Point (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €13,432,317	- €28,755,149	-214%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	- €14,238,256	€20,995,908	147%
Scenario 3	Supervision	- €15,381,695	€17,817,767	116%
Scenario 4	Structural modelling	- €14,377,034	€20,855,866	145%
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

The overall result of the cash-flow analysis for Case 8: Ronan Point is presented in the Figure C.38.

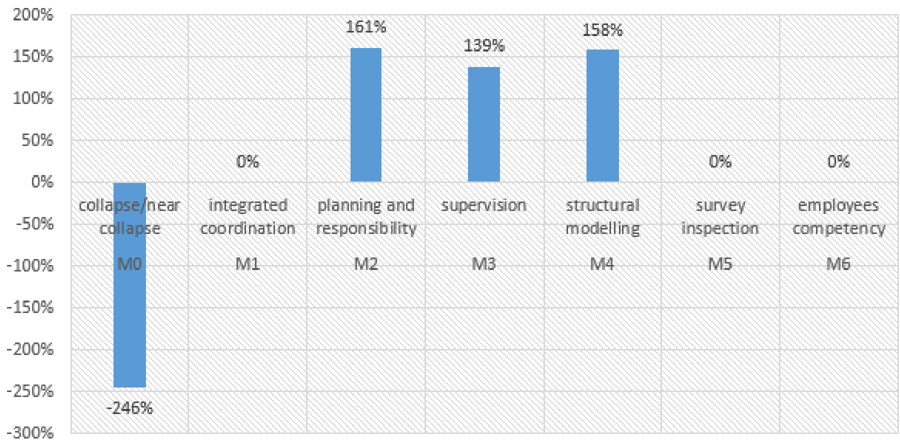

Figure C.38: Average profit/loss for Case 8: Ronan Point

C.9. Case 9: Bos en Lommerplein, Amsterdam

Scenario 0 (without measure)

- Initial investment (C_0)

  The construction cost of the damaged building in Bos en Lommer plaza is estimated using ”height charge principle” in [16]. The parameters used as input are GFA (11,000 m^2) [67]; building height (6 levels [58], assumed 4m per level; structural cost (€100/m^2) and completion cost (€150/m^2) [16]; and land cost in Amsterdam (approximately €737/m^2).

  The total present value of the investment is €22,513,474.

- Operation-maintenance (C_{om})

  The total GFA of the building is $11,000^2$ [67]. The unit cost is €87.82 per m^2 per year (Section 3.5.1). The total annual operation-maintenance cost is €965,984.

  It is assumed that in the year of failure (2006), the operation-maintenance cost is only 50% because the building was in service for half a year.

- Revenue (C_{ref})

  The average monthly office rent in Bos en Lommer district is approximately €210 per m^2, based on the market price (www.bedrijfspandenmatch.nl). The occupancy rate is assumed 100%. The estimated annual revenue is €2,310,000 per year.

  It is assumed that in the year of failure (2006), the revenue is only 50% because the building was in service for half a year.

- Financial consequences (C)

  The total financial consequences (C) due to the failure in 2006 is €12,773,371 (Appendix B.9).

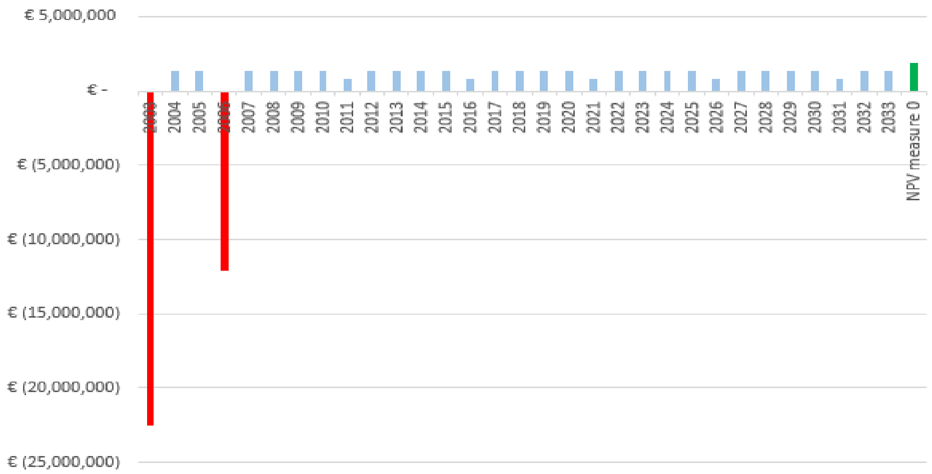

Figure C.39: Cash flow analysis for Case 9: Bos en Lommerplein, Scenario 0

Scenario 1 (with Integrated coordination)

- Measure Investment (C_m)

  Using the assumptions in Section 3.5.1, the cost of CIMS implementation is €90,000 (in 2011) [78], equivalent to present value €104,335.

- Weighted risk (R_w)

  The annual risk for Scenario 1 is €336 (Appendix B.2).

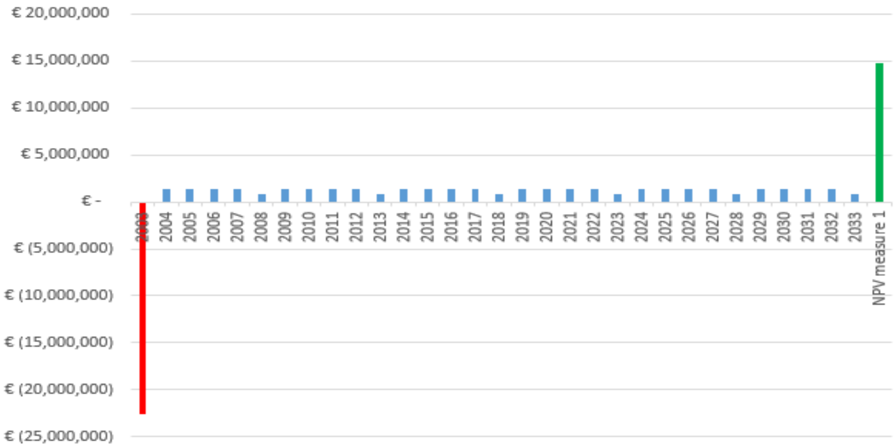

Figure C.40: Cash flow analysis for Case 9: Bos en Lommerplein, Scenario 1

Scenario 3 (with supervision)
The implementation of safety measure will incur additional costs to employ supervisors and delay cost due to the extra activity in a high complexity and dynamic project [57]. Other parameters remain the same.

- Measure Investment (C_m)

  The contractor size for the assessed building project is estimated 1,776 persons, based on its project value [36]. The number of supervisors required on site is assumed 4 personnel [72]. The duration of construction was 2 year [18]. The total budget for supervisors is €600,000.

  The delay costs for extra six months (Section 3.5.1) is approximately €€ 1,350,808.

  The total additional investment is then €1,950,808

- Weighted risk (R_w)

  The annual risk for Scenario 3 is €311 (Appendix B.8).

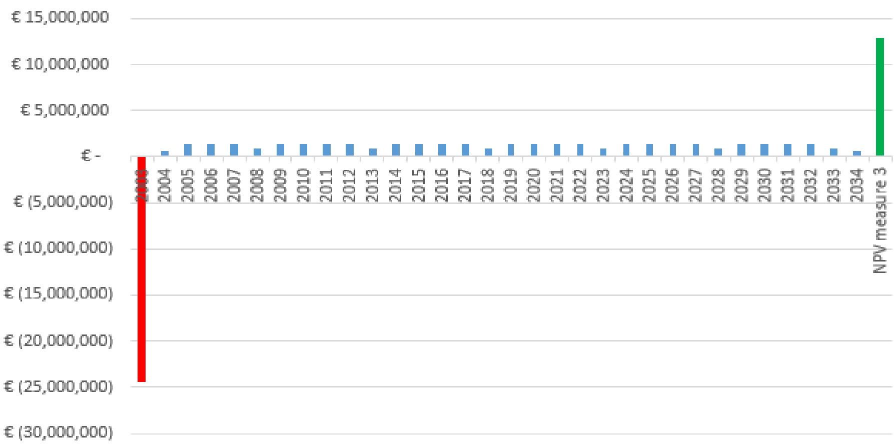

Figure C.41: Cash flow analysis for Case 9: Bos en Lommerplein, Scenario 3

Scenario 6 (with employees competency)

- Measure Investment (C_m)

  Hiring a rebar specialist labour will increase the cost up to 7% of the project value (Section 3.5.1). The additional investment is €1,590,580.

- Weighted risk (R_w)

  The annual risk for Scenario 6 is €346 (Appendix B.9).

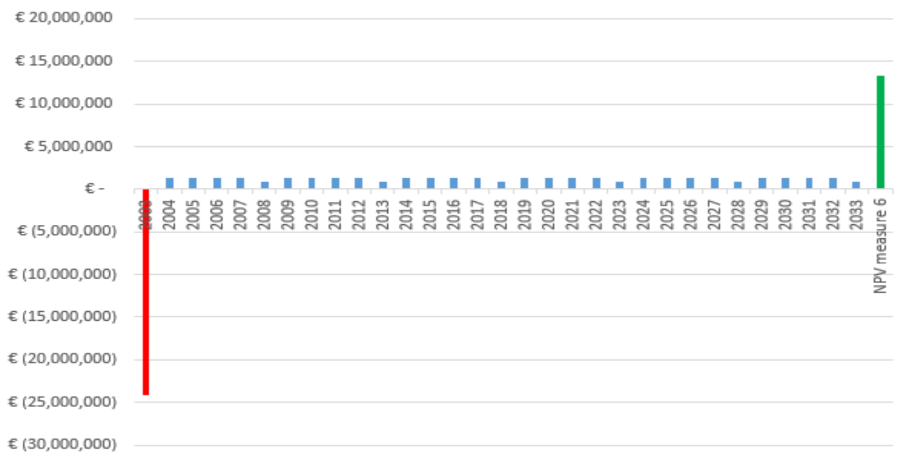

Figure C.42: Cash flow analysis for Case 9: Bos en Lommerplein, Scenario 6

Summary and sensitivity analysis

Presented below are the summary of all the scenarios before and after sensitivity analyses for Case 9: Bos en Lommerplein.

Table C.41: Summary: Case 9: Bos en Lommerplein (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €22,513,474	€1,941,565	9%
Scenario 1	Integrated coordination	- €22,617,809	€14,794,656	65%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €24,464,283	€12,948,614	53%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	- €24,104,055	€13,308,105	55%

Table C.42: Summary: Case 9: Bos en Lommerplein (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €27,287,470	- €20,205,451	-74%
Scenario 1	Integrated coordination	- €27,402,335	- €8,723,308	-32%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €29,586,218	- €10,872,578	-37%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	- €28,823,758	- €10,111,007	-35%

Table C.43: Summary: Case 9: Bos en Lommerplein (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €18,504,784	€17,559,532	95%
Scenario 1	Integrated coordination	- €18,599,375	- €30,757,379	165%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €20,227,131	€29,153,405	144%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	- €19,760,077	- €29,619,848	150%

Table C.44: Summary: Case 9: Bos en Lommerplein (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €22,513,474	€1,908,354	8%
Scenario 1	Integrated coordination	- €22,617,809	€14,794,656	65%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €24,464,283	€12,948,614	53%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	- €24,104,055	€13,308,105	55%

Table C.45: Summary: Case 9: Bos en Lommerplein (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €22,513,474	€1,941,565	9%
Scenario 1	Integrated coordination	- €23,968,617	€13,443,511	56%
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	- €25,965,091	€10,314,019	40%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	- €25,454,863	€11,956,951	47%

The overall result of the cash-flow analysis for Case 9: Bos en Lommerplein is presented in the Figure C.43.

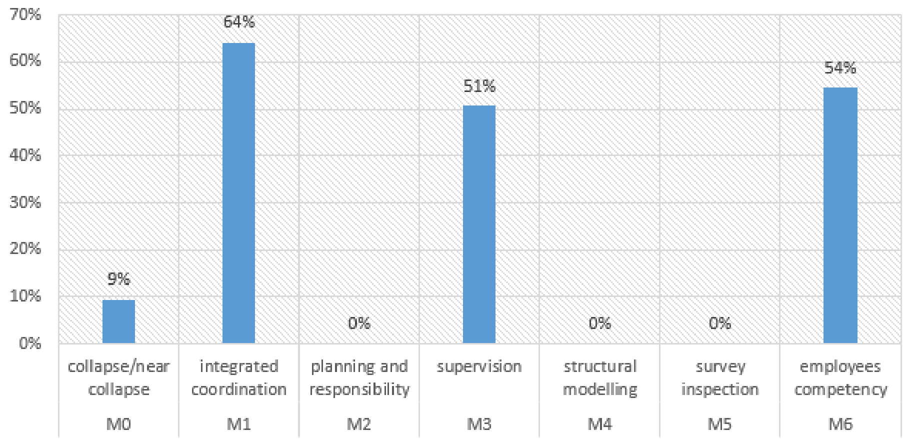

Figure C.43: Average profit/loss for Case 9: Bos en Lommerplein

C.10. Case 10: Amoco Tower, Chiacgo

Scenario 0 (without measure)

- Initial investment (C_0)

  The initial investment of Amoco Tower is approximately $ 120,000,000 in 1974 [39], equivalent to present value €440,574,273.

- Operation-maintenance (C_{om})

  The annual cost of operation-maintenance for Amoco Tower in 2016 was reported $ 8.26/ft^2 [10]. The GFA of the building is estimated 259,920 m^2 based on its footprint and amount of levels. The present value of total annual operation-maintenance cost is €24,507,921.

- Revenue (C_{ref})

  The annual revenue for Amoco Tower in 2016 was reported $ 30.60/ft^2 [10]. The GFA of the building is estimated 259,920 m^2 based on its footprint and amount of levels. The present value of total annual operation-maintenance cost is €80,804,929.

- Financial consequences (C)

  The façade damage in 1988 incurred cost of €262,791,426 (Appendix B.10).

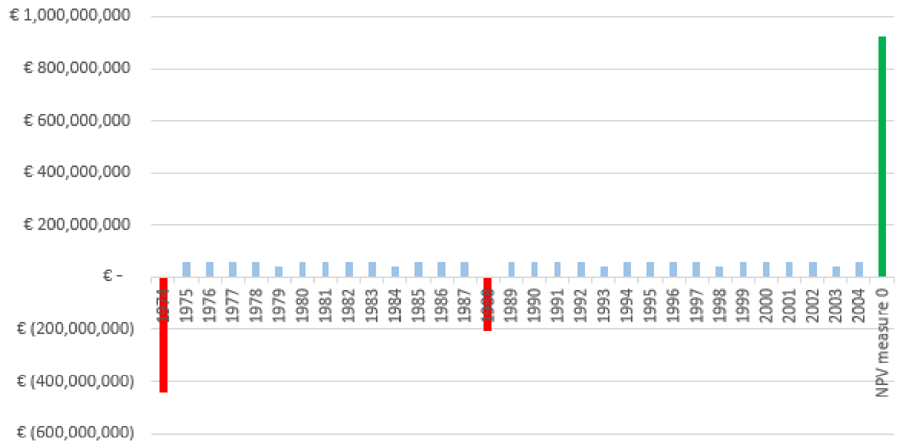

Figure C.44: Cash flow analysis for Case 10: Amoco Tower, Scenario 0

Scenario 4 (with structural modelling)

The implementation of safety measure will incur additional costs to develop computational and physical model. Other parameters remain the same.

- Measure Investment (C_m)

  The computational modelling cost is approximately 0.25% of investment [6] or €1,101,436 (Section 3.5.1).

  The cost of physical model for the whole building is assumed 1% of investment, while façade approximately takes 20% of the budget [16]. The physical model for the façade is then 0.2% of total investment or €881,149.

  The total additional investment is €1,982,584.

- Weighted risk (R_w)

  The annual risk for Scenario 4 is €5963 (Appendix B.10).

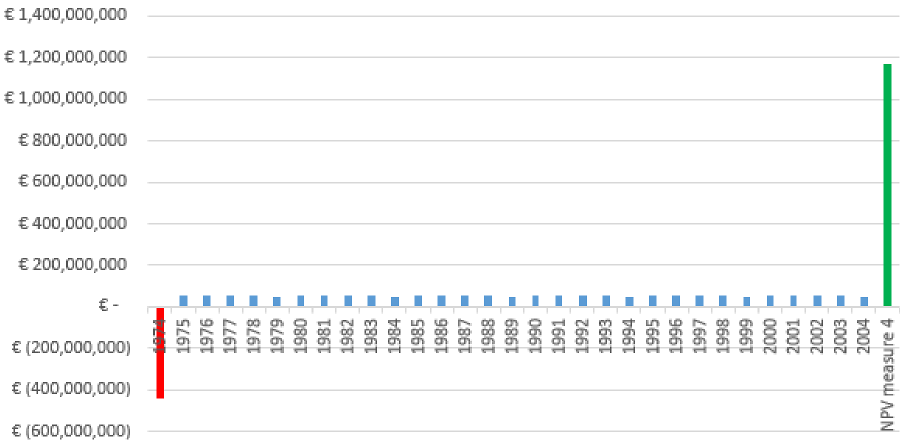

Figure C.45: Cash flow analysis for Case 10: Amoco Tower, Scenario 4

Scenario 5 (with Survey and inspection

- Measure Investment (C_m)

  The budget required to perform material inspection throughout the project is estimated based on the cost of laboratory test in Oregon [50].

  The total hourly cost is approximately $ 650. Included in the price are engineer's fee, technician's fee, tensile strength testing, and minimum charge.

  The project lasts for about 4 years 4.10, with the average working hour in the USA is 1,779 hours/year [43].

  The total investment for safety measure is €4,625,400.

- Weighted risk (R_w)

  The annual risk for Scenario 5 is €6,224 (Appendix B.10).

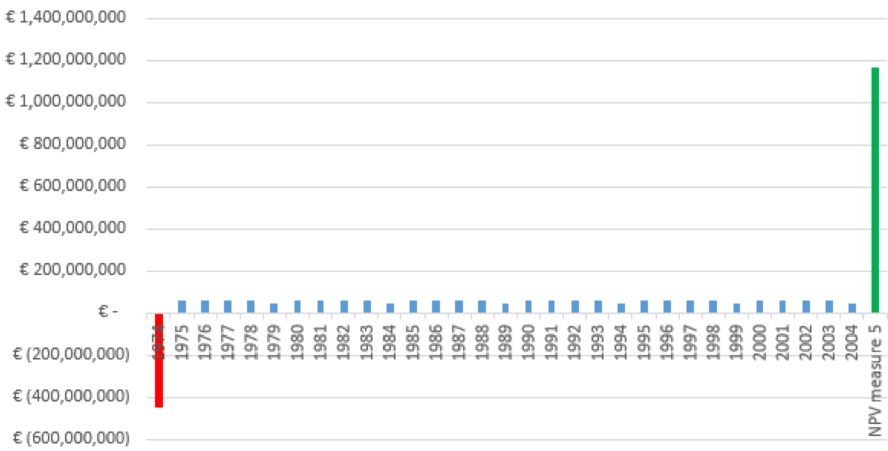

Figure C.46: Cash flow analysis for Case 10: Amoco Tower, Scenario 5

Summary and sensitivity analysis

Presented below are the summaries of all the scenarios before and after sensitivity analyses for Case 10, Amoco Tower:

Table C.46: Summary: Case 10, Amoco Tower (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €440,574,273	€924,274,744	210%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €442,556,857	€1,172,650,749	265%
Scenario 5	Survey and inspection	- €445,199,673	€1,170,000,094	263%
Scenario 6	Employees competency	-	-	-

Table C.47: Summary: Case 10, Amoco Tower (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €1,026,858,034	€240,352,752	23%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €1,031,478,895	€646,961,327	63%
Scenario 5	Survey and inspection	- €1,032,480,236	€645,947,330	63%
Scenario 6	Employees competency	-	-	-

Table C.48: Summary: Case 10, Amoco Tower (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €185,918,109	€1,211,488,027	652%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €186,754,740	€1,366,393,242	732%
Scenario 5	Survey and inspection	- €190,731,318	€1,362,411,662	714%
Scenario 6	Employees competency	-	-	-

Table C.49: Summary: Case 10, Amoco Tower (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €440,574,273	€924,274,744	210%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €442,556,857	€1,172,650,749	265%
Scenario 5	Survey and inspection	- €445,199,673	€1,170,000,094	263%
Scenario 6	Employees competency	-	-	-

Table C.50: Summary: Case 10, Amoco Tower (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €440,574,273	€924,274,744	210%
Scenario 1	Integrated coordination	-	-	-
Scenario 2	Planning and responsibility	-	-	-
Scenario 3	Supervision	-	-	-
Scenario 4	Structural modelling	- €468,991,313	€1,146,210,330	244%
Scenario 5	Survey and inspection	- €471,634,129	€1,143,559,414	242%
Scenario 6	Employees competency	-	-	-

The overall result of the cash-flow analysis for Case 10: Amoco Tower is presented in the Figure C.47.

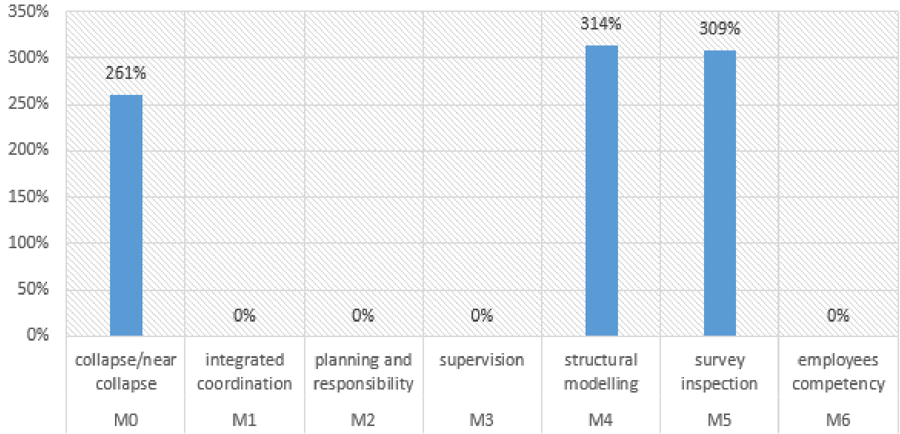

Figure C.47: Average profit/loss for Case 10: Amoco Tower

C.11. Additional scenarios applied to Case 2: Hyatt Regency, Kansas City

To have a better understanding regarding the conclusions of this research and their implementation in the building industry, two additional scenarios are applied to Case 2: Hyatt Regency. The two following analyses are not related to each other. The objectives of the additional scenarios are:

- Highlight the contribution of fatalities to the life cycle financial model

  The result of this study shows that the "Loss of human life" is the main contributor to the failure cost (Section 5.3.2). The first additional scenario is developed to compare the financial consequences for the two following conditions:

  – The actual case where the collapse caused 114 fatalities
  – Scenario if the 114 victims were injured instead of being killed

- Compare the efficiency of safety measures with the scenario without safety measure for a new project

  In this study, the objective is to determine the impact of safety measures applied to the failure cases. The approach of this thesis is learning from failure, comparing the Scenario 0 (scenario without measure that led to failure) with Scenario 1 up to Scenario 6 (scenario with safety measure). However, for a new project, it is not known whether the absence of safety measures will lead to failure or not.

  The second additional scenario is carried out to determine the efficiency of safety measures compared to the scenario without any of the safety measures for a new project. For Scenario 0 (without measure), it is assumed that the collapse does not occur, but the weighted risk (R_w) is present to compensate for the probability of failure. The failure probability for the Scenario 0 ($P_{w,0}$) is 10^{-4} [20], as there is no safety measure taken to reduce the probability.

Additional Scenario 1 (victims injured instead of killed)

In reality, the collapse of the hanging bridge in 1981 caused 114 fatalities. The financial consequence (C) is estimated at €790,777,772 (Appendix B.2). If all the victims were injured instead of killed in the incident, assuming other financial parameters remain the same as in the Appendix B.2, the financial consequence (C) is reduced to €226,477,772. Using the four sensitivity analyses (Section 3.5.2), the result of the the result of the financial assessment is summarized as follows.

Table C.51: Summary: Case 2 additional scenario 1, Hyatt Regency (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	- €166,422,936	-229%
Scenario 1	Integrated coordination	- €72,833,177	- €58,252,925	80%
Scenario 2	Planning and responsibility	- €72,728,842	€58,304,280	80%
Scenario 3	Supervision	- €77,167,573	€53,931,335	70%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.52: Summary: Case 2 additional scenario 1, Hyatt Regency (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €88,151,035	- €217,781,471	-247%
Scenario 1	Integrated coordination	- €88,265,901	€6,242,421	7%
Scenario 2	Planning and responsibility	- €88,151,035	€6,588,082	7%
Scenario 3	Supervision	- €93,515,097	€1,289,910	1%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.53: Summary: Case 2 additional scenario 1, Hyatt Regency (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €59,778,934	- €11,171,992	-19%
Scenario 1	Integrated coordination	- €59,873,525	€105,532,945	176%
Scenario 2	Planning and responsibility	- €59,778,934	€105,581,900	177%
Scenario 3	Supervision	- €63,440,670	€101,976,828	161%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.54: Summary: Case 2 additional scenario 1, Hyatt Regency (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	- €172,122,936	-237%
Scenario 1	Integrated coordination	- €72,833,177	€57,831,225	79%
Scenario 2	Planning and responsibility	- €72,728,842	€57,844,391	80%
Scenario 3	Supervision	- €77,167,573	€53,518,860	69%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.55: Summary: Case 2 additional scenario 1, Hyatt Regency (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	- €166,422,936	-229%
Scenario 1	Integrated coordination	- €75,695,892	€55,370,709	73%
Scenario 2	Planning and responsibility	- €77,092,573	€53,919,282	70%
Scenario 3	Supervision	- €81,568,803	€49,548,561	61%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 2 additional 1: Hyatt Regency is presented in Figure C.48. The graph shows the comparison between the Scenario 0 in the actual case and the additional case.

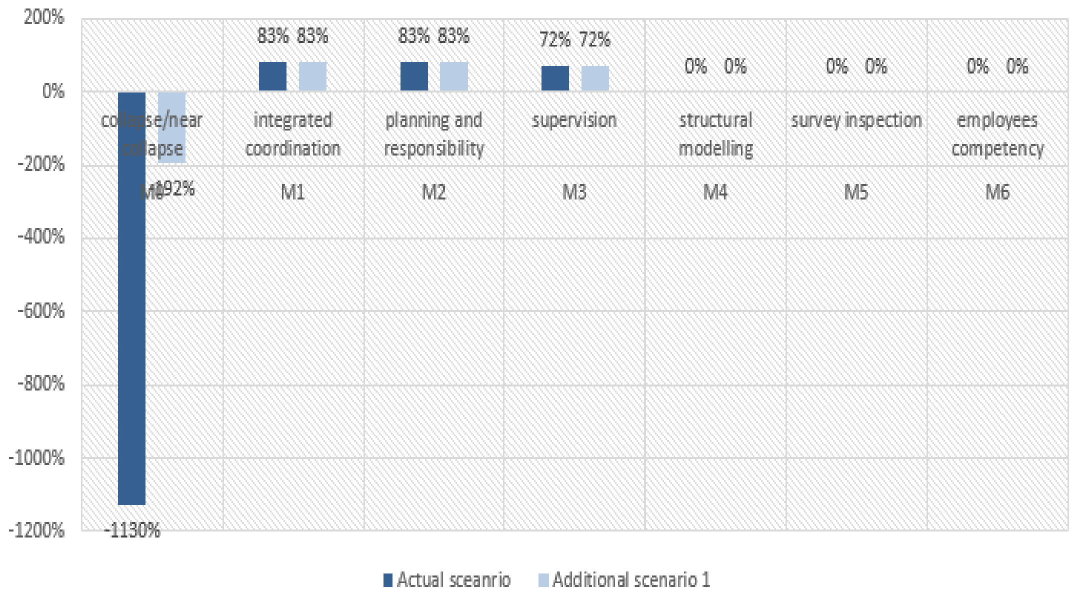

Figure C.48: Average profit/loss for Case 2 additional scenario 1: Hyatt Regency

Additional scenario 2 (scenario of a new project without measure)

The second additional scenario addressed the impact of not taking any of the safety measures to the financial analysis for a new project.

Supposed that for Scenario 0 (without measure), the collapse of the hanging bridge does not occur. The weighted risk (R_w) for the failure probability of 10^{-4} is €79,078 per year, based on the financial consequences for the actual calculation of Case 2: Hyatt Regency (Appendix B.2).

There is no additional investment in the Scenario 0. Other financial parameters and scenarios remain the same as the calculation in the Appendix C.2. The result of the financial analysis for the 30 years of assessment period is summarized as follows.

Table C.56: Summary: Case 2 additional scenario 2, Hyatt Regency (without sensitivity)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	€56,569,963	78%
Scenario 1	Integrated coordination	- €72,833,177	€58,252,925	80%
Scenario 2	Planning and responsibility	- €72,728,842	€58,304,280	80%
Scenario 3	Supervision	- €77,167,573	€53,931,335	70%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.57: Summary: Case 2 additional scenario 2, Hyatt Regency (Sensitivity 1: 5% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €88,151,035	€4,850,929	6%
Scenario 1	Integrated coordination	- €88,265,901	€6,242,421	7%
Scenario 2	Planning and responsibility	- €88,151,035	€6,588,082	7%
Scenario 3	Supervision	- €93,515,097	€1,289,910	1%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.58: Summary: Case 2 additional scenario 2, Hyatt Regency (Sensitivity 2: 1% interest rate)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €59,778,934	€11,171,992	-19%
Scenario 1	Integrated coordination	- €59,873,525	€105,532,945	176%
Scenario 2	Planning and responsibility	- €59,778,934	€105,581,900	177%
Scenario 3	Supervision	- €63,440,670	€101,976,828	161%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.59: Summary: Case 2 additional scenario 2, Hyatt Regency (Sensitivity 3: €10M/death and €100k/injury)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	€54,859,963	75%
Scenario 1	Integrated coordination	- €72,833,177	€57,831,225	79%
Scenario 2	Planning and responsibility	- €72,728,842	€57,844,391	80%
Scenario 3	Supervision	- €77,167,573	€53,518,860	69%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

Table C.60: Summary: Case 2 additional scenario 2, Hyatt Regency (Sensitivity 4: extra delay)

Scenario	Measure type	Investment	NPV	Profit/loss
Scenario 0	No measure	- €72,728,842	€56,569,963	78%
Scenario 1	Integrated coordination	- €75,695,892	€55,370,709	73%
Scenario 2	Planning and responsibility	- €77,092,573	€53,919,282	70%
Scenario 3	Supervision	- €81,568,803	€49,548,561	61%
Scenario 4	Structural modelling	-	-	-
Scenario 5	Survey and inspection	-	-	-
Scenario 6	Employees competency	-	-	-

The average result of the cash-flow analysis for Case 2 additional 2: Hyatt Regency is presented in Figure C.49. The graph shows the comparison between the Scenario 0 in the actual case and the additional case.

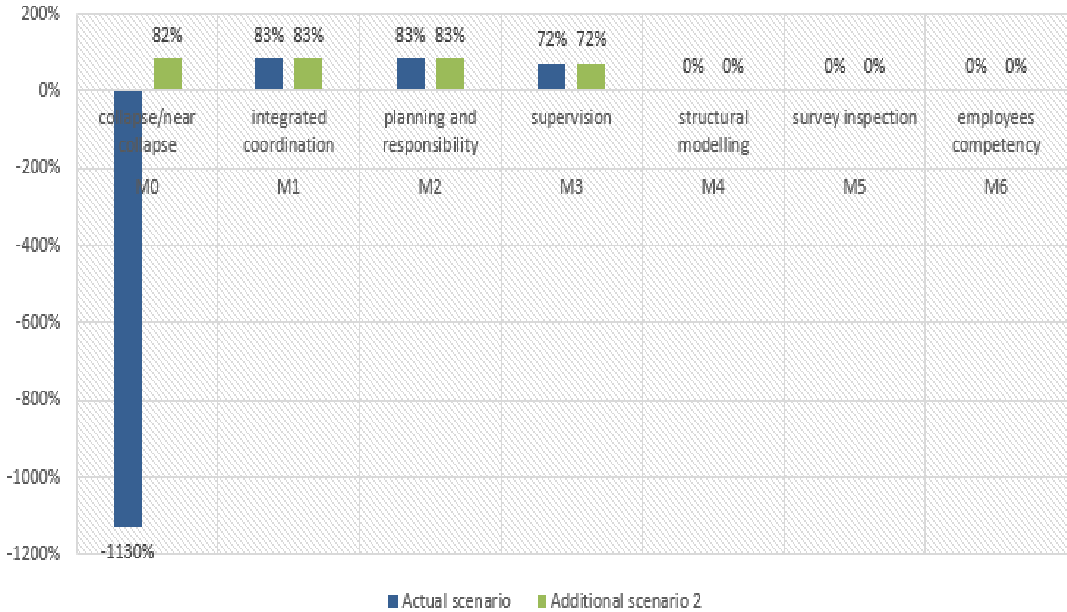

Figure C.49: Average profit/loss for Case 2 additional 2: Hyatt Regency