The design of a Human Reliability Assessment method for Structural Engineering

Johan de Haan

UNIVERSITY OF TWENTE.

COLOPHON

Title	The design of a Human Reliability Assessment method for Structural Engineering
Location	Delft / Enschede / Staphorst
Status	Final Version
Date	September 2012
Pages	96
Author	
Name	Johan (J.) de Haan
Address	muldersweg 8 7951 DG Staphorst
Email	haanjohande@hotmail.com
University	University of Twente
Faculty	Faculty of Engineering Technology
Master program	Civil Engineering and Management
Graduation Committee	
Graduation professor	Prof. Dr. Ir. J.I.M. Halman *(University Twente)*
First supervisor	Dr. S.H. Al-Jibouri *(University Twente)*

University of Twente
Faculty of Engineering Technology
Building de Horst, number 20
PO box 217
7500 AE Enschede
The Netherlands

Delft University of Technology
Faculty of Civil Engineering
PO Box 5048
2628 CN Delft
The Netherlands

ABSTRACT

In the recent past a number of buildings collapsed in the Netherlands under apparent normal circumstances. The causes of these failures are predominantly human error within the design or construction of the building. Examples of this are the collapse of five balconies of an apartment building in Maastricht in 2003, and the partial collapse of a roof structure under construction of a football stadium in Enschede in 2012.

Based on these developments it is of importance to investigate the current building practice concerning the occurrence of human error. The objective of this research is to investigate the effect of human error within the design process on the reliability of building structures. Based on this, the following research question is defined:

> *What are the consequences of human error within the structural design process on the structural reliability of a typical building structure?*

The research question is answered by proposing a Human Reliability Assessment method and subsequently analyse the effect of selected human actions within the structural design process. This method is envisioned as a monitoring method for use within engineering/construction organizations. The research consists of two consecutive parts. Firstly a literature study is performed to examine the current knowledge concerning human error in structural engineering. Secondly, based on the literature findings, a model for Human Reliability Assessment in structural engineering processes is proposed. This model is subsequently used to investigate the effect of human error within a specified structural design process.

LITERATURE STUDY

The literature study focusses on four aspects: the occurrence of structural failure, the basic aspects of human error, the basics of Human Reliability Assessments and probabilistic quantification methods.

Concerning the occurrence of structural failure, it can be concluded that the majority of the failures are caused by human error (Fruhwald, Serrano, Toratti, Emilsson & Thelandersson, 2007). In most researches a value of eighty to ninety percent is mentioned (Ellingwood, 1987; Stewart, 1993; Vrouwenvelder, 2011). Based on the researches of Fruhwald et al. (2007), Boot (2010) and ABC-meldpunt (2011) it can be concluded that the occurrence or errors are of the same order of magnitude for design and construction, with slightly higher frequencies for the design phase.

An important aspect of failure is that in general multiple causes can be identified (CUR, 2010), and that taking away one of these causes usually mitigates the undesired situation. A useful model to represent error causation is the "Swiss cheese" model (Reason, 2000; Reason, Carthey & de Leval,

2001). The model exists of several defensive layers between an hazard and an undesired situation. In an ideal world these layers would be intact. However in the real world holes are occurring, making an undesired situation possible. Another relevant aspect of failure is the cognitive level on which an error is made. A subdivision of this is given by Reason (1990): a skill-based level, rule-based level and knowledge-based level. This subdivision is roughly based on the complexity of the task at hand and the level of attention.

One method to investigate human error within design is by means of a Human Reliability Assessment (HRA). These techniques mostly contain three basic techniques (Kirwan, 1994): identify which errors can occur, deciding how likely the errors are to occur and reducing this error likelihood. Most of the HRA techniques are aimed towards subdividing a process in a task sequence, and subsequently analyse these task sequences on human error. An example is the 'Cognitive Reliability and Error Analysis Method' (CREAM), which is used within the main research.

The last aspect discussed in the literature study is the use of probability analysis techniques for quantifying human error probabilities. A frequently used technique is reliability analysis methods which focus on relative effect of failures on the global reliability index of the structure. Another technique is scenario analysis, in which scenarios for errors are investigated to quantify relative consequences associated with these errors. A useful computation method for these kinds of analysis is Monte Carlo analysis, which uses repeated random sampling to calculate results for the analysis.

MAIN RESEARCH

In order to investigate the effect of human error in design tasks, a HRA method for specific use within engineering tasks is proposed. A simplified flow chart of this methodology is presented in figure 1. The model encompasses basically four elements: A qualitative analysis, a human error quantification stage, a design simulation stage and a probabilistic analysis.

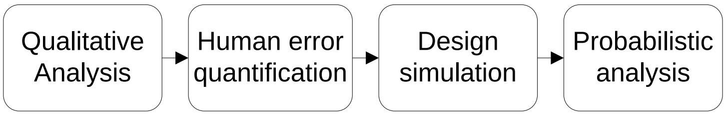


Figure 1: Basic steps within the HRA model

The first step in the HRA model is to define the process of interest and its boundaries (qualitative analysis). Furthermore, a selection of the most error prone processes within the overall process is required in order to focus the HRA efforts. The selected process is a structural design process of a beam element within a common office building. The office building is envisioned as a framework of concrete beams and columns supporting a slab floor. The overall stability is arranged by means of a concrete core. Within the analysis two beam types are considered: a statical determined beam element and a statical undetermined beam element. Furthermore two scenarios for specific analysis are selected: the level of professional knowledge and the level of design control.

The second step within the HRA method is to quantify the probability of failure within an individual design task. This probability of failure is represented by a probability distribution function expressed by two parameters: a Human Error Probability (HEP) and an Error Magnitude (EM). The EM is a parameter which describes the severity of an error. The procedure for determining HEPs consists of two methods: a basic HEP method and an extended HEP method. The extended method is labour intensive and requires quite some knowledge concerning human factors. The simplified method requires considerate less efforts and knowledge, however this method is only applicable for standard design tasks. The simplified method distinct seven basic design tasks, each subdivided in three cognitive levels: a rule-, a skill- and a knowledge based task level.

The third step is to combine the task probability distributions to obtain an overall probability distribution of the element strength due to errors in the process. For this, a Monte Carlo simulation procedure is proposed. Within this simulation process, each design task is modelled with an algorithm which models the design task at hand and the occurrence of failure. Furthermore design control is modelled as well in order to investigate the proposed scenarios. For this a subdivision is made between self-checking (by the designer) and normal supervision. Based on the analysis performed in the case study it can be concluded that the proposed simulation method is useful for combining task probability distributions into an overall probability distribution. However improvements are required for practical use of the model.

The last step in the model is to determine the probability of failure of the engineered structure. For this a probabilistic analysis method based on plastic limit state analysis is proposed. The overall probability distributions found in step three combined with probabilistic loading conditions are used to determine the structural failure probability. Based on the analysis is can be concluded that the structural failure probability can increase considerable.

Finally it can be concluded that the proposed HRA model has the potential to quantify the effect of human error within carefully defined boundary conditions. However further research is required to increase the accuracy of the model and its practical use. From the case study it can be concluded that the statical determined beam element is slightly more susceptible to structural failure. Within both structural types, the influence of design experience on the structural failure is limited. Furthermore, the effect of normal supervision on the failure probability in comparison to a process with only self-checking is about a factor 2,4 to 4,0. A design process without supervision and self-checking results in an unrealistic failure probability. However the occurrence of this seems not logical as self-checking is always present, mostly in a subconscious manner.

SAMENVATTING

In het recente verleden zijn er een aantal gebouwen ingestort in Nederland onder ogenschijnlijk normale omstandigheden. De oorzaak hiervan is voornamelijk te vinden in het falen van mensen betrokken bij het ontwerp of uitvoering van de constructie. Een voorbeeld hiervan is het instorten van een vijftal balkons van een appartementen gebouw in Maastricht in 2003. Een ander voorbeeld is het gedeeltelijk instorten van een in aanbouw zijnde dak-constructie van een voetbal stadium in Enschede in 2012.

Gezien deze ontwikkeling is het van belang om het bouwproces te onderzoeken op het gebied van menselijk falen. De vraag hierbij is hoe menselijke fouten invloed hebben op het bouwproces, en wat hiervan de gevolgen zijn. In de literatuur is informatie te vinden over de kwalitatieve eigenschappen van menselijk falen, echter met betrekking tot kwantitatieve informatie is de literatuur beperkt. Een uitzondering hierop zijn de zogenaamde menselijke betrouwbaarheid analyses (HRA). Echter deze zijn voornamelijk toegespitst op operationele taken in risico gevoelige industrieen, zoals de luchtvaart- en nucleaire industrie.

Gezien de overdenkingen in de voorgaande alinea is het volgende onderzoeksdoel geformuleerd:

> *Het doel van dit onderzoek is om het effect van menselijke fouten binnen het constructieve ontwerp proces met betrekking tot de betrouwbaarheid van gebouwen te analyseren, door een menselijke betrouwbaarheids analyse toegespitst op het ontwerp proces uiteen te zetten, en vervolgens het effect van menselijke handelingen in een specifiek ontwerp proces te analyseren.*

Literatuur studie

Om de uit het onderzoeksdoel voortvloeiende hoofdvraag te beantwoorden is allereerst een literatuurstudie uitgevoerd. Het doel van deze literatuurstudie is om de huidige ontwikkelingen op het gebied van menselijke factoren in het ontwerp proces in beeld te brengen, en om de hoofdstudie te ondersteunen met relevante informatie.

Uit wereldwijd onderzoek naar falen in constructies blijkt dat de meerderheid ontstaat door menselijke fouten (Fruhwald et al., 2007). Meestal worden getallen rond de tachtig tot negentig procent genoemd (Ellingwood, 1987; Stewart, 1993; Vrouwenvelder, 2011). Gebaseerd op de onderzoeken van Fruhwald et al. (2007), Boot (2010) en ABC-meldpunt (2011) kan geconcludeerd worden dat ruwweg de helft van de constructieve fouten worden gemaakt gedurende het ontwerpproces, en iets minder dan de helft gedurende het bouwproces.

Een belangrijk aspect van een menselijke fout is dat er meestal meerdere oorzaken zijn aan te wijzen voor het optreden van fouten (CUR, 2010).

Het voorkomen van een van de oorzaken voldoet meestal al om falen te voorkomen. Dit proces is goed gedemonstreerd met het 'gatenkaas' model van Reason (Reason, 2000; Reason et al., 2001). Een ander relevant gegeven vanuit de psychologie is het niveau waarop een mens een bepaalde taak uitvoert. Reason (1990) onderscheidt hiervoor drie niveaus: een vaardigheid-, regel- en kennis- niveau. Deze verdeling is grofweg gebaseerd op de complexiteit van de taak, en het denkniveau waarop de taak wordt uitgevoerd.

Eerder in de samenvatting zijn de zogenaamde menselijke betrouwbaarheid analyses (HRA) genoemd. Deze technieken bevatten meestal drie basis functies: het identificeren van mogelijke fouten, het voorspellen van de mate van voorkomen van deze fouten en het verbeteren van de menselijke betrouwbaarheid. De meeste technieken zijn erop gericht om het proces onder te verdelen in een takenreeks, en deze dan te analyseren door per taak een foutkans op te stellen. Een voorbeeld hiervan is de 'Cognitive Reliability and Error Analysis Method' (CREAM).

Hoofdstudie

Om het effect van menselijke fouten in het ontwerpproces te onderzoeken is een HRA methode voor het specifiek gebruik in constructief ontwerpen uiteengezet. Deze methode is onder andere gebaseerd op informatie van Stewart (1993) en Hollnagel (1998). Een vereenvoudigde stroomschema van dit model is weergegeven in figuur 2. Hierin kan gezien worden dat het model in zijn basis bestaat uit vier stappen: een kwalitatieve analyse, een menselijke fouten analyse, een ontwerp simulatie en een probabilistische analyse. Dit model wordt gebruikt in deze studie om een specifieke ontwerp situatie te analyseren. De keuze voor deze specifieke ontwerp sitautie wordt ook ingegeven door het HRA model.

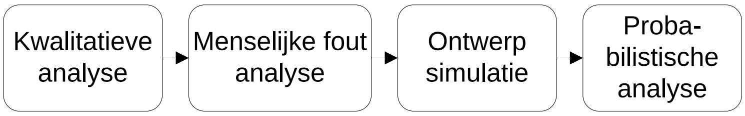


Figure 2: Basis stappen in het HRA model

De kwalitatieve analyse is bedoeld om te onderzoeken welke scenarios relevant zijn om te analyseren met behulp van de HRA methode. Verder wordt de context van de analyse bepaald in deze stap. Scenario selectie is benodigd omdat een HRA analyse erg arbeidsintensief is, en niet alle processen even relevant zijn om te analyseren met de methode. Uit de analyse in dit proefschrift blijkt dat horizontale elementen (waarschijnlijk) het meest gevoelig zijn voor menselijke fouten (in een kantoorgebouw). Om deze reden wordt het HRA model gebruikt om een gewapend betonnen balk in een kantoorgebouw te analyseren. Verder richt the analyse zich specifiek op twee scenario's: het kennis niveau van de ingenieur en de mate van controle in het ontwerp-proces.

De volgende stap is om met behulp van een menselijke fout analyse een menselijke fout kans (HEP) te berekenen. Hiervoor wordt een uitgebreide en simpele HEP methode voorgesteld in dit proefschrift. De uitgebreide methode is geschikt voor alle typen ontwerp proces, echter het gebruik ervan vereist veel inzicht in de psychologie van de mens, waardoor het minder geschikt is voor toepassing door ingenieurs. Om deze reden is een simpele HEP methode voorgesteld, voor het gebruik in standaard ontwerp situaties. Deze simpele methode bestaat uit een keuze tabel waarbij een standaard taak en werkniveau moet worden bepaald, waaruit vervolgens een HEP waarde voortkomt.

Naast de HEP waarde wordt in de kwantitatieve analyse een Fout Marge (EM) bepaald voor iedere basis taak. Deze twee parameters (HEP en EM) vertegenwoordigen de kans op een menselijke fout in een basis taak. Om de totale menselijke fout in het gehele ontwerp te kunnen vinden, worden deze parameters gekoppeld door middel van een simulatie proces. In dit simulatie proces wordt iedere basis taak gemodelleerd met een algoritme. Deze algoritmen tezamen vormen het ontwerp proces. Daarnaast is ontwerp controle gemodelleerd met een algoritme waarin alle, of enkele, basis taken opnieuw worden geevalueerd (zodra het voorlopige eindresultaat zich niet binnen redelijke grenzen bevindt). Uit de analyse van dit proces met behulp van de case studie, blijkt dat deze methode bruikbaar is voor het kwantificeren van menselijke fouten. Echter verbeteringen met betrekking tot het modelleren van controle is wenselijk in verder onderzoek.

In de laatste HRA stap wordt door middel van basis mechanica en probabilistische modellen, een faalkans voor de constructie berekend. Hierbij worden de resultaten van de voorgaande stap gecombineerd met probabilistische belasting condities. Deze condities zijn gebaseerd op probabilistische modellen beschreven in JCSS (2001). Verder wordt een zogenaamde Monte-Carlo simulatie gebruikt voor de daadwerkelijke analyse. Uit de resultaten van deze stap blijkt dat de constructieve faalkans behoorlijk kan toenemen door menselijke fouten in het ontwerp proces.

Het kan geconcludeerd worden dat de voorgestelde HRA methode bruikbaar is voor het kwantificeren van de effecten van menselijke fouten binnen zorgvuldig gedefinieerde randvoorwaarden. Echter verder onderzoek is benodigd om het gebruik van het model in de praktijk mogelijk te maken. Verder blijkt uit de analyse dat een goede ontwerpkennis de faalkans lichtelijk reduceert. Tot slot blijkt uit de analyse dat controle door een meerdere de faalkans reduceert met een factor van ongeveer 2,4 tot 4,0. Verder heeft zelf controle ook veel effect. Deze zelf controle is altijd aanwezig, vaak op een onderbewuste manier.

Error is a hardy plant;
it flourishes in every soil.
— Martin F. Tupper

ACKNOWLEDGMENTS

This report is the final result of a research on human error in structural engineering. The research is intended as the final step of two independent master studies: Civil Engineering and Management at the University of Twente and Structural Engineering at the Technical University of Delft. For this two separate reports are composed, both discussing common aspects and university specific aspects. This report is the final report for the University of Twente, focussing on managerial aspects of human error quantification.

Almost 12 months of work have come to an end with the finalization of this report. At the end of this journey, and looking back to the process, it can be concluded that it was an interesting and educational process. Especially conducting research without intensive guidance on an iterative and discovering basis was very interesting.

I would like to thank the members of my graduation committees: Prof. Halman, Prof. Vrouwenvelder, Mr. Al-Jibouri, Mr. Terwel, Mr. Hoogenboom and Mrs. Rolvink. I would like to thank Prof. Halman and Mr. Al-Jibouri for there guidance from a process perspective, which enabled me to consider the problem outside its technical boundaries. Furthermore my gratitude goes to Prof. Vrouwenvelder by helping me to focus on the things which mattered. This has undoubtedly saved me a considerate amount of time. Finally I would like to thank Mr. Terwel, Mr. Hoogenboom and Mrs. Rolvink for there guidance throughout the process. This guidance did provide me with new ideas when I needed it, and has inspired me throughout the process.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Part I

MAIN RESEARCH

1

INTRODUCTION

1.1 INTRODUCTION SUBJECT

Designing and building an engineered structure in the Netherlands is bound to strict building regulations. Building codes, codes of practise, education, risk control measurements, are all aimed towards minimizing the risks of structural failure. Despite these efforts, structural collapses within the Netherlands have illustrated the inadequacy of the current building practise. This will be demonstrated with two recent examples.

Balconies Maastricht
On the 23th of april 2003 five balconies of an apartment building collapsed due to sudden column loss, resulting in two deadly casualties. The triggering cause of the accident was insufficient strength in a concrete ridge, which was meant to transfer the column forces to the building foundation. The underlying cause was a design error of the structural engineer. Another important contributing cause of the collapse was the design of the balcony which lacked robustness [1] as no 'second carriage way' existed. (CUR, 2010).

Football stadium Enschede
On the 7th of July 2011 during construction activities for expansion of the football stadium in Enschede, the stadium roof partly collapsed. The accident resulted in two deathly casualties and nine wounded. The accident was (among others) a consequence of the lack of sufficient stability element in the truss system (for the loading conditions at that moment). The accident was mainly caused by a series of malfunctions in the building process concerning the safeguard of structural safety (OVV, 2012).

Both examples show the cause and consequence of errors in design and construction of building structures. An interesting aspect is the presence of human error within both examples, which is far from a coincidence. Researchers such as Ellingwood (1987), Kaminetzky (1991), Stewart (1993), Fruhwald et al. (2007) and Vrouwenvelder (2011) have all concluded that most of the structural failures are caused by human errors. The objective of this research is to investigate the effect of human error in construction.

The problem with human errors within design is that they are not readily quantifiable. Numerous researchers have investigated this problem. However quantifying the probability of human error inevitable leads to unreliable and subjective results (Swain, 1990; Kirwan, 1996; Hollnagel, 1998; Reason, 2000; Grozdanovic & Stojiljkovic, 2006). Despite these set-backs, further research in the effect of human error seems necessary due to the alarming failure numbers.

---

[1] Defined as the ability of a structure to withstand events like the consequences of human error, without being damaged to an extent disproportionate to the original cause

1.2 STRUCTURE OF THE REPORT

This thesis is primarily a research report. This report is structured according to the framework described by Kempen & Keizer (2000). This framework divides the research into four main phases: 1) Orientation, 2) Research, 3) Solution and 4) implementation. Figure 3 presents and overview of the thesis structure based on the framework of Kempen & Keizer (2000).

Orientation phase
In chapter 1 a introduction to the subject is presented. Subsequently, chapter 2 discusses the research methodology. This chapter states the problem, the research objective, research questions and the research strategy.

Research phase
Within the research phase a theoretical framework is composed by means of a literature study. First the causes of structural failure within building structures are examined. Secondly, the phenomena 'Human Error' is investigated by discussing technical, human factors and psychological literature. After that Human Reliability Assessment technologies are discussed in detail. Finally probabilistic modelling methods for human error quantification are briefly discussed.

Solution phase
Within the solution phase a model for Human Reliability Assessment within structural engineering is set-apart. Basically four assessment steps are discussed in this chapter: scenario/context selection, human error quantification, design simulation and probabilistic analysis. Readers who are interested in technical details on the used model are advised to read this chapter.

Implementation phase
The last step in the framework is to implement the model in practice. Within this research, this step is limited to implementation within a single design situation. Readers who are interested in the results of the model are advised to read this chapter.

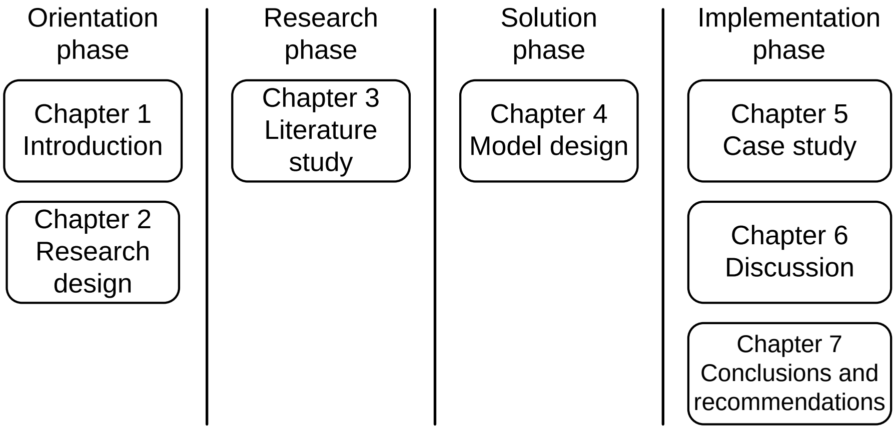


Figure 3: Thesis structure

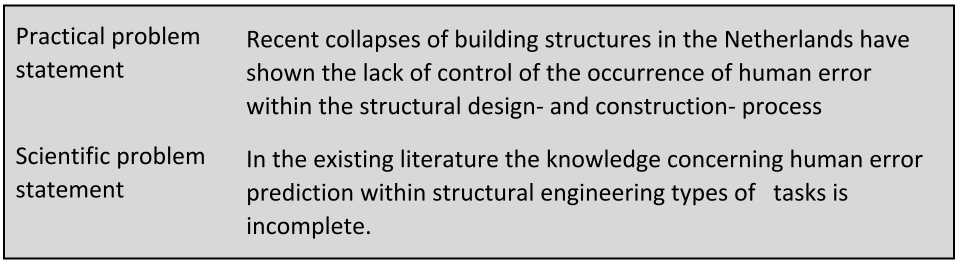
2

RESEARCH METHODOLOGY

In this chapter the research design is presented. The framework is based on theoretical information from Verschuren & Doorewaard (2007). First the problem definition and research scope are formulated. Subsequently, the outline of this study is presented in a research framework (research objective and research questions). The applied research methodology and strategy for each of the phases of the research are clarified in this section as well.

2.1 PROBLEM DEFINITION

Human Error has proven to be a problematic issue within the building industry, as is shown in the introduction. Especially quantitative error prediction and error causation are issues of concern. To summarize the problem analysis, the practical problem statement and the scientific problem statement are formulated as follows:



Practical problem statement	Recent collapses of building structures in the Netherlands have shown the lack of control of the occurrence of human error within the structural design- and construction- process
Scientific problem statement	In the existing literature the knowledge concerning human error prediction within structural engineering types of tasks is incomplete.

2.2 RESEARCH OBJECTIVE

The practical problem definition pinpoints an important aspects of human error within design from an engineering point of perspective: "the lack of control". This lack of control is something which is worrying every engineer, as most designed systems are based on extensively investigated assumptions leaving no space for unanticipated deviations. Furthermore building engineers need human error approaches that are simple and efficient to use, and which produce results that are practically valuable. From this perspective, this thesis focusses on the practical aspects of human error by considering human error from a human reliability perspective. By doing so, it also provides insights for theoretical aspect related to human reliability. Based on this assumption the objective for the research is defined as follows:

The objective of this research is to investigate the effect of human error within the structural design process on the reliability of building structures. (*objective <u>of</u> the research*)

Doing so by

proposing a Human Reliability Assessment method and subsequently analyse the effect of selected human actions within the structural design process on structural reliability. (*objective <u>in</u> the research*)

2.3 DEMARCATION OF THE PROBLEM

The problem definition already focussed the research on human error within building structures. Furthermore three restrictions concerning the boundaries of the research are pointed out beneath in order to focus the research further.

Firstly, the research proposes a method for human error diagnosis rather then human error management. It is acknowledged that in order to control the occurrence of error, human error management is required. This, and the use of the diagnosis method within human error management is left for further research.

Secondly, the research focusses on the design process within building processes, which entails that the construction process is not considered. It is acknowledged that human errors within the construction process are important contributors to structural failure. However, limitation of the scope of the research is required to acquire sufficient depth within the research to attain a relevant result.

Finally, the research is meant as an explorative research on the possibilities to quantify human error within structural engineering processes. Due to this, the probabilities of human error are determined within a large margin.

2.4 RESEARCH QUESTIONS

After defining the problem, clarifying the objective and stating the problem demarcation, the research question is stated as follows:

What are the consequences of human error within the structural design process on the structural reliability of a typical building structure?

Based on the research question, three sub-questions are defined to answer the research question. Furthermore, sub-question one and three are subdivided further. For every sub-question, a brief explanation is given what will be investigated and why.

1. *What is the current knowledge within scientific literature concerning the assessment of human error in structural engineering?*

1.1 What are the main causes of structural failure, and in which construction phase do they occur?
Sub-question 1.1 elaborates on the occurrence of structural failure by focussing on literature which describes failure statistics. This information is used to set-apart the consequences of human error within structural engineering. Furthermore, this information is used to determine the basic causes of failure and which building phase is most error prone.

1.2 What are the technical, human factors and psychological characteristics of human error?
Within this sub-question the basic aspects of human error from an engineering perspective are investigated. This information is required to understand the basic concept of human error in order to establish a conceptual framework for human error (quantification).

1.3 What are the characteristics of Human Reliability Assessments?
Sub-question 1.3 investigates the basics of Human Reliability Assessments, the different techniques used for it and its limitations. This information is used to design a Human Reliability Assessment method for application in structural engineering.

1.4 What are the possibilities to quantify human error and subsequently structural failure?
Based on this sub-question, several aspects of probabilistic quantification techniques are investigated. Probabilistic quantification is an important part of advanced Human Reliability Assessment tools, and as such required for the design of the method proposed in this thesis.

> *2. What is the configuration of a Human Reliability Assessment method specifically aimed towards quantifying the probability and consequences of human error in typical design processes within structural engineering?*

In order to answer this question, a Human Reliability Assessment model for use in structural engineering is proposed. This model is required in order to analyse human error within the structural design process. Furthermore, the model is used within the case study. This sub-question answers the following part of the research objective: "proposing a Human Reliability Assessment method [...]"

> *3. What are the consequences of human error within a design process of a typical structural engineering process on the structural reliability of a building structure?*

3.1 Which structural engineering process is relevant for analysing with the proposed Human Reliability Assessment method?
Based on this sub-question a structural engineering process which is potentially vulnerable for the occurrence of human error within the design process is selected. Furthermore, two scenarios based on process characteristics are identified as relevant assessment scenarios. This focus on relevant

processes is required in order to focus the limited research efforts on processes worthwhile considering.

3.2 What is the probability and consequence of expected human errors within the specified process on the structural reliability of a building?
Based on this sub-question, the severity of human error is determined by considering the consequences on the final product (a building). This subquestion answers the following part of the research objective: "[...] analyse the effect of selected human actions within the design process on structural reliability."

2.5 RESEARCH STRATEGY

This research consists of three consecutive parts, each based on the three defined sub-questions. For each consecutive part, the used research strategy will be defined in this section.

The literature study is conducted by using a search and find methodology. First, key words searching was applied using the websites scholar.google.com and www.scopus.com. Some of the key words are: human error, human reliability assessment, structural failure, failure costs, Monte Carlo simulation, FMEA, safety risk analysis. Furthermore the same key words are used to search for information in the library of the Technical University of Delft. The second method was to search for information on authors of interest for this thesis. These authors are: E. Hollnagel, B.J.M. Ale, R.E. Melchers, J.T. Reason and M.G. Stewart.

Furthermore, most literature is found by selecting papers from the reference lists within the previous found papers. Finally some papers were provided by the supervisors during review sessions. these papers are: Ale et al. (2012), Boot (2010), Fruhwald et al. (2007) and Stewart (1993).

The second part consists of developing a Human Reliability Assessment model. The outlines of the model was set-apart first, based on the findings from the literature study. After that the model was worked out in more detail. This was predominantly performed on an iterative manner. New insights were obtained by assessing the performed work, reinvestigating some literature sources and discussing about the results with the supervisors. Due to the explorative character of this research, verification of the model is limited and is based on the case study and the discussion sessions with the supervisors.

The third part consists of performing a case study with the model. The first step within this case study is to select a relevant structural design process, and research scenarios within this process. This selection process is based on literature which provides quantitative information about human error and structural failure. The rest of the case study is performed based on the findings in the second step.

3

LITERATURE STUDY

3.1 INTRODUCTION

The literature study discusses aspects of human error within structural engineering. The objective of this study is to assess the current knowledge within scientific literature concerning the assessment of human error in structural engineering. Four topics will be considered. First the effect of human error within building structures is considered by investigating the causes of structural failure (section 3.2). Secondly, the phenomenon 'Human Error' is investigated by discussing technical, human factors and psychological literature (section 3.3). After that section 3.4 elaborates on so called Human Reliability Assessment (HRA) technologies. Finally probabilistic modelling methods for human error/failure are briefly discussed in section 3.5.

3.2 STRUCTURAL FAILURE

Failure of structures or parts of structures are occurring throughout the world. Within the Netherlands their numbers are limited due to strict regulations and sufficient building knowledge. However a world without failure seems impossible, slips and lapses and gross-errors will always occur.

In line with van Herwijnen (2009) failure of a structure is defined as the unsuitability of the structure to serve the purpose where it was built for. The collapse of (parts of) a structure is the heaviest form of failure (van Herwijnen, 2009). The author classifies four basic ways of failure:

- the collapse of (parts of) a building;
- unequal settlements;
- strong deformations of construction parts;
- noticeable and disturbing vibration of walkable surfaces.

This section will examine the literature on failure of structures. It starts with outlining the findings on structural failure worldwide, followed with some information on failure statistics in the Netherlands specifically. This section concludes with a short review on the cost of structural failure.

3.2.1 *Structural failures worldwide*

A number of surveys on structural failures have been reported during the years. The purpose of these studies is to quantify sources of failure and to indicate their relative importance in the building process. A general conclusion from such studies is that failure without exception occur due to human error (see Fruhwald et al., 2007).

Fruhwald et al. (2007) cites several other researches concerning the causes of failure. Fruhwald refers Walker (1981) on this topic: "inappropriate appreciation of loading conditions and of real behaviour of the structure was found to be the prime cause in almost one third of the failure cases investigated." From a research of Matousek & Schneider (1976), an investigation of 800 cases of failure from different sources, Fruhwald concludes: "[...] a majority of mistakes is related to conceptual errors and structural analysis. Incorrect assumptions or insufficient consideration of loads and actions was found to be a common type of error." The causes of failure and the phase in which the failure is made are discussed beneath.

The research of Fruhwald et al. (2007) is specifically aimed at timber structures, containing 127 failure cases. The most common cause of failure found in the investigated cases is poor design or lack of strength design (41%), in total half of the failures were due to design errors (53 %). About 27% was caused during construction. Wood quality, production -methods and -principles only caused 11% of the failures. The outcomes of this research on the causes of failure are presented in table 1, together with similar information on steel and concrete structures received from literature. From this it can be concluded that design errors are also a common cause of failure within steel- and concrete- structures.

Table 1: Failure causes (in % of cases) for different building materials (Fruhwald et al., 2007, page 26)

Failure cause	Timber %	Steel %	Concrete %
Design	53	35	40
Building process	27	25	40
Maintenance and re-use		35	
Material	11		
Other	9	5	20

Ellingwood & Dusenberry (2005) compiled results from a series of investigations during the years 1979-1985, to identify where in the building process errors occur. This list is expanded in the research of Fruhwald et al. (2007). This list is given in table 2 to provide an indication of where in the design and construction process failures occur.

Based on table 2, Fruhwald et al. (2007) concludes: "the occurrence of errors are of the same order of magnitude for design/planning and construction respectively, with slightly higher frequency for the design phase. Failures due to material deficiencies or maintenance are relatively uncommon."

Table 2: Percentage of failures by the phase in which they were made (Fruhwald et al., 2007, page 6)

Reference	Planning /design %	Construction %	Use /maintenance %	Other %	Total %
Matousek	37	35	5	23	98[d]
Brand and Glatz	40	40	-	20	100
Yamamoto and Ang	36	43	21	-	100
Grunau	40	29	31[a]	-	100
Reygaertz	49	22	29[b]	-	100
Melchers et al.	55	24	21	-	100
Fraczek	55	53	-	-	108[c]
Allen	55	49	-	-	104[c]
Hadipriono	19	27	33	20	99

[a] Includes cases where failure cannot be associated with only one factor and may be due to several of them.
[b] Building materials, environmental influences, service conditions.
[c] Multiple errors for single failure case.
[d] Error in report Fruhwald, should be 100 %

It should be noted that the classification of failures is not consistent between different investigators. Also, the results are incomplete and biased. For example only failures resulting in severe damage may be reported and much of the available data are reported voluntary and are not a random sample (Ellingwood & Dusenberry, 2005). Also information about errors and mistakes are difficult to get, since the involved parties often have a strong interest to conceal facts (Fruhwald et al., 2007). However this failure data provides in general an idea about technical and organizational defects in the design and construction process.

3.2.2 *Structural failures in the Netherlands*

Two recent (and ongoing) studies in the Netherlands have shed some light on the occurrence of failure in the Dutch building Industry.

The first study is the graduation thesis conducted by W.F. Boot in 2010 (Boot, 2010). This study presents 151 cases of structural damage of various kinds and identifies their causes. The source of the data is Dutch case law (decisions of the 'Raad van Arbitrage voor de Bouw', the 'Stichting Arbitrage-Instituut Bouwkunst' and the 'Commissie van Geschillen' of the KIVI NIRIA).

Boot (2010) analyses the type of failure as an attempt to pinpoint the causes of failure. The author concludes that most failures are related to design errors, execution errors or a combination of both. 34% of the structural failures is caused by design errors. These failures include (among others) calculation errors, failure to consider relevant loads and drawing errors. 32% of the structural failures is caused by construction errors. These failures include unwanted removal of temporary supports, non-conformance to design intent and inadequate assembly by construction workers. 20% of the structural failures is caused by a combination of design and construction errors. The remaining 11% are due to material deficiencies (6%), improper use (3%), circumstances beyond ones control (1%) and errors in manufacturing (1%).

Boot (2010) also discussed the phase in which the failures were made. 26 % of the failures were made in the design phase, 23 % in the construction phase, 18 % in both the design and construction phase and 17 % of the failures were made during renovation or expansion.

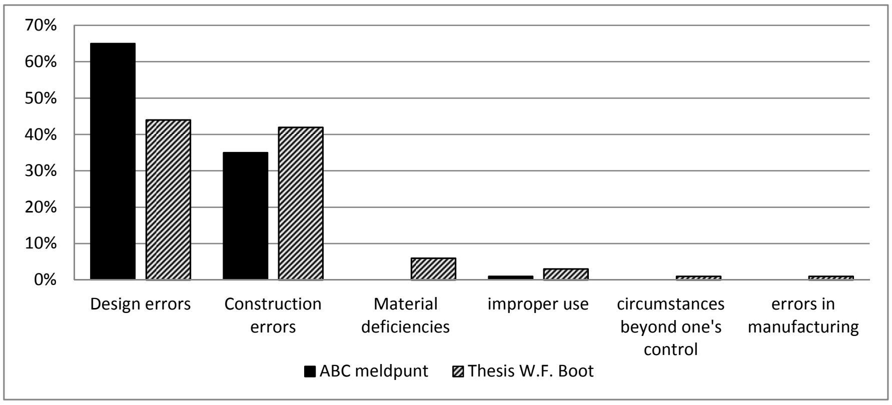
The second study is based on the findings of the 'ABC-meldpunt', set-up by TNO in commission of the 'Platform Constructieve Veiligheid'. The 'ABC meldpunt' registers structural failures which did lead, or could have led, to structural damage. Typical structures included in the database are houses, office buildings, bridges and tunnels. The registrations are based on voluntary and confidential reporting of the construction industry by means of an on-line enquiry (www.abcmeldpunt.nl), ABC-meldpunt, 2009).

From the period 2009 till 2011, 189 reports are received. An analysis of these reportings is presented in ABC-meldpunt (2011). In line with the findings of Boot, design and construction errors are the dominant types of causes. 65% of the failures are design errors and 35% are production errors. Improper use of the construction has occurred in one case, the usage of new materials and circumstances beyond ones control did not occur in a single case.

The two main causes for design errors are insufficient knowledge/ qualification for the project (25%) and incorrect schematic representation of the force balance, or not including the force balance (21%). Production errors are mainly a consequence of incorrect composition of materials/ incorrect construction phasing (34%) or improper measurements (19%).

The phase in which the failures were made is also presented. 61% of the failures were made during design and detailed engineering, 31% were made during construction and 7 % during renovation/expansion.

A comparison between both researches on the topic 'causes of failure' is presented in figure 4. From this figure it can be seen that the design and construction failures are the main causes for the occurring of errors, varying from 99% (ABC meldpunt) to 86% (thesis Boot). However, the subdivision between the design- and construction- phase differs considerable between both researches. Within the ABC research 65% of the errors are caused by design errors and only 35% due to construction errors. In the



[a] Adaptation ABC meldpunt: design- and construction errors are evenly divided between design errors and construction errors.

Figure 4: Comparison ABC meldpunt and Thesis Boot concerning the causes of failure

thesis of Boot the distribution is almost equal. Finally the percentage of failures originating from other failures the design- and construction- process differs considerable between both researches (11% in thesis Boot against 1% in ABC- meldpunt).

The findings on failure causes within the Netherlands differ considerable with the findings worldwide. The table of Fruhwald et al. (2007), as presented in table 1, states that 20% of the causes of failure is originated outside the design- and construction process. Boot (2010) concludes that 11% of the failure has a cause outside the design- and construction- process and the ABC meldpunt reports only 1% on this aspect.

The differences between the separate investigations could be a consequence of the small number of respondents. Within the thesis of Boot and the 'ABC meldpunt' the number of respondents was 151 and 189 respectively, and the number of respondents in Fruhwald et al. (2007) is 127. Another possibility could be the limited variety in the background of the respondents. For example within the thesis of Boot and the 'ABC meldpunt', only the construction industry is involved and not the end users or other relevant parties. And within the construction industry only observed noticeable cases are reported. Despite the differences between the discussed research, there results are very well useful as they provide basic insights in the aspects of structural failure.

3.2.3 *Costs of failure*

Within the Netherlands some researchers have attempted to quantify the failure costs of the construction industry. USP marketing consultancy BV has conducted several researches based on opinions of directors of industry in the Netherlands (Busker, Busker, 2010). The survey of 2008 shows a total failure cost of 11,4 % as percentage of the turnover. This was 7,7 % and 10,3 % in 2001 and 2005 respectively (general failure costs), with an average of 10%. USP concludes from this two possibilities: the failure costs in the Netherlands are rising or the awareness among directors of industry has increased.

An in-depth research on the failure costs of two projects as part of a broader research of 15 projects has been performed by Mans, Rings, van den Brand & Derkink (2009). The term failure costs in this research is limited to the following definition: costs of recovery of the (structural) failures, before completion of the project. So only failures which were discovered during construction were included, leaving out construction failures which were discovered in later stages. The two projects show failure costs of 6 and 8 % in comparison with the structural construction costs. It is concluded by Mans et al. (2009) that the failure costs of the 15 projects vary from 0 to 8 % with an roughly estimated average of 4 % (structural failure costs). Furthermore, Mans et al. (2009) concludes that this costs could be prevented with only a minor extra investment of 0,8% of the total construction costs.

From these two researches it can be concluded that the general failure costs are somewhat around 10 % and the structural failure costs are approximately 4 %. It should be noted that these numbers are a rough estimate with considerable uncertainty.

3.3 HUMAN ERROR

Section 3.2 provided general information on failure statistics within the building industry. An interesting aspect noted in that section is the occurrence of human error and its effect on structural failure (human error is seen as the basic cause of failure). Especially within the modern technological systems, the consequences of human error can be devastating. Accidents within the nuclear industry such as Three Mile Island [1] and Chernobyl [2], and within the building industry for instance the collapse of a stadium in Enschede (the Netherlands), have shown this devastating potential. This chapter discusses more in detail the background of structural failures and human errors. Three aspects are considered. Firstly subsection 3.3.1 elaborates on several subdivisions of human failure. Subsequently, in subsection 3.3.2 several human error models are discussed. Finally, subsection 3.3.3 discusses the nature of human error by focussing on its cognitive aspects.

---

[1] The Three Mile Island accident was a partial nuclear meltdown on March 28, 1979. The accident initiated with a failure in the secondary, non-nuclear section of the plant, followed by a stuck open relief valve in the primary system, which allowed large amounts of nuclear reactor coolant to escape. The mechanical failures were worsened by the failure of plant operators to recognize the situation due to inadequate training and human factors (USNRC, 2009)

[2] The Chernobyl disaster was a nuclear accident that occurred on 26 april 1986 at the Chernobyl Nuclear Power Plant in Ukraine. Lack of human factors considerations at the design stage is one of the primary causes of the Chernobyl accident. Furthermore, human error and problems with the man machine interface were attributing to the disaster (Meshkati, 1991)

3.3.1 *Aspects of human error*

As mentioned in chapter 3.2, most failures are caused by human error. Results from numerous investigations of structural failures have led Kaminetzky (1991) to conclude that all failures are human errors and that they can be divided into three categories:

1. Errors of knowledge (ignorance)
2. Errors of performance (carelessness and negligence)
3. Errors of intent (greed)

Other researchers, such as Ellingwood (1987),Stewart (1993) and Vrouwenvelder (2011), do recognise the human error as the main cause of structural failures as well. But unlike Kaminetzky, they do not underline that all failures are human failures, restricting it to a maximum of 90%.

Another division of human errors, more based on operational task analysis is shown beneath (Swain as cited in Melchers, 1984). This division is frequently used within Human Reliability Analysis related to plant operations:

- Errors of omission (e.g. failure to perform a task)
- Errors of commission (e.g. incorrect performance of a task)
- Extraneous acts.
- Sequential errors
- Time-limit errors (e.g. failure to perform within allocated time)

Based on his research in structural engineering, Melchers (1984) concludes: "the limited available evidence suggests that the first two categories are probably of most importance for structural-engineering projects, with the last item being of only minor importance."

Besides categorising human errors, categorizing the factors which influence human errors is of interest. These factors originate from aspects within the person, the organization or within the environment. Vrouwenvelder (2011) elaborates on this by presenting six factors which influence the probability of human error:

1. Professional skill.
2. Complexity of the task, completeness or contradiction of information.
3. Physical and mental conditions, including stress and time pressure.
4. Untried new technologies.
5. Adaptation of technology to human beings.
6. Social factors and organisation.

Van Herwijnen (2009) gives 5 important factors which underline the factors given by Vrouwenvelder. Furthermore the author recalls the economic development as a relevant factor. Mans et al. (2009) also underlines that the factor ‘completeness or contradiction of information‘ is an important aspect of structural safety within Dutch building projects: "It is concluded that parties in an individual building project do not always have the same view of structural safety, that in most projects no specific decisions are made about the level of structural safety [...]".

The question remains on which level of the organization errors, and more specifically human errors, occur. Is it on a personal level or on a more broader based organizational level? In order to provide insight in this question, a case study on structural failure held in the Netherlands (CUR, 2010) proposes to classify the causes of errors in three levels:

- Micro level: causes such as failures by mistakes or by insufficient knowledge of the professional.
- Meso level: causes arising from the organization of the project or the management.
- Macro level: causes arising from the rules, the culture within the sector or other external circumstances.

This classification is used within the CUR report to categorise 15 case studies of collapses within constructions. This report was set-up after major collapses occurred in the Netherlands, which started many initiatives by both government as well as building industry to avoid similar events in the future. It concludes that in general multiple causes can be identified for the appearance of a failure. These causes are based in all three levels; micro-, meso- and macro-level. The removal of only one of the causes can be sufficient to mitigate the failure.

3.3.2 *Models of human error*

Humans have always sought for means to find the causes of failure. Within the literature several models and metaphors are available to assist with this search. Within this section some of these models will be discussed.

A basic model which simplifies causal effects to a single chain is Heinrich‘s domino model (see figure 5, Hudson (2010)). Within this model each domino presents a factor in the accident sequence such as the social environment and the unsafe act himself. These factors are arranged in a domino fashion such that the fall of the first domino results in the fall of the entire row. If one of the domino’s is removed, the sequence is unable to progress and the undesired situation will not occur (Storbakken, 2002). Hudson (2010) criticises this model as it is not able to present accident causation in a non-linear fashion and it fails to model the non-deterministic character of error causation (error causation is not deterministic but rather more probabilistically).

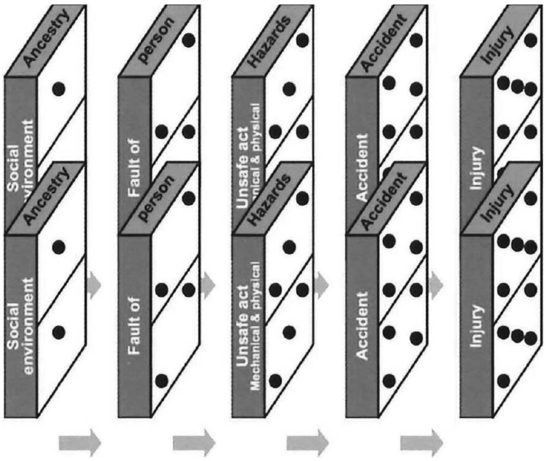


Figure 5: Heinrich‘s domino model. removing one domino prevents subsequent domino‘s from falling (Hudson, 2010, page 6)

A more sophisticated model is developed by the psychologist James Reason (Reason, 2000; Reason et al., 2001). This model is generally termed the “Swiss cheese“ model. Williams (2009) refers to the same model by calling it the ‘Window of opportunity model of causation‘.

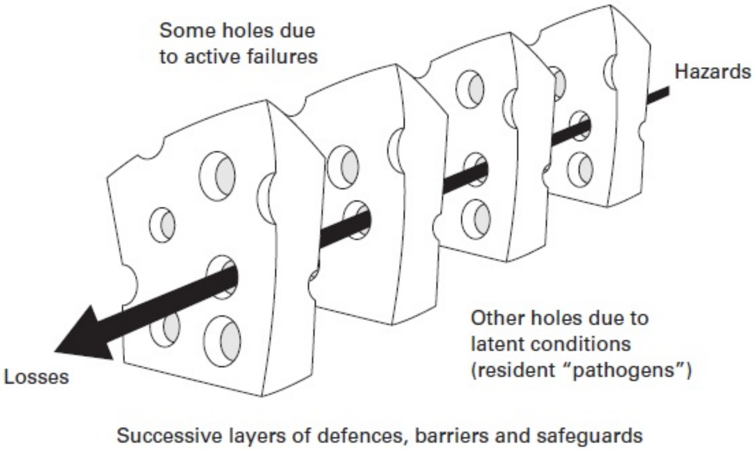


Figure 6: The “Swiss cheese“ model of accident causation. (Reason et al., 2001, page ii21)

Reason (2000) presents general knowledge about causes of major accidents, and presents tools and techniques for managing the risk of organizational accidents. Reason distincts two kinds of accidents: those that happen to individuals and those that happen to organizations. The “Swiss cheese“ model is of particular interest for the organizational accidents. The model exist of several defensive layers as presented in figure 6, which represent the defensive functions within a company. These layers can be ‘Hard‘ defences (e.g. personal protection equipment, alarms, etc.) or ‘Soft‘ defences (e.g. legislation, training, etc.).

In an ideal world all the defensive layers would be intact, allowing no penetration by possible accidents. In the real world, however, each layer has weaknesses and gaps as represented in figure 6. These 'holes' are not fixed and static, they are constantly moving due to the changing conditions. Particular defences can be removed deliberately, or as the result of errors and violations.

These holes are created in two ways: active failures and latent conditions. Nearly all adverse events involve a combination of these two sets of factors. Active failure are the unsafe acts committed by people who are in direct contact with the project. They have several different forms: slips, lapses, fumbles, mistakes and procedural violations. Latent conditions arise from decisions made by designers, builders, procedure writers and top level management. All such strategic decisions can lead to unsafe conditions in the system. Latent conditions have two kinds of adverse effects: firstly they can translate into error provoking conditions within the workplace (for instance time pressure, under-staffing and inexperience), secondly they create long standing holes of weakness in the defences (for instance unworkable procedures and design- and construction- deficiencies). Latent conditions can be present within the organization for years, before they combine with active failures and local triggers to create an accident opportunity. Active failures are often hard to foresee, while latent conditions can be identified and repaired before an accident occurs.

Hudson (2010) commented on the "Swiss cheese" model concerning causal mechanisms the following: "the causal mechanisms by which latent failures or conditions create unsafe acts could be quite different from the causal mechanisms operating once the hazard was lined up and the unsafe acts ready to be carrier out." Hudson (2010) noted that the "Swiss cheese" model is deterministic, but no longer linear. Furthermore the model misses the possibility to address common effects of higher order causes and lower order barriers. Concerning this latter Hudson (2010) has collected evidence within commercial aviation that the nature of the outcome can be predicted by factors well off the line of direct causality.

Reason elaborates further on failure theorem in a paper based on accident investigation in various hazardous domains (Reason et al., 2001). This investigation suggests that a group of organizational properties, called the vulnerable system syndrome (VSS), renders some organizations more vulnerable for failure. The authors state: "VSS has three interacting and self-perpetuating elements: blaming front line individuals, denying the existence of systematic error provoking weaknesses, and the blinkered pursuit of productive and financial indicators."

The investigation further states that these systematic shortcomings are present in all organizations, to a certain extend: "recognising its presence and taking remedial actions is an essential prerequisite of effective risk management." For this two types of organizational learning are recognised: 'single loop' learning that fuels and sustains VSS and 'double loop' learning. The solution lies in 'double loop' learning (Reason et al., 2001): "a crucial remedial step is to engage in 'double loop' organizational learning that goes beyond the immediate unsafe actions to question core assumptions about human fallibility and to identify and reform the organizational conditions

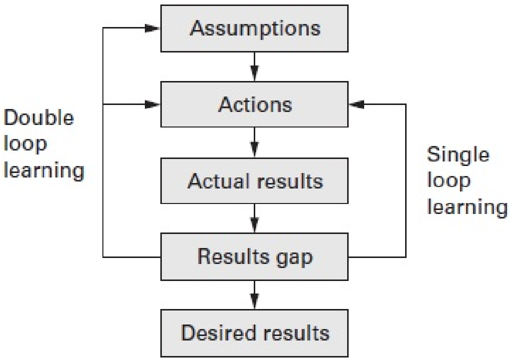


Figure 7: Single loop versus double loop learning (Reason et al., 2001, page ii25)

that provoke it.“ A schematic visualization of ‘single loop‘ and ‘double loop‘ learning is presented in figure 7.

An aspect closely related to the ‘Swiss cheese model‘ and the Vulnerable System Syndrome, is the so called Performance Shaping Factors (PSF), a term frequently used within the field of Human Reliability Assessment (HRA). More details on HRA is given in section 3.4, PSF will be discussed below.

According to DiMattia, Khan & Amyotte (2005), PSFs are those parameters influencing the ability of a human being to complete a given task. Examples are stress, complexity, training, experience and event factors. From this perspective PSFs are the factors that may cause human error incidents, and PSF analysis is meant to prevent the occurrence of future human errors by means of error management in the organization (Grozdanovic & Stojiljkovic, 2006).

A categorization of PSFs based on the process of human information handling and decision making is given by Grozdanovic & Stojiljkovic (2006). This categorization is presented in figure 8. According to this figure, a decision is influenced by three groups of PSFs: the available information, the knowledge base and the skills/experience. After the decisions are made, another set of PSFs influences the final outcome: the environment, the available equipment, communication and organization.

Prevention techniques for improving PSFs can be subdivided in two categories, quite similar to the earlier mentioned categories of active/latent condition of Reason. This subdivision acknowledges department based and department exceeding tasks:

- Immediate PSFs: the improvement of immediate PSFs cannot be expected to prevent other trouble occurrence. The prevention strategy against the immediate PSFs tends to depend on the specification of object task, so the strategy cannot be applied for tasks in other departments.

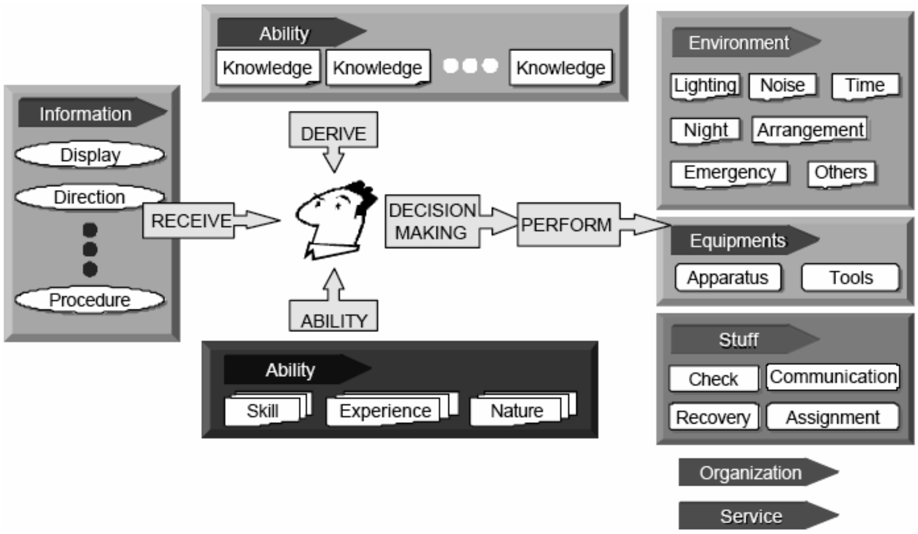


Figure 8: Categories of Performance Shaping Factors (PSF) from Okada (Grozdanovic & Stojiljkovic, 2006, page 135)

- Latent PSFs: as latent PSFs exist in other departments, the prevention strategy against the latent PSFs is expected to reduce the possibility of human error occurrence.

Finally it can be concluded from above literature findings that errors are an important source of unpredictability within the design- and construction-process. Ellingwood & Kanda (2005) writes that this can be managed in two ways: by maintaining an efficient and effective quality control process and by managing risk through monitoring secondary indicators of potential trouble.

Quality control requires (among others) independent checking procedures and a traceable documentation system. Quality assurance has a significant limitation: it assures the quality of management systems, but not of their content. Secondary indicators of potential trouble are for instance the experience, financial and political climate. The idea is to monitor the indicators and use them as a warning of increased risk within the process. Within the engineering practice, quality assurance is (among others) ensured by using extensive checking of the design by the designer, the supervisor or third parties. Concerning this Stewart (1993) states that the majority of the engineers believe that the best safeguard against structural failure are extensive checking of designs and close supervision of construction.

3.3.3 *Cognition of human error*

One of the questions remaining unanswered is what the exact nature of human error is. This is not an easy question, simple design tasks involves experience and insight which are hard to measure. Furthermore, it was found that even a simple design involves quite complex cognitive [3] tasks

---

[3] Cognition is defined as a group of mental processes by which input is transformed, reduced, elaborated, stored, recovered and used (OED, 2012)

(Melchers, 1984). Within this section an attempt is made to pinpoint some characteristics of human error based on findings within the field of psychology. A psychological definition of human error is given by Reason (1990), page 9:

> *Error will be taken as a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some change agency.*

A more pragmatical definition of human error is given by Swain and Guttmann (sited from Kirwan (1994), page 1), which is adopted in this research:

> *Any member of a set of human actions or activities that exceeds some limit of acceptability, i.e. an out of tolerance action [or failure to act] where the limits of performance are defined by the system.*

For understanding human error, it is important to understand the factors which give rise to the production of errors. There are three major elements in the production of an error according to Reason (1990): the nature of the task and its environmental circumstances, the mechanisms governing performance and the nature of the individual. Also the notion of intention is an important aspect of error, defining human error begins with a consideration of the intentional behaviour. Another important factor which is described in Hollnagel (1993) is the distinction between competence and control as separate aspects of performance: "the competence describes what a person is capable of doing, while the control describes how the competence is realised, i.e., a person's level of control over the situation."

Error classification, which is necessary for error prediction, can be done on different levels. Reason (1990) distinguishes three levels at which classifications are made: the behavioural, contextual and conceptual levels. These corresponds approximately to the 'what? ', 'where? ' and 'how? ' questions about human errors.

At the behavioural level of classification, errors may be classified according to some easily observable aspects of the behaviour. These can include either the formal characteristics of the error (omission, commission, etc.), or its more immediate consequences (damage, injury). The contextual level of classification goes beyond the basic error characteristics and includes also assumptions about causality. Such categorizations are valuable as it draws attention to the complex interaction between 'local' triggering factors and the underlying error properties. However even these contextual factors cannot explain why the same or very similar circumstances not always lead to the same type of error. The conceptual level of classification is based on the cognitive mechanisms involved in producing the error. These classification is potentially the most promising because it tries to identify the underlying causal mechanisms (Reason, 1990).

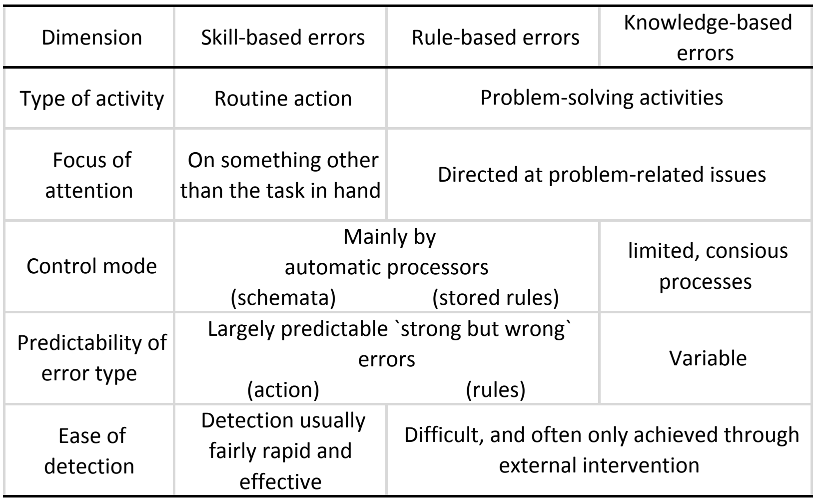
Another distinction made by Reason (1990) is based on the origins of the basic human error types. This distinction is related to the process of the particular action (planning, storage and execution). These error types are conceptually tied to underlying cognitive stages or mechanisms. This distinction (or conceptual framework) consists basically out of two types of mistakes: slips/lapses and mistakes. Slips and lapses are actions which deviate from current intention due to execution failures and/or storage failures. Mistakes are actions which may run according to plan, but where the plan is inadequate to achieve its desired outcome.

In line with the level of cognitive operation in error production, mistakes occur at the level of intention formation, whereas slips and lapses are associated with failures at the more subordinate levels of action selection, execution and intention storage. As a consequence, mistakes are more complex than slips and lapses.

If the division in two (slips and mistakes) is used, differentiating based on cognitive mechanisms is not possible. Both slips and mistakes can take 'strong-but-wrong' forms, where the wrongful behaviour is more in keeping with past practise than the current circumstances demand. One way of resolving these problems is to differentiate two kinds of mistakes: rule based mistakes and knowledge based mistakes.

So finally to summarise the argumentation of Reason on error types, there are three error types distinguished: skill-based slips and lapses, rule-based mistakes and knowledge-based mistakes. These three error types may be differentiated by a variety of processing, representational and task related factors. Some of these are summarized in table 9, to provide some insight in the difference between the three error types. It should be noted that these error types are based on the cognitive task level, and as such generally applicable.

Figure 9: Summary of the distinctions between skill-based, rule-based and knowledge-based errors. (page 62 Reason, 1990, abbreviated)



Dimension	Skill-based errors	Rule-based errors	Knowledge-based errors
Type of activity	Routine action	Problem-solving activities	
Focus of attention	On something other than the task in hand	Directed at problem-related issues	
Control mode	Mainly by automatic processors (schemata)	(stored rules)	limited, consious processes
Predictability of error type	Largely predictable `strong but wrong` errors (action)	(rules)	Variable
Ease of detection	Detection usually fairly rapid and effective	Difficult, and often only achieved through external intervention	

To illustrate the usage of knowledge and the relation with errors in a daily working situation, Reason (1990) developed a Generic Error-Modelling System (GEMS). This system is depicted in figure 10.

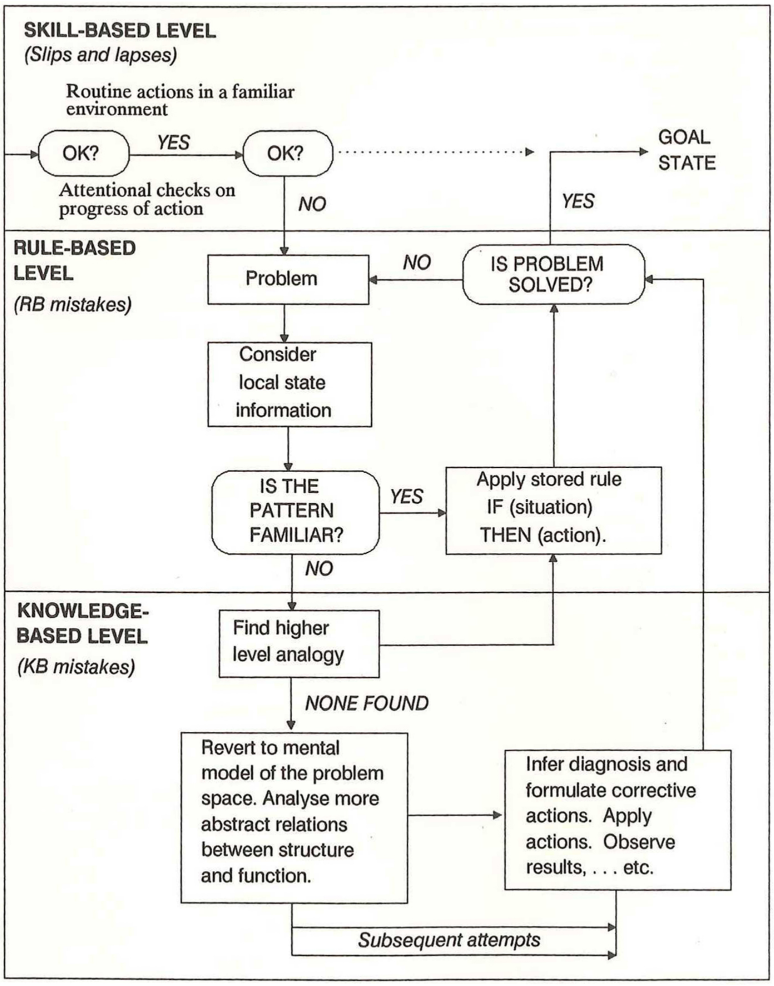


Figure 10: Outlining the dynamics of the generic error-modelling system (GEMS) (Reason, 1990, page 64)

The model visualises the dynamical system of errors by illustrating the cognitive steps which are required to reach a goal. The first step is made on the skill-based level, by the performance of a highly routinised activity in familiar circumstances. The rule-based level is engaged when an attentional check detects a deviation from the planning. The idea behind this is that humans always try to solve a problem with 'rules' they already know. If these rules are not sufficient, the far more effort-full knowledge-based level is used to solve the problem. It should be noted that the lines between the three levels are not as clear-cut as envisioned, iteration between the different levels are constantly occurring. Another final note is that within one specific task all three levels could be active at the same moment. An example is car driving; watching the traffic and switching the indicator on are activities on two different levels, occurring at the same moment.

GEMS is based on a recurrent theme in the psychological literature, given by Rouse (1983): "humans, if given a choice, would prefer to act as context-specific pattern recognizers rather than attempting to calculate or optimize." This means for the GEMS model that humans are strongly biased to find a solution on the rule-based level before going to the far more effort-full knowledge-based level.

The idea of different kinds of errors on different cognitive levels is an interesting notion from a probability perspective. Quantifying probabilities are mostly based on the behavioural level of classification as will be outlined in the following sections. In order to increase the accuracy of the probabilities and to be able to propose usable improvements, cognitive aspects such as discussed in this section should be incorporated in the risk analysis.

3.4 HUMAN RELIABILITY ASSESSMENT

The probabilistic risk assessments which deal with human error are generally termed Human Reliability Assessments (HRA). This section discusses HRA in detail as it will be used extensively in the main research of this thesis. Within this section, the basics of HRA are discussed in subsection 3.4.1. The HRA process is discussed in subsection 3.4.2. Subsection 3.4.3 sets-apart three different HRA methodologies to get some idea about the technique. Subsection 3.4.4 finally discusses particular HRA application within structural design.

3.4.1 *Basics of human reliability assessment*

Human Reliability Assessment (HRA) deals with the assessment of human potential in a system. HRA can be used to estimate the quantitative or qualitative contribution of human performance to system reliability and safety (Swain, 1990). The majority of work in human error prediction has come from the nuclear power industry through the development of expert judgement techniques such as HEART (Human Error Assessment and Reduction Technique), CREAM (Cognitive Reliability and Error Analysis Method) and THERP (Technique for Human Error Rate Prediction) (DiMattia et al., 2005).

According to Kirwan (1994), HRA has three basic functions which are:

- Identifying which errors can occur (Human Error Identification)
- deciding how likely the errors are to occur (Human Error Quantification)
- enhancing human reliability by reducing this error likelihood (Human Error Reduction)

Swain (1990) denotes the first function as the qualitative part and the second function as the quantitative part. The third function is not mentioned by Swain:

> *The qualitative part of HRA largely consists of identifying the potential for human error, i.e. error like situations. The basic tool for identifying this error potential consists of task analysis [...] by observation,*

> *interviews, talk-troughs, error records, etc. [...] The quantitative part of HRA includes the estimation of time-dependent and time-independent Human Error Probabilities (HEP) [...] Such estimations are made by the use of human performance data, human performance models, and analytical methods associated with the HRA methods used.*

HRA is an interdisciplinary discipline, involving reliability engineers, engineers, human-factors specialists and psychologists. According to Kirwan (1994) two reasons are fundamental for this: it requires an appreciation of the nature of human errors and it requires some understanding of the engineering of the system.

One of the basic features of HRA is the allocation of so called Performance Shaping Factors (PSF). PSFs are the factors that affect human behaviour, and human error is also an aspect of human behaviour. From this perspective, PSFs within the human error characteristics are regarded as contributing factors to human error. These considerations have a close link with the aspects of human error discussed in section 3.3, in which PSFs are discussed in more detail.

Origin HRA

Grozdanovic & Stojiljkovic (2006) and Kirwan (1994) provide both an overview of the development of HRA from the origin in the 60s. A short summary is presented in this paragraph to show the trends that have driven human reliability over the past decades. During the first decade of HRA, there was a desire to create human-error data-banks. There was also the need to consider Performance Shaping Factors (PSF), to guide the analyst in deriving the human-error rate for a particular task. After a while, it was being realised that the data-bank approach was not working. This is largely due to the now-obvious reason that humans are not, and never will be, the same as simple components, and should never be treated as such.

In the 70s, three strands of HRA research were evolving. The first involved a continuation of the database approach (on a more semi-judgemental basis). The second strand was the simulation approach, which uses distributions of performance times combined with Monte Carlo simulation to simulate the human reliability. The third strand was the time-reliability approach, involving the modelling of the 'mean-time-to-failure' ratio for hardware components. In the first half of the 1980s, there was a drive towards understanding human error at a deeper, psychological level. The predominance of engineering approaches was now going into reverse, and greater credibility was being given to more psychological and expert-opinion-based quantification approaches. A recent development is the shift from quantitative HRA towards qualitative HRA insights.

There are now a vast amount of HRA tools available, each of them focused on a particular usage or based on particular information sources. The comprehensive Safety Methods Database of Everdij, Blom & Kirwan (2006) provides an overview of 726 techniques, methods, databases, or models that can be used during a safety assessment. 142 of these tools are related to human performance analysis techniques.

Categorization HRA tools

Several categorizations within the HRA tools are available in order to require insight into the use of it. Most HRA tools are based on the usage within operation functions within a particular hazardous industry such as the nuclear industry, aviation and offshore industry. According to Kirwan (1996) HRA techniques can be divided according to their particular information source into two categories: those using a database and those using expert opinions. Examples of database based methods are Technique for Human Error Rate Prediction (THERP), Human Error Assessment and Reduction Technique (HEART), Justification of Human Error Data Information (JHEDI) and Cognitive Reliability and Error Analysis Method (CREAM), examples of expert opinion based methods are Succes Likelihood Index Method (SLIM), Absolute Probability Judgement (APJ) and Paired Comparisons (PC).

Hollnagel (1998) distinct first and second generation HRA. First generation HRA are based on the limited university of the binary event tree, which causes a low complexity level within the classification schemes due to this limited university. Examples are THERP and HEART. Second generation HRAs use enhanced event trees which extend the description of error modes beyond the binary categorisation of success-failure. A second property of the second generation is that it explicitly states how the performance conditions affect performance. An example of a second generation HRA tool is the CREAM methodology.

Harrison (2004) distincts two approaches of HRA which is closely related to the distinction of Hollnagel (1998). The writer distinct an 'engineering' approach and a 'cognitive' approach. The engineering approach is based on a quantitative decomposition, the base assumption is: "human performance can be adequately described by considering individual elements of the performance. Total performance is an aggregate of the individual performance elements." Within this approach, the human is treated as components within a complex system. This approach is the dominant approach to HRA, and is comparable to the first generation approaches mentioned by Hollnagel. The cognitive approach is based on the explicit use of models and theories of cognitive functions which underlie human behaviour (comparable with Hollnagels second generation). This method is used to a lesser extent, the cognitive psychology is still immature and the human cognition is not directly observable.

3.4.2 *The HRA process*

The HRA process is depicted in figure 11. Not all of these steps are important within the scope of this research. For instance error reduction will not be discussed into detail as this research focusses primarily on Human Error Identification and Quantification. Based on the guidebook on HRA of

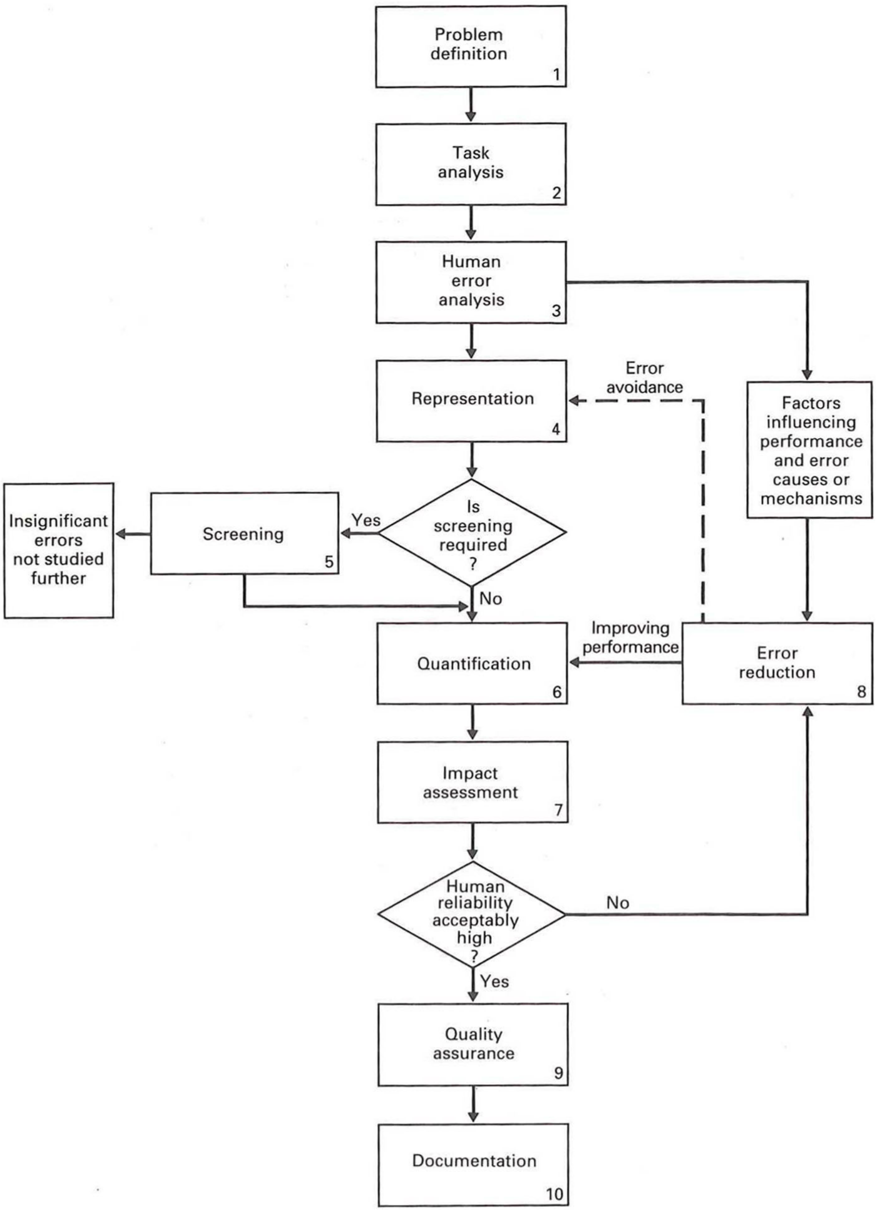


Figure 11: the HRA process (Kirwan, 1994, page 32)

Kirwan (1994), some components are briefly outlined below.

Task Analysis (at 2) refers to methods of formally describing and analysing human-system interactions. There are many different kinds of task analysis techniques, which are usually fairly straightforward. Examples are the hierarchical task analysis, link analysis and tabular task analysis. Human Error Identification (at 3) deals with the question of what can go wrong in a system from the human error perspective. Some of the Human Error Identification approaches are: Human error Hazard and Operability study and Murphy Diagrams. Human Error Quantification (at 6) is the most developed part of the HRA process, there are a number of sophisticated tools available. All Human Error Quantification techniques involve the calculation of a Human Error Probability (HEP), which is the measure of a Human Reliability Assessment. Human Error Probability is defined as follows:

$$\mathsf{HEP} = \frac{\text{The number of times an error has occurred}}{\text{The number of opportunities for that error to occur}} \tag{1}$$

Examples of Human Error Quantification techniques are: APJ, PC, HEART, THERP and CREAM. Some of these techniques will be explained in section 3.4.3. Once the errors have been presented and quantified, the overall risk level can be determined in the Impact Assessment (at 7). One of the last steps within the model is to determine if the calculated/estimated human reliability is acceptable. After this step error reduction or quality assurance follows as a last step.

Limitations HRA

HRA is not commonly accepted as a reliable risk assessment tool. There are a couple of reasons for the fact that fully adequate HRAs do not exist. Swain (1990) provides two reasons. Firstly there are real problems in performing a HRA regardless of the HRA method used, and there is a wide variety in the effectiveness of existing HRA methods. Secondly, design and operation of many complex systems are inadequate for reliable human performance. Kirwan (1996) supports this statement by criticizing the validity of HRAs based on two counts: firstly, the quantitative prediction of human performance is seen as doubtful. And secondly, the theoretical underpinnings of the technique is seen as too crude to be plausible.

To illustrate the shortcomings of HRAs, Swain (1990) provides seven inadequacies within HRAs, which seem plausible at this moment as well:

- The scarcity of data on human performance that are useful for quantitative predictions of human behaviour in complex systems.
- Because of the lack of real-world data on human performance, less accurate methods are used like stop-gap models and/or expert judgement
- Methods of expert judgement have not demonstrated satisfactory levels of consistency and much less accuracy of prediction.
- The issue of calibrating human performance data from training simulators has not been seriously addressed.
- Demonstrations of the accuracy of HRAs for real-world predictions are almost non-existent.
- Some HRA methods are based on highly questionable assumptions about human behaviour.
- The treatment of some important performance shaping factors (PSF) are not well addressed.

Regarding the quantitative prediction of HEPs, Grozdanovic & Stojiljkovic (2006) states that there are three major technical problems for generating this. The first problem is the degree of specificity inherent in the data for the particular situation, as large variations exist between each situation. The second problem is the usefulness of the data on how to improve human reliability, as the HEP data does not give information on this. The third problem with purely quantitative data is that such data only state the external form, or observable manifestation, of the error.

Despite the limitations of HRA, it still represents a very useful tool for designing complex systems and for assessing the human-induced risks of such systems to the public (Swain, 1990). Harrison (2004) ads to this that analysing and measuring dependability without assessing human reliability is at best incomplete and at worst misleading. Hollnagel (1998) supports this: "The need is, however, present whenever or wherever an interactive system is being designed, since the reliability of the system must be a concern."

Concerning the reliability of the HRA methods, Kirwan, Kennedy, Taylor-Adams & Lambert (1997) has validated three HRA techniques: THERP, HEART and JHEDI using 30 active HRA assessors. This resulted (among others) in the following conclusion "the results were that 23 of the assessors showed a significant correlation between their estimates and the real HEPs." Based on this validation it becomes clear that HRA has the potential to predict human error probabilities.

3.4.3 *Examples HRA methodologies*

In this section three HRA methodologies (THERP, HEART and CREAM) will be discussed in some detail to give an idea of the methods used in practise. These methodologies are selected for further research as they are quite influential within the HRA theory and information concerning these technologies is readily available.

THERP

The Technique for Human Error Rate Prediction (THERP) is a methodology for assessing human reliability, developed by Swain & Guttmann (1983). THERP is a total methodology. It deals with task analysis, error identification, representation and quantification of HEPs (Kirwan, 1994).

For the quantification part, THERP provides several subsequent functions. A database of human errors can be modified by the assessor to reflect the impact of PSFs on the scenario. Then a dependency model calculates the degree of dependence between two actions. This is followed by an event-tree model that combines HEPs calculated for individual steps into an overall HEP. Finally error-recovery paths are assessed.

THERP's strengths are that it has been well-used in practice and that it offers a powerful methodology which can be altered by the assessor. THERP's disadvantages are that it can be resource-intensive and that it does not offer enough guidance in modelling both scenarios and the impact of PSFs on errors (Kirwan, 1994). Another disadvantage of THERP is that it is relatively psychologically opaque, dealing only with external error modes rather than psychological error mechanisms (Hollnagel, 1998).

HEART

The Human Error Assessment and Reduction Technique (HEART) is developed by J.C. Williams (Williams, 1986, 1988), a British ergonomic with experience of many hazardous technologies. According to Williams (1988), HEART is developed not only to assess the likelihood and impact of human unreliability, but to apply human factors technology to optimise overall systems design.

Within the HEART methodology, a couple of Generic Task Types (GTT) are given. To each of these GTTs, a range of human unreliability values as well as a suggested nominal value is assigned (table 3). Besides these GTTs, a set of error producing conditions (EPC) is given, to which a multiplication factor (E) is assigned (table 4). Finally a weighting factor (P) should be assigned to each error producing condition based on the judgement of the designer (Hyatt, 2006). The Human Error Probability (HEP) is then computed from:

$$\mathrm{HEP} = \mathrm{GTT}\prod_{1}^{n}\{(E_i - 1)P_i + 1\}, \text{ and smaller than 1} \tag{2}$$

GTT	General Task Type nominal value for human unreliability (table 3)
E_i	assigned EPC factor (table 4)
P_i	assigned weighting factor applied to individual EPC factor

A small example is presented to demonstrate the usage of HEART within the building industry. Say for instance we look at the calculation procedure of a fairly normal task, the design computations of a typical reinforced concrete beam. Say for instance the computation is executed under time pressure and as a consequence only minor independent checking is executed. The generic task description (GTT) would be D; a fairly simple task. The weighting factor (P) is set to 0.1. It should be noted that this factor is subjected to personal interpretation which leaves quite some space for variation. The error producing conditions are a shortage of time (2) and little or no independent checking (17) (see table 4). The HEP for this example is:

$$\mathrm{HEP} = 0.09 \cdot \{(11 - 1)0.1 + 1\} \cdot \{(3 - 1)0.1 + 1\} = 0.228 \tag{3}$$

The methodology is highly questionable as regards to determining accurate human error probabilities but can be valuable for comparing situations (Hyatt, 2006). Reason (2000) criticises the method on the absent of

Task type	Generic tasks	Nominal error probabilities (5th-95th percentile bounds)
A	Totally unfamiliar, performed at speed with no idea of likely consequence	0.55 (0.35 to 0.97)
B	Shift or restore system to a new or original state on a single attempt without supervision or procedures	0.26 (0.14 to 0.42)
C	Complex task requiring high level of comprehension and skill	0.16 (0.12 to 0.28)
D	Fairly simple task performed rapidly or given scant attention	0.09 (0.06 to 0.13)
E	Routine, highly practised, rapid task involving relatively low level of skill	0.02 (0.007 to 0.045)
F	Restore or shift system to original or new state following procedures, with some checking	0.003 ($8 \cdot 10^{-}4$ to $7 \cdot 10^{-}3$)
G	Very familiar, highly practised, time to correct, job aids	0.0004 ($8 \cdot 10^{-}5$ to $9 \cdot 10^{-}4$)
H	Respond correctly to system even when supervisory system provides accurate interpretation on system state	0.00002 ($6 \cdot 10^{-}6$ to $9 \cdot 10^{-}5$)
M	Miscellaneous task for which no description can be found	0.03 0.008 to 0.11

Table 3: Proposed nominal human unreliability (GTT) (Williams, 1988, page 439)

agreement between different assessors: "When people are asked to make absolute probability estimates of a particular kind or error type, their judgements may vary by orders of magnitude from person to person." However an extensive survey of the human factors literature has revealed that the effects of various kinds of manipulation upon error rates show a high degree of consistency across a wide variety of experimental situations (Reason, 2000). Despite these set-backs, the methodology is regarded as the best available account of the factors promoting errors and violations within the workplace according to Reason (2000). Reason declares: "the fact that they can be ranked reliably- so that we can assess the relative effects of the different factors- represents a major advance and an extremely valuable addition to the safety-concerned manager's tool box."

EPC Type	Error producing condition (EPC)	Multiplying factor (E)
1	Unfamiliar situation, potentially important, only occurs infrequently or is novel	17
2	A shortage of time available for error detection and correction	11
3	Channel capacity overload, e.g., by flooding with new information	6
10	The need to transfer specific knowledge from task to task without loss	5.5
16	Poor quality of info conveyed by procedures and person-to-person interaction	3
17	Little or no independent checking or testing of output	3
20	Mismatch between educational level of individual and requirements of task	2
25	Unclear allocation of function and responsibility	1.6
38	Age of personnel performing perceptual tasks	1.02

Table 4: Error producing conditions (E) (Williams, 1988, page 438-439) (abbreviated)

CREAM

The Cognitive Reliability and Error Analysis Method (CREAM) is developed by Erik Hollnagel and extensively described in Hollnagel (1998). This method is a representative method of the second generation HRA methods. CREAM has two main features: it emphasizes the important influence of the context on human performance and has a useful cognitive model and framework which could be used in analysis. The core of CREAM is that human error is not stochastic, but more shaped by the context of the task.

The main advantage of CREAM is its emphasises on the complex interactions between human cognition, and the situations or context in which the behaviour occurs. This model of cognition is an alternative to the traditional information processing models. Rather than describing the human mind as an information processor, the focus is on how actions are chosen. It does not define specific routes of human information processing, but rather describes how a sequence of actions can develop as the result of the interaction between competence and context. The basic notion of this is that the degree of control that a person has over his actions may vary, and that this to a large extent determines the reliability of performance (Hollnagel, 1998).

A second advantage is the useful cognitive model and framework elaborately presented in Hollnagel (1998), which can be easily used within quantifying probabilities. From this perspective CREAM is considerably simplified in comparison with other methods, as CREAM focuses on the level of the situation or working conditions rather than on the level of the individual actions.

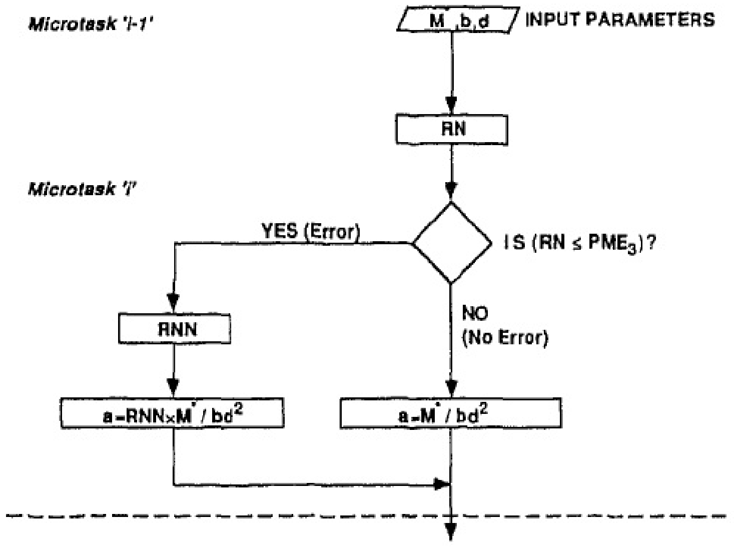
The CREAM methodology proposes a two step approach to quantifying error probabilities. The first step is an initial screening (basic method) of tasks, followed by a second step to analyse only the most important probabilities (extended method). A deficit for use of this model within engineering is that it is primarily focussed on operator tasks within hazardous industries, such as aviation and nuclear power industry. Despite this setback, CREAM is usable within engineering types of tasks as Hollnagel has attempted to keep the methodology generally applicable. The CREAM method is selected as a basis for the HRA model for (design) engineering tasks defined in this thesis. The CREAM method is used as it emphasises the complex interaction between human cognition and the situation or context in which the behaviour occurs. Further elaboration on the extended quantification method within the CREAM method can be found in chapter 4.

3.4.4 *HRA in design*

Most Human Reliability Assessment (HRA) literature and techniques are directed towards operational tasks, which differs from designing tasks considered in this thesis. A particular research program aimed towards HRA in design situations is commenced in the eighties/nineties in Australia at the University of Newcastle. This research program is published in several papers: Melchers (1984), Melchers (1989), Stewart & Melchers (1988), Stewart (1992a), Stewart (1992b) and Stewart (1993). This section summarises some of the relevant results of this research program.

The HRA method proposed is based on Monte-Carlo simulation. The mathematical model used to simulate human error was developed from event-tree methodology. This methodology enables a design task (or macro-task) to be divided into successive individual components (or micro-tasks) (Stewart, 1992b). On this way first understanding the influence of human error on the 'micro' (or single task) level is obtained, which is then translated to understanding on the macro-level (Stewart, 1992a). The procedure comprises the following steps: at each micro-task a random variable is generated and compared with the given Error Rate for the represented operation. This enables a binary decision (either "error-included" or "error-free") to be made. If the error is included, the output of the micro-task is multiplied with an Error magnitude. This Monte-Carlo simulation process is presented in figure 12.

This Monte-Carlo procedure requires two sets of parameters originating from human behaviour. These parameters are the probability of human error (HEP) within a micro-task and the error magnitude (EM) if such an error has occurred. One of the main difference between HRA within operational types of tasks and within design tasks is the occurring Error Magnitude. Within design this is defined as a numerical deviation within a design pa-



RN = Random Number
RNN = Error magnitude for calculation error
PME3 = error rate for calculation micro-task

Figure 12: Section of event tree for calculation micro-task $a = \frac{M^*}{bd^2}$ (Stewart, 1993, page 282)

rameter from the expected numerical value. According to Melchers (1989), these probabilities of human error are clearly related to task complexity, and cannot be represented by Poisson process models in which errors are modelled as random events over some tasks. In the remainder of this section three micro-tasks will be discussed concerning the two sets of parameters. These tasks are: simple calculation, table look-up and table interpolation.

Simple calculation

A calculation is defined as a discrete number of mathematical operations on a set of numbers leading to a recorded result. For simple calculations it was found in a study among engineering students, that the error rate was about 0,01 to 0,015 with considerable scatter (Melchers, 1989). A more intensive study found that the error rate increased directly with the number of mathematical operations to be performed (Melchers, 1989). In this study a higher error rate for an one-step calculation of about 0,025 was observed. The results could be categorized in three groups: computation errors, decimal error and round-off errors. The number of round-off errors was found to be small, and was ignored in further analysis (Melchers, 1984). An overview of the other two categories is shown in table 5.

Based on the calculation results presented above, Melchers & Harrington (1984) (as sited from Stewart, 1992b) have proposed a distribution curve for the error magnitude in an one-step calculation task. This distribution curve is shown in figure 13. Visual interpretation of this curve reveals that the distribution consist of two separate curves: a log-normal distribution with

Table 5: Error frequency within a one-step and two-step calculation task (Melchers, 1984)

	One-step S.S.[a] = 1244 P_E	Two-step S.S.[a] = 1211 P_E	Combined S.S[a] = 2455 P_E
Computation	0,0072	0,0157	0,0114
Decimal	0,0056	0,0049	0,0053
Overall	0,0128	0,0206	0,0167

[a] Sample Size

a standard deviation of 1,35 representing the computation errors and a discrete distribution representing the decimal errors.

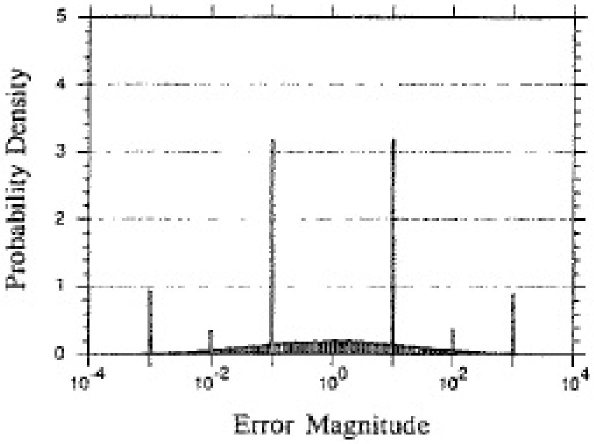


Figure 13: Distribution curve of the error magnitude of a one-step calculation task (Melchers & Harrington (1984), sited from Stewart (1992b))

Table look-up

This micro-task is defined as the ability of a designer to look-up a specific value from a table of values. The average error rate for a table look-up is estimated to be 0,0126. (Melchers, 1984). However this can increase to 0,06 if a more complex table was used, and if there was a high degree of task repetition (Melchers, 1989). The error magnitude of the table look-up task is presented in figure 14. Visual interpretation of this figure based on relevant tables for look-up tasks reveals that 10 % of the errors have approximately a value of 2 to 4 times the correct value. A Normal distribution with a standard deviation of 0,80 (if the correct value is 1) would approximate this result.

Table interpolation

This task is defined as comparing tabulated values and then selecting the correct value corresponding to a specific ranking instruction. The average error rate from this micro-task is 0,0135 (Melchers, 1984) for rather simple tasks. An error rate of up to 0,08 was obtained for more realistic tables

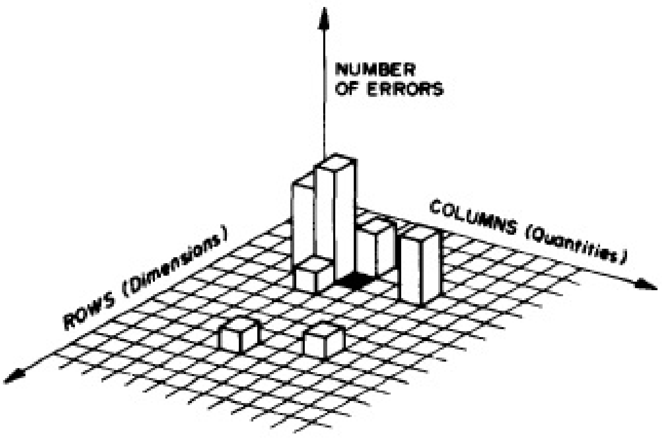


Figure 14: Distribution curve of the error magnitude of a table look-up task. The shaded location represents the correct results. (Melchers, 1984)

(Melchers, 1989).

Conclusion
Based on the findings in Melchers (1984, 1989), Stewart (1992b) presented a summary on the average error rate of the micro-tasks discussed above. This summary is presented in table 6.

Table 6: Summary of average micro-task error rates (Stewart, 1992b)

Microtask	Average error rate
Table ranking	0,0135
Table look-up	0,0126
Chart look-up	0,0200
One-step calculation	0,0128
Two-step calculation	0,0256
Three-step calculation	0,0384
Five-step calculation	0,0640
Six-step calculation	0,0768

Error variation
It might be expected that error rates for individuals (for a specific task) will vary due to differing ability, personal characteristics, work environments and other factors that affect task performance. Within the Cognitive Reliability and Error Analysis Method (CREAM) presented in Hollnagel (1998), this is accounted for by adjusting the Nominal Error Probabilities (NEP). Stewart (1993) proposes to represent this variation in error rates by a log-normal distribution, based on findings of Swain & Guttmann (1983). The mean of the log-normal distribution is equal to the average error rate as

presented in table 6. A usable measure of variance is the Error Factor (EF), as expressed in equation 4.

$$\mathrm{EF} = \sqrt{\frac{\Pr(E_{90^{th}})}{\Pr(E_{10^{th}})}} \qquad (4)$$

Within this formula $\Pr(F_{10^{th}})$ and $\Pr(F_{90^{th}})$ are the error rates corresponding to the 10^{th} and 90^{th} percentiles respectively (Apostolakis, 1982). Stewart (1992b) proposes to use an Error Factor of EF = 3 for design tasks.

3.5 PROBABILITY OF FAILURE

In this section the probability of structural failure is discussed. Analysing probabilities is used within Human Reliability Assessments to quantify human error probabilities. Furthermore probability analysis is commonly used in risk [4] assessment techniques. Concerning this Baker, Schubert & Faber (2008) wrote that an ideal design is the one having minimal risk, achieved by balancing the reduction of risks against the cost of the risk reducing measurements. Within human factors, reduction of risks can be translated to taking human error prevention measurements which are realistically and applicable within the current engineering practice. This section will first answer the question how to quantify probabilities (subsection 3.5.1) and then elaborate on how to execute a risk assessment (subsection 3.5.2).

3.5.1 *Quantifying probabilities*

There are some problems with quantifying failures and the chance of collapse. In 1987, Ellingwood noticed that most of the errors are difficult to quantify, as their source is human imperfection. Quantifying this is hard due to the difficulty to obtain complete and unbiased statistics (Fruhwald et al., 2007). Given this, the solution of the error problem is not strictly a matter of statistics, probability and reliability theory. However despite the challenges (assigning probabilities to the exposures), occurrence probabilities are required to efficiently allocate resources for risk reduction (Baker et al., 2008).

The question remains which analysis tool should be used to quantify the probabilities. Many Techniques and methods have been developed to support the safety assessment process of a particular operation, procedure or technical system. Everdij et al. (2006); Everdij & Blom (2006) have developed a database of well over 700 safety methods. The list contains methods for hazard identification, mathematical models, etc. The methods come from several domains of application, such as nuclear power industry, aviation, etc.

Most of the methods concerning the quantification of probabilities can be categorized as so called Probabilistic Risk Assessment (PRA) tools. These

---

[4] Defined as the combination of the probability of occurrence of a hazard and the magnitude of the consequence of occurrence.

methods are characterized by a systematic methodology to evaluate risks associated with a complex system. In a PRA, risk is characterized by two quantities: the magnitude of the possible consequence and the probability of occurrence (Stamatelatos, 2000). A PRA can be quantitative as well as qualitative.

One method for analysing human reliability is a straightforward extension of Probabilistic Risk Assessment (PRA). In the same way that equipment can fail in a plant, so can a human operator commit errors. In both cases, an analysis would articulate a level of detail for which failure or error probabilities can be assigned. The analysis to assess human error is termed Human Reliability Assessment (HRA) and is already discussed in section 3.4. A shortfall of this method is its focus on operational types of activities instead of design activities, caused by its usual application in operational industries such as aviation, nuclear- and offshore- industries. Melchers (1984) wrote: "Virtually no information appears to exist about tasks such as those performed in design." It seems that this statement is still valid as not much has changed in the past decades concerning HRA in design.

3.5.2 *Risk Analysis*

There are several tools developed within the literature to model human error and risk with the help of probability calculations. Some of these tools will be set-apart in this section. A basic model for describing the effect of human error on structural resistance is presented by Vrouwenvelder, Holicky & Sykora (2009), by defining a multiplier on the resistance within the basic reliability function of $Z = R - S$. Within this reliability function, failure will occur if $Z \leqslant 0$. Furthermore S is defined as the loadings acting on the structure and R is defined as the resistance of the structure. The multiplier on the resistance is termed:

$$R = R_0 + \Delta \tag{5}$$

The term R_0 is the resistance based on the correct design, appropriate construction and use of a structure, unaffected by any error. Δ represents the effect of errors on the resistance. Within the paper, probability of occurrence is conservatively assumed to be 1.0 and the effect of an error is approximated by the normal distribution with a zero mean and a standard deviation of 0.15 or 0.30 μ_{R0}.

This basic formula can be enhanced by using more accurate numbers for the mean and standard deviation. The paper of El-Shahhat, Rosowsky & Chen (1995) elaborates on this by presenting two approaches for addressing the issue of human failure during engineering and construction. These methods are:

- Reliability analysis of human error; within this analysis, the relative effect of failures in load and resistance on the global reliability index of the structure is evaluated. This is done with the help of statistical information on the occurrence and magnitude of errors.

- Scenarios for failures during construction; different scenarios for errors during the construction are investigated to quantify relative consequences associated with these errors.

Global structural reliability and human errors

The first method, assessing global reliability and human errors, is also examined in the paper of Nowak & Carr (1985). This paper terms this method as 'sensitivity analysis for structural errors'. According to the authors, this method provides engineers with a tool which can calculate the relative importance of different types of failure on structural reliability and concentrate on the most important failures. According to the paper frequencies of failures can be established from experience, and their consequence can be identified through sensitivity analysis. Establishing frequencies based on experience, however, is doubtful. The paper does not present these frequencies of errors as a proof that these numbers can be found easily. As mentioned before several researchers have doubted the possibility to quantify frequencies with sufficient accuracy (Fruhwald et al., 2007; Ellingwood, 1987; Ellingwood & Dusenberry, 2005).

Nowak & Carr (1985) have applied the approach to the analysis of a concrete bridge slab, a timber bridge deck and a steel frame beam-to-column connection. The paper presents usable sensitivity functions, as example the reliability function of the concrete slab is presented in figure 15. In this reliability function, the concrete slab is investigated on the parameters effective depth, strength of the concrete, spacing between rebars (s), dead load (D), live load (L) and Impact (I). It can be seen from figure 15 that effective depth is the most sensitive parameter. Despite the interesting reliability indexes, Nowak & Carr (1985) provides no statistical data on the occurrence and magnitude of errors.

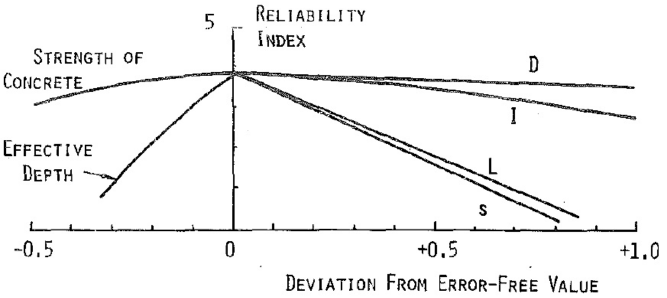


Figure 15: Sensitivity functions for the concrete slab (Nowak & Carr, 1985, page 1741)

Scenario Analysis

The second approach, scenario analysis, assumes different error scenarios and calculates the corresponding failure probabilities. In comparison to reliability analysis, this method focusses on a the most relevant risks, omitting the need for statistical data on all risks. Ellingwood (1987) demonstrates this method in his basic form. According to Ellingwood (1987), scenarios for analysing errors and their effects should include the following elements:

- the identification of likely error-causing scenarios;
- the percentage of errors that are detected and corrected by quality assurance programs;
- the possibility that undetected errors cause structural defects, which may subsequently lead to damage or failure.

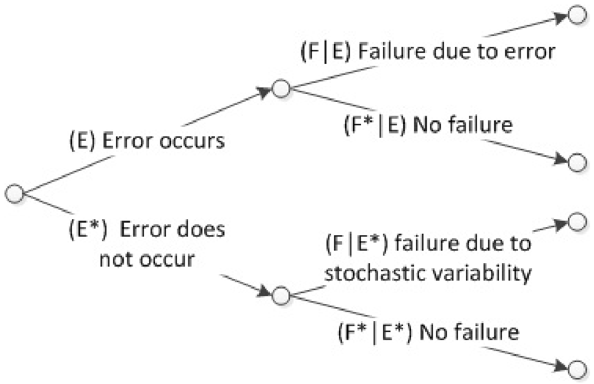


Figure 16: Event tree analysis of failure (Ellingwood, 1987, page 414)(abbreviated)

The mathematical model of the error effect on structural reliability can be developed by the event tree shown in figure 16. Let E be the event that an error occurs and is undetected. The probability of failure can be calculated as:

$$P(F) = P(F \mid E)P(E) + P(F \mid \bar{E})P(\bar{E}) \tag{6}$$

In which E is the event that a gross error does occur, and $\bar{E}$ is the event that a gross error does not occur. $P(F \mid E)$ is the probability of failure on the condition that event E occurs and $P(F \mid \bar{E})$ is the probability of failure due to stochastic variability. It is common to make the assumption that structures that contains errors never fail as a consequence of stochastic variability in loads and strengths. From this it can be concluded that structures fail either due to an error or due to a stochastic variability.

An often used mathematical method to analyse scenarios is by means of Monte Carlo analysis. These analysis are a class of computational methods that rely on repeated random sampling to compute their results. Two papers present good examples of the use of Monte Carlo analysis within human error scenarios. It concerns the papers of Epaarachchi & Stewart (2004) and Stewart (1993).

The first example concerns the modelling of human error within a construction by Epaarachchi & Stewart (2004). This paper discusses a human reliability model to estimate the probability of structural collapse during the construction of typical multi-storey reinforced-concrete buildings due to human error. Epaarachchi & Stewart (2004)concludes that inspection has quite an influence, the Final-Error system risks have been reduced by about 70-80 % for all three shoring systems when compared to Initial-Error system risks.

The second example is provided by Stewart (1993). Within this paper, a Human Reliability Analysis (HRA) model is set forth to simulate the effect of human error on the design and construction of a reinforced concrete beam. The method consists of an event tree which is analysed using Monte-Carlo simulation techniques. The paper concludes that structural safety is more vulnerable to construction errors if there is no error control. Furthermore it concludes that structural reliability for two design checks is only marginally higher than that obtained for a single design check. Another paper of Stewart (Stewart & Melchers, 1988) provides more insight in the effect of control and checking on structural safety. According to this paper, self-checking detects only the small or minor errors that may occur in calculations, and that self-checking cannot adequately safeguard against error due to misconceptions, oversight or misunderstanding. With independent checking, larger errors are more easily detected than smaller ones. The paper concludes that independent detailed checking is a more effective control measure in comparison with self-checking.

The papers of Epaarachchi & Stewart (2004) and Stewart (1993) provide a good example of how to use a PRA/HRA Monte Carlo analysis within engineering, in order to receive realistic values for the effect of human error on the structural properties of a building. With regard to the content, both investigations focus (among others) on the effect of checking and inspection on the occurrence of errors. Both researches conclude that checking and inspection have quite a positive effect on the detection of errors.

A critical note on the scenario approach is the impossibility to detect and quantify unknown and undetected errors. By focussing on the risks which are produced by the scenarios the probability exists that unknown risks occur, causing a major failure.

3.6 CONCLUSION

The literature study discussed aspects of human error within structural engineering. The objective of this study is to assess the current knowledge within scientific literature concerning the assessment of human error in structural engineering. In this section the results will be evaluated and the use of the literature findings in the main study will be discussed.

The literature study started with a section focussing on the causes of structural failure (section 3.2). Within this section general remarks on failure of structures and statistics of failure are given. Based on these findings it is concluded that most structural failures are caused by human error. Furthermore the occurrence of errors are of the same order of magnitude for design/planning and construction respectively, with slightly higher frequency for the design phase. This information pinpoints the problem of human error within structural engineering, which is used within the main research to focus on the relevant aspects of human error.

The following section (section 3.3) focusses on the basic aspects of human error from an engineering perspective. An important notion of human error are the so called models for accident causation, which enable conceptual thinking of error causation. An important model is the 'swiss cheese' model of Reason et al. (2001) which consists of a number of defensive barriers after the unsafe act, once the hazards is introduced, and before the incident. Holes are occurring in these barriers due to latent failures or conditions, creating an opportunity for the incident to occur. Within the main research this information is used by modelling the design process with design steps in which an unsafe act can occur and with control/design steps which prevent the error from occurring (barriers). Another aspect is the non-linear and non-deterministic character of error causation which makes it hard to predict errors deterministically (Hudson, 2010). A solution for this is to represent errors by means of probability distributions instead of simple failures rates. This aspect is adopted in the model represented in the main research.

In order to understand human error, the cognitive behaviour of human error should be taken into consideration. An important aspect is error type distinction based on cognitive notions. For this Reason (1990) distinguishes three cognitive demand levels: Skill-based, Rule-based and Knowledge-based. Skill-based slips and lapses occurring during automatic behaviour which require little concious thought or when attention is being diverted. Rule-based mistakes occur when a known rule is incorrectly applied, or a situation is misinterpreted. Knowledge-based mistakes result from a deficit of knowledge. This analogy is used in the main research to distinguish three cognitive tasks levels within the proposed Human Error Probability quantification model.

Section 3.4 discusses the characteristics of Human Reliability Assessments (HRA). HRA deals with the assessment of human potential in a system. According to Kirwan (1994) it consists of three basic functions: identifying which errors can occur, decide how likely they will occur and reducing there error likelihood. Several aspects of HRA are discussed, such as quantitative HRA methods, HRA within design tasks and there limitations. Within the main research, these insights are extensively used within the proposed HRA model for design tasks.

The last section (section 3.5) discusses the possibilities to quantify human error and structural failure. For quantifying human error a reliability analysis method is discussed. Within this analysis failure will occur if the loadings acting on the structure are larger then the resistance of the structure. Human error is presented by means of a multiplier on the resistance. Another aspect is to use scenario analysis which assumes different error scenarios to calculate the corresponding failure probabilities. Both aspects, reliability analysis and scenario analysis are used in the main research to establish a structural failure probability based on human error probabilities.

4

HUMAN RELIABILITY ASSESSMENT MODEL

4.1 INTRODUCTION

Within this chapter a Human Reliability Assessment model for use within structural engineering processes will be set-apart. Within chapter 5 this model will be used to analyse the consequences of human error in a predefined case. This chapter consists of nine sections. Section 4.2 discusses the application area of the model. Section 4.3 states relevant model requirements. Section 4.4 sets apart the model, and discusses its basic form. The sections 4.5 to 4.8 will subsequently discuss the basic steps of the model in detail. Finally, the conclusion of this chapter is presented in section 4.9.

4.2 APPLICATION AREA

Concerning the application area of the model, the following two aspects are of interest: which processes are suitable to analyse with the HRA model and who are the intended users of the HRA model. Within this section these two questions will be discussed.

Type of processes
The model is intended for use in engineering processes, and more specifically structural design processes. These types of processes are characterised by an iterative procedure to determine the design of an engineered system. A common aspect of these processes is that the output of the process, and his intermediate processes, primarily consists of numerical design parameters. In order to cope with this, the following two aspects are incorporated in the HRA model:

- The error consequence within a basic task is presented by a numerical deviation from intended.
- The basic tasks are coupled by means of an analogy based on the calculation sequence of the structural design process.

This methodology enables a clear relation between cause and effect. However this goes at a certain cost. The process of interest must be suitable to present with a calculation sequence. However, this does not entail that it should be a real calculation process. For instance the choice between two building types can be presented by a choice between two separate calculation sequences (which represent the calculations required in each building type).

From this it can be concluded that the model is predominantly suitable for structural design processes which can be modelled by means of a calculation sequence. This entails that quite a large part of the design process can be modelled, but not all, or only on a very complex way. Furthermore, the model seems usable for tasks within the construction process as well. However re-evaluation of the model is required to adjust it to the specific needs within construction tasks, as design tasks differ somewhat from construction tasks.

intended users
The HRA method is designed in order to compare different process layouts with each other, concerning the effects of human error within these processes. As such it can be seen as a risk monitoring model. This intended use is a consequence of the impossibility of the model to quantify the consequences of human error on a absolute manner. As only relative results can be obtained, only comparison of scenarios within the model is possible. This entails that comparison of the results with cases outside the model is not possible as it can be misleading. It should be noted that this is the case in most HRA methods.

Based on this, the following three applications can be distinguished. It should be noted that this list is not intended as a complete list, other applications are very well possible as well.

- Evaluation of the effects of different organizational design processes. An examples is the design layout of organizational control mechanisms.
- Evaluation of the effects of different organizational conditions. Examples are working conditions, level of knowledge and level of support.
- Evaluation of the effects of different design codes. For example, assess the difference between the current European design code and the old Dutch design code, concerning there effects on human error occurrence.

It can be concluded that the model has roughly three application areas. First of all, organizations which perform structural engineering tasks can use this model to investigate the possibilities to improve there structural design processes (concerning human error proneness). Examples are engineering companies and building contractors. Secondly, design code institutions can use this model to assess different design codes concerning there effects on human error occurrence. Finally research institutions can use this model as a basis for further research, or use the model in line with the previous two application possibilities.

4.3 MODEL REQUIREMENTS

Before introducing the model, the model requirements will be stated in this section. The model requirements are based on insights from literature and discussion sessions with the research supervisors. Model requirements can be subdivided in: functional requirements, operational requirements, preconditions and points of departure.

Functional requirements
The main functional requirement of the Human Reliability Assessment

method is to quantify human error within structural engineering in a realistic and useful manner. In line with Ale, Hanea, Sillen, Lin, Gulijk & Hudson (2012) and Hudson (2010) the functional departure point is: "[...] that control systems need to be capable of at least as much variation as the body to control" (Ale et al., 2012). This entails that the model intends to meet the following functional requirements:

- *Suitability model;* the model should be able to represent human error in a structural engineering context.
- *Error causation;* the relation between an error and the causes of error should be presented on a realistic manner.
- *Cognitive aspects;* the model must be able to take the cognitive behaviour within a design process into account.
- *Organizational context;* the effect and influence of the organizational context must be accounted for in the model.
- *Presentation results;* the final result (human error consequences) should represent the true behaviour of error occurrence.

Error causation and the influence of context are hardly to model with a HRA model due to the non-linear [1] and non-deterministic [2] behaviour of accident causation (Ale et al., 2012; Hudson, 2010). In order to tackle this problem, errors can at best be presented on a probabilistic manner (Hudson, 2010). As a consequence the consequences of human error are probabilistic functions as well. Due to this considerations, the requirements concerning failure causation and result presentation will be eased a little: relation and effect are considered as probabilistic, which entails that no direct causal relation will be given but rather a directional thought of the error cause by means of a probability.

Operational requirements

The operational requirements are imposed by the end users. The Human Reliability Assessment tool is developed for use within construction companies, engineering companies and government bodies. The end-users are typically trained in engineering or a related profession, Furthermore, there human factors knowledge is regarded as limited. With this in mind the following operational demands are imposed on the model:

- *Engineering use;* the model must be usable by assessors without a background in human factors or psychology.
- *User friendly;* the model must be user friendly and misinterpretation of the model should be prevented.

Pre-conditions

Pre-conditions are commencing from rule and regulations. Concerning the model, rules and regulations within the building process are of concern. As the model is only intended as a research model, the pre-conditions on the model is limited to one:

---

[1] Non-linearity entails that the causal effects are not simplified to a single chain, but represented by an ever-increasing tree of binary or more combinations.

[2] Non-deterministic entails that the relation between two values is not deterministic, e.g. it is not sure that every time when A occurs, B will occur as well.

- *Use in engineering processes;* engineering process are largely defined by building regulations and rules. The HRA model should be useful for use within these pre-defined processes.

Points of departure
The following points of departure / restrictions are imposed on the model:

- *Design tasks;* the model is aimed towards design tasks within typical structural engineering processes. Within this it is specifically aimed towards design tasks which can be modelled by means of a calculation sequence.
- *Diagnosis method;* the model is a diagnosis method, not a management method. It is aimed towards monitoring design processes on there human error proneness and monitoring the effect of risk control measurements.
- *Explorative research;* this research is intended as an explorative research, which entails that only a basic model will be presented. Furthermore, extensive validation is not performed.

4.4 MODEL BASICS

The model is among others based on two distinct HRA methods which are described in chapter 3. The first method is the Cognitive Reliability and Error Analysis Method (CREAM) of Hollnagel (1998). The second method is the design HRA method proposed by Stewart and Melchers (Melchers, 1984, 1989; Stewart & Melchers, 1988; Stewart, 1992a,b, 1993).

The CREAM method is used to quantify Human Error Probabilities (HEPs), while the design HRA of Stewart and Melchers is used to couple these HEPs to derive an error probability on element level. The CREAM method is used as it emphasises the complex interaction between human cognition, and the situation or context in which the behaviour occurs. This is deemed necessary to meed the functional requirements. The design HRA of Stewart and Melchers provides a useful flow chart to transform HEPs of individual design tasks to an error probability on the structural level.

The model starts with a general idea about the particular engineering task, of which insights on the effect of human error is required. Through four distinctive HRA steps a failure probability of the structure due to human error is obtained. A stepwise overview of this model is shown in figure 17. The four steps are briefly set apart in the remainder of this section. The sections 4.5 to 4.8 elaborate each on a separate step of the model in detail.

The first step is a qualitative analysis of the design system/situation of interest. It starts with identifying the considered process and determining its boundary conditions. This is followed by selection of the following three aspects: scenarios for further research, the design context and the required design steps. This process is required in order to focus on the design aspects, which are worthwhile considering with a quantitative HRA analysis. This is deemed necessary as a quantitative HRA analysis is very labour intensive. Furthermore, this step serves as a basis for the remainder of the

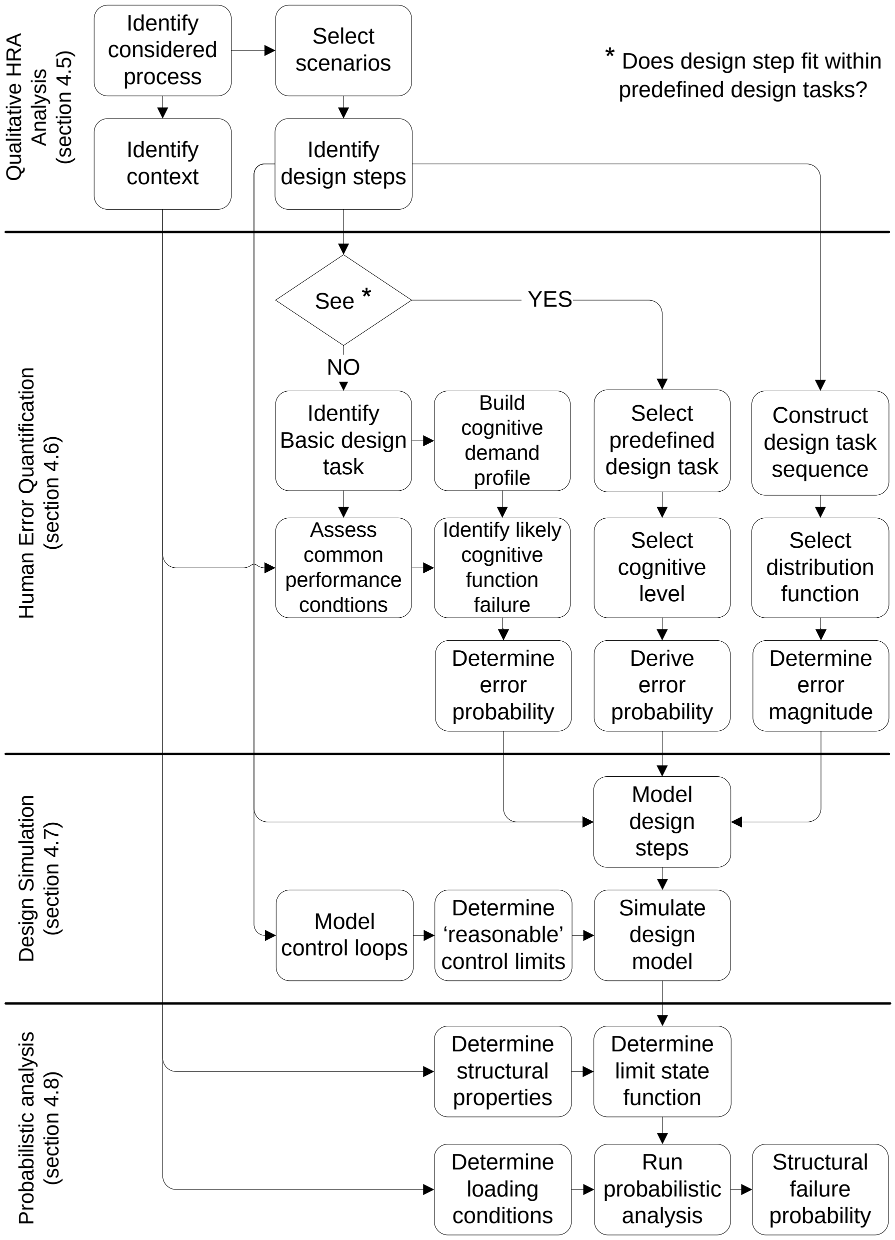


Figure 17: Flow chart of the Human Reliability Assessments model

HRA. The qualitative analysis is discussed in detail in section 4.5.

The second step is the Human Error Quantification (HEQ) within the HRA procedure. Based on the identified design steps and design context, a Human Error Probability (HEP) and Error Magnitude (EM) for each design task is determined. These HEPs and EMs together form a probabilistic representation of human error within a design task. The underlying method to quantify human error is based on the assumption that within each design task, basic cognitive tasks can be distinguished. The second step is discussed further in section 4.6.

The third step is the design simulation process. Within this process the individual HEPs and EMs are combined by means of a Monte-Carlo simulation. This process results in a probabilistic representation of the strength on structural element level. The third step is worked out in section 4.7.

The last step is a probabilistic analysis. Step 3 resulted in a probabilistic strength distribution on element level. These distributions together with relevant loading distributions and material characteristics are used within a probabilistic analysis to determine the probability of failure of the structure. In total two structural beam types are considered: a statically determined beam and a statically undetermined beam within a frame structure. A detailed elaboration on this last step is presented in section 4.8.

4.5 QUALITATIVE HRA ANALYSIS

The first step in the HRA model is to define the process of interest and its boundaries. This process consists of four steps which are shown in figure 18. The first step is to identify the design process of interest. Based on this, the design context and scenarios for further research are selected. The research context is used as input for the process, while the scenarios are used to focus the research. The last step is to identify all design tasks within the considered process. This is required as the human error probabilities are determined in the basic task level.

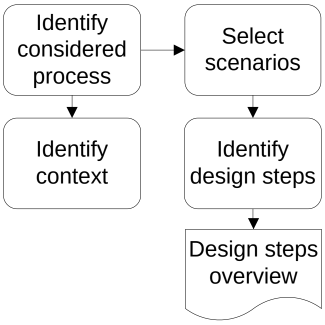


Figure 18: Basic model of Qualitative HRA analysis

4.5.1 *Scenario identification*

The HRA tool is mainly set-up as a performance prediction HRA (in contrast to retrospective HRA analysis, see Hollnagel (1998) for more details). Within HRA for performance prediction, selection of the scenario or event sequence for further analysis is required. This typically involves drawing up a complete list of all potential system failures that can reasonably be expected. From this list one particular scenario at a time must be selected as the target for the HRA (Hollnagel, 1998). Techniques which can be used for this are fault tree analysis (FTA) or a failure mode and effect analysis (FMEA or FMECA). According to NASA (2002) these techniques complement each other. First (usually) a FMEA is constructed to identify the worst failure modes. After this a FTA is used to investigate these failure modes in more detail.

4.6 HUMAN ERROR QUANTIFICATION

The second step within the HRA method is to quantify the error probability within typical engineering tasks. This error probability is represented by a probability distribution function described by two parameters. These parameters are a Human Error Probability (HEP) and an Error Magnitude (EM). The procedure for determining HEPs consists of two methods: a basic HEP method and an extended HEP method. (see figure 19). The extended method is basically the extended quantification method of the CREAM method defined by Hollnagel (1998, chapter 9). This method is however labour intensive and requires quite some knowledge concerning human factors/psychology. In order to make the HEP quantification accessible for use by engineers, a simplified method is proposed for standard engineering tasks. This simplified method is basically a predefined extended method, based on standard engineering tasks.

The second parameter, the Error Magnitude, consist of a method based on information from literature (Melchers, 1984, 1989; Stewart, 1992b). This methodology consists of three steps, which are quite easy to perform. The HEPs are determined on the basic task level, while the EM are determined on the micro-task level. This is due to the fact that a micro-task is defined at the parameter level, while each micro-task consists of multiple basic tasks. As EMs can only be given on a parameter level, and HEPs are defined on the basic task level, the distinction in both levels is applied (shown in figure 19).

This section consists of four subsections. Subsection 4.6.1 discusses the extended HEP method. Subsection 4.6.2 discusses a small survey which is used to determine the reliability of the HEP quantification methods. Subsection 4.6.3 discusses the simplified HEP method, and subsection 4.6.4 discusses the EM method.

4.6.1 *Extended HEP method*

The extended HEP method is meant to determine the Human Error Probability (HEP) of each basic design task. It should be noted that the extended HEP method is basically an adapted CREAM quantification method, which is defined in Hollnagel (1998, chapter 9). The methodology requires the completion of four distinctive steps. The idea behind these steps is to subdivide each basic task into basic cognitive tasks, on which standard failure probabilities are defined. The input of this procedure consists of the identified design steps, the context of the design and classification diagrams from the CREAM methodology. The four steps will will be discussed in the remainder of this section.

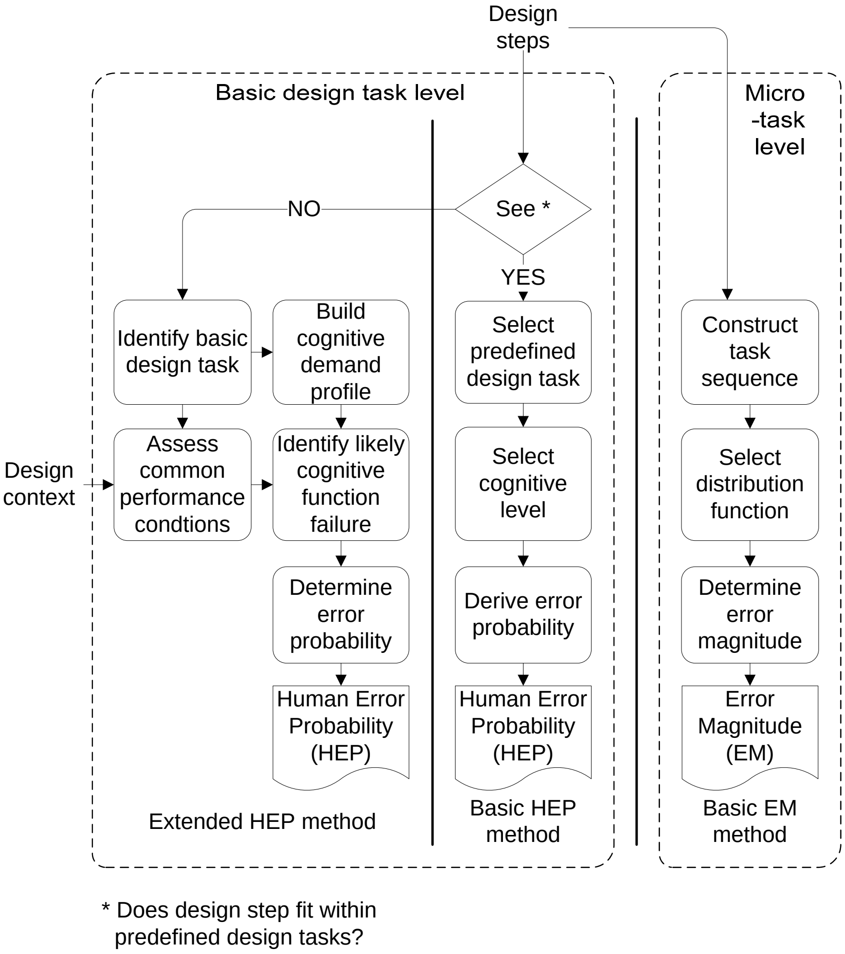


Figure 19: Basic model of human error quantification within the HRA model

A detailed flow chart of these four steps is presented in figure 20, in order to get an idea of the process and its input and output values. It can be seen from this figure that in total five classification diagrams from the CREAM method are used within the procedure (These diagrams are presented in appendix C). The output consists of three parts: a cognitive demand profile, a cognitive function failure and a failure probability. The first two products are intermediate results, while the latter is the end result.

Step 1: Build a cognitive demand profile.
The first step in the CREAM method is to build a cognitive demand profile. The purpose of this profile is to show the specific demands to cognition that are associated with a basic task. The model starts with a basic task, which is part of the overall design process. Subsequently the description of this basic task is refined by identifying a list of critical cognitive activities (CCA) that characterise this basic task. For this the CREAM method distinguishes 15 CCAs, of which 13 are deemed applicable within a design context: coordinate, communicate, compare, diagnose, evaluate, execute, identify, monitor, observe, plan, record, scan and verify.

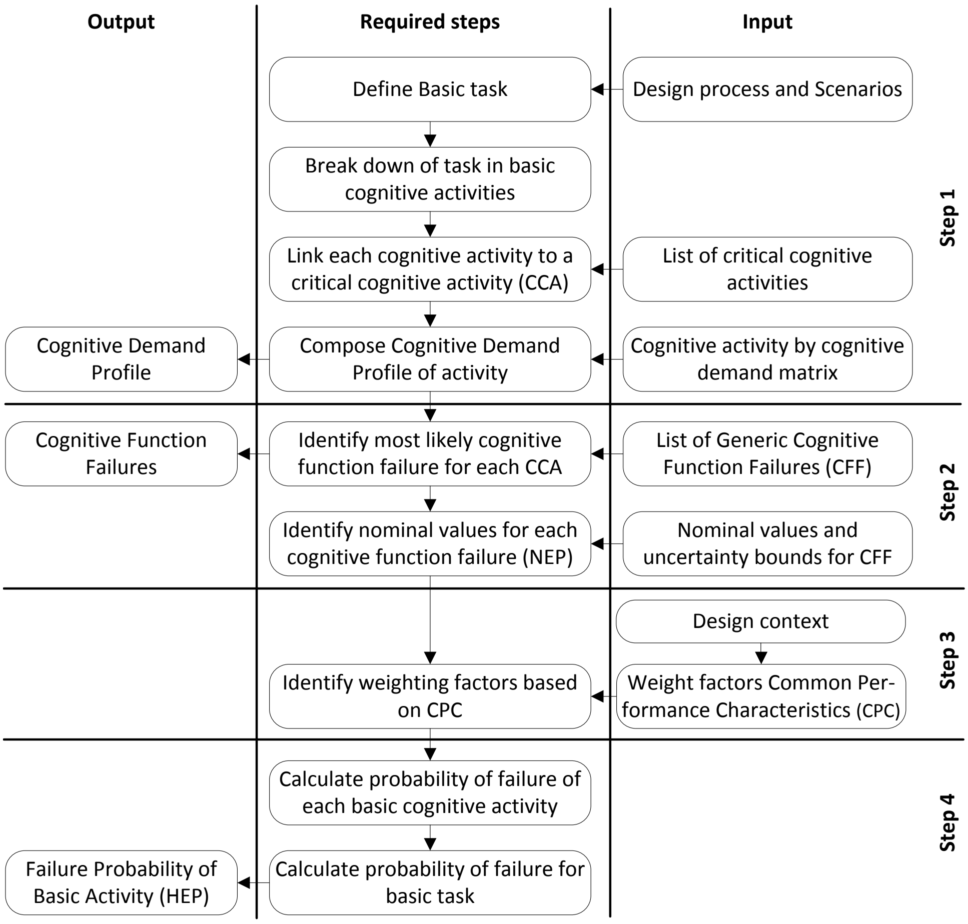


Figure 20: Flow Chart of the extended HEP-method for determining a Human Error Probability (HEP)

These CCAs are subsequently transformed to a Cognitive Demand Profile by linking each CCA to one or more of the four Basic Cognitive Functions (BCF) distinguished by the CREAM methodology. The idea behind this is that there are four basic cognitive functions that have to do with observation, interpretation, planning and execution. Each CCA can then be described in terms of which combination of the four basic cognitive functions is required. As an example, coordination involves planning as well as execution: the planning is used to specify what is to be done, and the execution is used to carry it out or perform it. This linkage is presented in the cognitive activity by cognitive demand matrix presented in appendix C. This linkage results in a cognitive demand profile, of which an example for a 'consult' task is shown in figure 21.

Step 2: Identify likely cognitive function failure.
The previous step resulted in a cognitive demand profile. Within this step, this profile is transformed to a cognitive function failure. This is done by selecting dominant failure types. For this, the predominant type of failure which is to occur for the task as a whole should be selected from a list of Cognitive Function Failures (CFF, given in appendix C). An example of this profile for a 'consult' task is given in figure 22. Based on information from

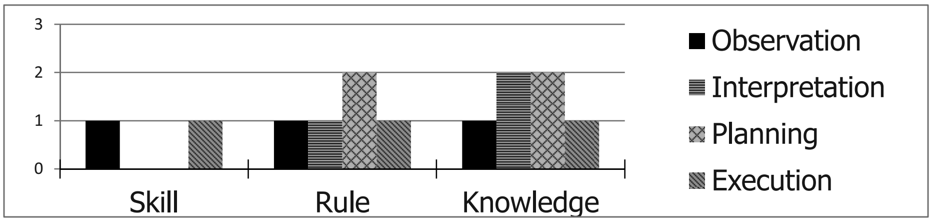


Figure 21: Example of a Cognitive Demand Profile used within the extended HEP-method

literature, the CREAM-method proposes a Nominal Error Probability (NEP) for each type of failure within the cognitive function failure, this results in a NEP-value for each basic task.

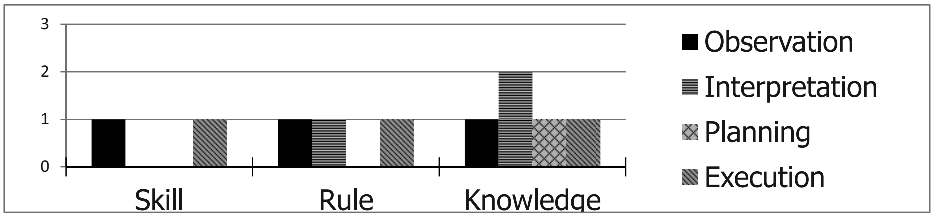


Figure 22: Example of a Cognitive Function Failure used within the extended HEP-method

Step 3: Assess Common Performance Conditions (CPC).
In this step the conditions under which the performance is expected to take place is characterised in order to take into account. This is taken into account as human cognition and performance take place in, hence are determined by, the context. Within the CREAM-method, the context is characterized by 9 CPCs. Based on the organizational situation concerning these CPCs (originating form the design context), a weighting factor is given. The product of these weighting factors results in a global weighting factor. The list of CPCs is given in appendix C.

Step 4: Determine error probability.
In this step the NEP-value of each basic cognitive activity is multiplied with the corresponding weighting factor which characterise the CPCs. The overall human error probability of the basic task is subsequently calculated by adding these basic failure probabilities based on full independence between the cognitive activities $(1 - \prod_{i=1}^{n}(1 - P_i))$.

4.6.2 *Survey extended HEP method*

The extended HEP method is based on a four steps which are discussed in subsection 4.6.1. Finding HEPs with this method requires quite some personal interpretation by the human reliability assessor. Due to this, the quantification of human performance is seen as doubtful (Kirwan, 1996; Swain, 1990; Reason, 2000). Furthermore, the underlying CREAM method is predominantly aimed towards operational types of tasks (in contrast to design tasks which are of concern in this research). The question arising from this is: how reliable is the proposed HEP quantification method? Within this research a case study is performed among engineering students to answer this question.

The survey consisted of four questions. The first two questions focus on determining a cognitive demand profile for a given task, while the latter two questions focus on identifying likely cognitive function failures. The complete survey is given in appendix D. In total 15 engineering students have completed the survey. Most students were master students or undergraduate students. Within the survey, the sample group was predefined (engineering students) as the HEP quantification methodology requires engineering judgement/insight of the tasks at hand. This restriction is deemed justified as the HEP quantification will mainly be used by engineers as well. Another aspect of the survey is its very basic explanation of the tasks at hand within the survey. This is deemed necessary in order to represent the real situation in which a HEP quantification is performed. A detailed analysis of the survey results is presented in appendix D. The conclusions based on this survey are given beneath.

Conclusion survey

It can be concluded from question one and two (determining a cognitive demand profile) that engineers are capable to compose a cognitive profile for an engineering task. However the scatter within the results is considerable as the extended HEP method is not specifically designed for engineering/design tasks. This becomes particularly clear from question one as ‘interpretation‘ is not a basic cognitive task. There is a good explanation for this, but this is quite confusing for an engineer performing a quick Human Reliability Assessment.

Within the result of question three and four (identifying likely cognitive function failures), a large scatter in the results is found. Based on this it can be concluded that selecting an error function is quite an unreliable action. The main cause for this is probably the lack of human factor knowledge of engineers, as they have to select an error mode (which requires this kind of knowledge).

It can finally be concluded that the extended HEP method is not reliable, if conducted by an engineer without prior extensive training. This is due to the focus of the underlying CREAM-method on operational types of tasks, which produces another type of function failure then design tasks. A second contributing factor is the lack of human factors knowledge of most engineers.

The survey can indirectly be used to analyse the subjectivity of the simplified HEP-method, as this method is based on the extended HEP-method. It should be noted that there is some difference. The simplified HEP-method is assessed with much care, furthermore the results are discussed with the supervisors. This differentiates from the survey results, as they are based on a questionnaire of which it is not sure how accurate the questions are answered. Despite this, it can be concluded that the results of the simplified HEP-method are somewhat subjective as well. Due to the explorative character of this research, improvement measurements are not investigated further, and is left for further research.

4.6.3 *Simplified HEP method*

Within the structural design process typical design tasks are frequently returning. Examples are consulting norm requirements and calculating a formula. These typical design tasks are not readily covered by a single cognitive activity within the extended HEP method, hence subdivision of these tasks is required to match these design tasks within the extended HEP method. Subdivision of frequently occurring design tasks on an independent basis is not very efficient, and requires quite some human factor/psychological judgement which is not always available to the HEP assessor.

For this reason a simplified HEP method is proposed consisting of a matrix based on the type of design activity and the required cognitive level. seven basic design tasks are identified, of which the HEPs are calculated. These seven basic design tasks are typically more thorough then the cognitive activities of the extended HEP method. For example "communication" is mentioned within both methods. However within the extended HEP methodology it involves passing on or receiving person-to-person information, while within simplified method "communication" is thought of as a thorough discussion on design aspects.

These seven basic design tasks serve as a basis for all HEPs within the considered design process of the case study. Selection of these seven basic tasks is based upon an assessment of al task types within typical design processes. It should be noted that this list is not intended as a complete list and extra addition may be required in the light of other design processes. For instance if the construction process is of interest as well, a logical addition would be to add "instruct" as a basic task. However the operational types of cognitive tasks mentioned in the CREAM methodology are quite suitable for direct usage within the construction process. For example "execute" and "monitor" (which are mentioned in the CREAM method) are typical construction tasks. The seven basic tasks and their definitions are given beneath.

Consult
Reading and interpreting guidelines or norm requirements. "Consult" typically is more advanced then "obtain".

Obtain
Adopting a design parameter from a resource such as a drawing. Typically for tasks in which thorough interpretation of the resource is not required.

Derive
Selecting a value from a range of values based on previous determined se-

lection criteria.

Determine
Taken a decision based on engineering judgement and available design parameters.

Calculate
Calculating a parameter based on available design values. This task typically involves inserting values in a calculation program, calculator or hand calculation, and retrieving the outcome.

Insert
Placing a calculated/derived parameter in a design program / design document. "Insert" is opposite to "obtain".

Communicate
Thorough discussion on basic design parameters, the design or other aspects. This task typically involves passing on or receiving person-to-person information, interpretation of the information and reasoning about the implications of the information.

Another subdivision is made on the level of complexity which can be distinguished within each basic task. This subdivision is made in order to tackle the problem of task difficulty within the seven basic tasks. For this, three different levels of cognitive demands are distinguished: a skill-based, a rule-based and a knowledge-based level. This division is in line with the cognitive stages presented by Reason (1990, chapter 3). Each level requires another set of cognitive activities resulting in another HEP value. It should be remarked that not all basic tasks are acting on all three cognitive levels, as the knowledge based level is deemed unrealistic within obtain- and insert activities. The definition of the three cognitive levels are given beneath.

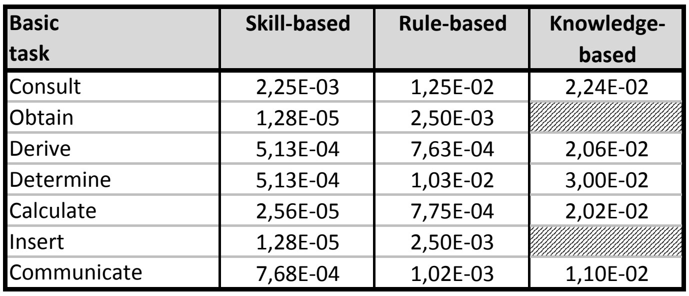
Skill-based level
Comprising of highly routinised activities in familiar circumstance. Errors are typically occurring when the actions of a person are different to their intentions. They often occur during automatic behaviour which require little concious thought, or when attention is being diverted.

Rule-based level
Comprising of problem solving activities by means of previous established if-then-rules. Errors occur when a known rule is incorrectly applied, or a situation is misinterpreted.

Knowledge-based level
Comprising of problem solving activities based on a higher level analogy. Errors results from a deficit of knowledge. A person may intend to implement a plan or action, but the plan or action is incomplete or flawed by a lack of knowledge and does not result in the desired outcome.

The simplified HEP method based on the seven basic tasks and three cognitive levels is shown in figure 23. In total 19 distinctive HEPs are distinguished within the simplified HEP. Derivation of these numbers is presented in appendix E. From figure 23 it can be concluded that skill-based activities have generally a HEP-value of $1,25 \cdot 10^{-5}$ to $2,25 \cdot 10^{-3}$, rule-based activities have HEPs from $7,75 \cdot 10^{-4}$ to $1,25 \cdot 10^{-2}$ and the HEPs for knowledge-based activities vary from $1,1 \cdot 10^{-2}$ to $3,0 \cdot 10^{-2}$.

In order to obtain these values an extra Common Performance Conditions (CPC) is applied. This CPC (termed task factor) takes the difference between operational type of tasks (on which the CREAM method is based), and design types of tasks into account. This amplification factor is based on a comparison of the intermediate results (on the knowledge based level) with HEP values obtained for design types of tasks (Stewart, 1993). It should be noted that further calibration of these results on real cases or structural design simulations is required in order to improve the reliability of these values.



Basic task	Skill-based	Rule-based	Knowledge-based
Consult	2,25E-03	1,25E-02	2,24E-02
Obtain	1,28E-05	2,50E-03	▨
Derive	5,13E-04	7,63E-04	2,06E-02
Determine	5,13E-04	1,03E-02	3,00E-02
Calculate	2,56E-05	7,75E-04	2,02E-02
Insert	1,28E-05	2,50E-03	▨
Communicate	7,68E-04	1,02E-03	1,10E-02

Figure 23: Human Error Probabilities of the simplified HEP method

4.6.4 *Error Magnitude method*

Determining the Error Magnitude (EM) of an error probability requires the completion of three distinctive steps. The EMs are determined on the Micro-task level and are based on the task characteristics. The three steps are given beneath. The EM is basically a distribution function in which the standard deviation represents the deviation from the design value. Furthermore the mean value equals the error free design value.

construct task sequence
A task sequence is defined on the micro-task level consisting of several basic tasks. Each micro-task represents a sequence of basic tasks required to deduce a design parameter.

Select distribution function
The characteristics of the task are assessed in order to link a distribution function to the micro-task. three distribution functions are distinguished: Log-Normal functions for calculation tasks, normal functions for the remaining six basic tasks and a discrete function for special situations.

Determine error magnitude.
In this step the standard deviation of the distribution function is deter-

mined. This is based on two characteristics of the task: task complexity and task overview. This results in an Error Magnitude (EM) for the micro-task of concern.

Determining the error magnitude is based on selecting a standard deviation from table 7. The HRA assessor couples a complexity level (given in row one) to a task sequence. If the task sequence lacks a clear overview, the task complexity should be increased with one level. In case of a controllable situation, the task complexity should be decreased with one level. This results in a standard deviation for the selected distribution function.

Table 7: Values for the standard deviations of the Error Magnitudes

Task complexity	Normal distribution	Log-normal distribution
very complex	1,4826	1,0277
complex	0,9648	0,6688
neutral	0,7803	0,5409
simple	0,6080	0,4219
very simple	0,4299	0,2980

Calculation EMs consists of a combined distribution function: a Log-normal function and a discrete function. This is based on the findings of Melchers (1984). The first distribution consists of computational errors, with the following properties:

- $\frac{2}{3}$ of the errors are caused by computational errors, represented by a log-normal function.
- Assumed is that negative and positive errors are equally occurring. This entails that the median of the distribution curve should be equal to 1, which results in a mean value of 0 ($e^{\mu} = median$).

The second distribution consist of decimal errors with the following properties:

- $\frac{1}{3}$ of the errors are caused by decimal mistakes, representing by a discrete distribution.
- The order of magnitude of decimal errors are $10^{(-)1}$, $10^{(-)2}$ and $10^{(-)3}$, comprising $\frac{1}{3}$, $\frac{1}{18}$ and $\frac{1}{9}$ of the errors respectively.

Furthermore, some 'determine' activities are based on choices between two calculated parameters. An example is to determine if the calculated reinforcement is lower than the maximum allowable reinforcement. In these cases the EM consisted of choosing the wrong value. Finally, some of the EM are for $\frac{1}{2}$ of the errors based on logical values, in order to approach a realistic EM (see Appendix F for details).

4.7 DESIGN SIMULATION

The next step in the analysis is to combine the individual distribution functions of the micro-tasks into an overall distribution function on the element level of a structure. Hollnagel (1998) advises to use the structure of an underlying fault tree to calculate the overall Failure Probability. However within this research the underlying system is not a fault tree but a design sequence existing of tasks which are linked together through calculation sequences. This problem is tackled by using a Monte-Carlo simulation procedure to determine the overall failure probability of a design process. For this a micro-task simulation sequence is used, which will be explained in detail beneath.

An important notion of human behaviour which is not addressed in section 4.6 is the level of control a person has over the tasks he or she performs. This notion will be addressed in this chapter as it is incorporated in the Monte-Carlo simulation procedure. Hollnagel (1993) describes control as the person‘s level of control over the situation. The level of control is influenced by the context as it is experienced by the person, by knowledge or experience of dependencies between actions and by expectations about how the situation is going to develop (Hollnagel, 1998). Within engineering type of tasks, the effect of control is considerable as calculations and decisions are regularly checked on correctness and applicability.

4.7.1 *Simulation procedure*

If the simulation procedure is simplified to its very basics, four distinctive elements are remaining which are depicted in figure 24. The first element is a list of micro-tasks which represent the activities within the design process. The second element is the internal control by the designer, which is termed in line with Annex B of NEN-EN-1990 (2002) as Self-checking. The combination of both these elements is termed the overall process (element 3). The final element is the internal control by the supervisor, which is termed normal supervision in line with Annex B of NEN-EN-1990 (2002). These elements will be set-apart in this section in more detail. The code script for modelling this simulation procedure is presented in appendix H.

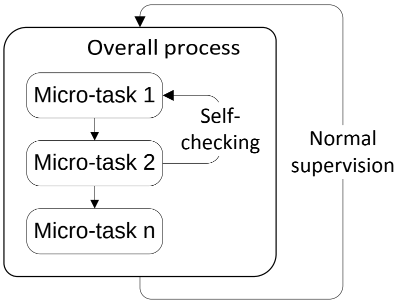


Figure 24: Basic simulation procedure of the Monte-Carlo simulation

Micro-tasks
The procedure for simulating each micro-task is based on the task-cycle approach presented in Stewart (1993). The micro-task procedure is given in figure 25 for the typical micro-task "calculate reinforcement". The procedure starts with input parameters which can be the output of a preceding micro-task or an input parameter from outside the considered design process. The next step is to generate a Random Number (RN) between 0 and 1, and to obtain a Human Error Probability (HEP) for the micro-task at hand (from the list given in appendix F). If the Random Number (RN) is smaller then the HEP-value, a failure occurs and subsequently the output of the micro-task is multiplied with a Error Magnitude (EM). If the Random Number is equal or larger then the Failure Probability no error occurs and subsequently the output of the micro-task is not multiplied with an Error Magnitude. It should be noted that the EM is a random value from the applicable distribution function.

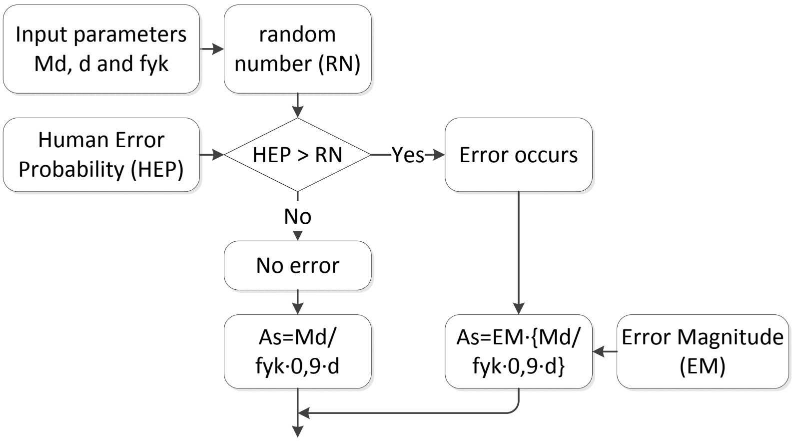


Figure 25: Basic procedure of a micro-task

Self-checking
The lowest level of control described in annex B of NEN-EN-1990 (2002) is self checking: "Checking performed by the person who has prepared the design." The level of control within a design task is particularly dependent of the knowledge of the designer and his ability to appraise the results of a micro-task. This entails that the level of control of a designer over each micro-task depends on the task within the micro-task and the knowledge level of the designer of this particular task.

Within the Monte-Carlo simulation, self-control is based on the notion that a designer uses his previous experience as a reference for assessing the correctness of the results. The adopted process is shown in figure 26. Within this process, the output of a series of micro-tasks is compared with the correct output of the series of micro-tasks. If the output is within predefined bounds, the output is deemed correct and the design process continues. If the output is not within these predefined bounds, reconsidering of the series of micro-tasks is performed. If the output is not within the predefined bounds after one reconsiderations, the design process is continued with the incorrect output. This process is very basic but encompasses some very basic aspects of self-checking: comparison of the results with an output which the designer deems realistic and reconsidering for a finite number of times if the designer suspicions in-correctness. The values for the predefined bounds are presented in appendix H. The limits are different for experienced and inexperienced designers.

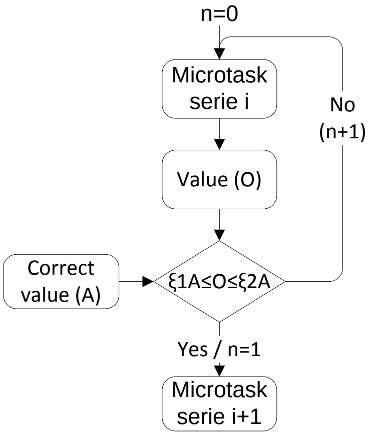


Figure 26: Procedure of self checking

Overall process

The overall process consists of all micro-tasks and all self-checking loops performed by the designer. Besides basic micro-tasks, the process consists of two control loops. Figure 27 presents the steps within the overall process. The micro-tasks are bundled in segments on which a self-checking loop is envisioned. For instance "Calculate beam dimensions" consists of six micro-tasks, after which a control loop is performed on the beam height and beam width.

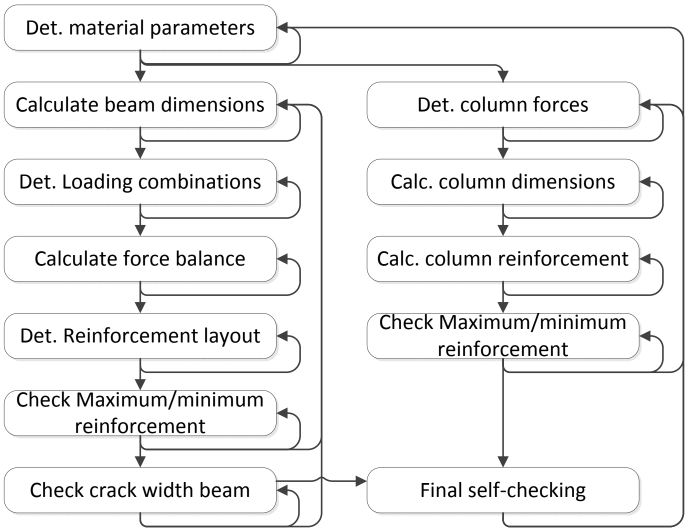


Figure 27: Overview of the steps within the overall process

Normal supervision

The final element of the procedure is the internal control by the supervisor, which is termed normal supervision. Within this process parts of the process are recalculated by the supervisor on a basic manner, subsequently the results are compared with the results obtained by the designer. If these results differ considerable from the results obtained by the designer, the complete process is re-evaluated. This process has much in common with control based on an independent concurrent design, with the difference that the process is simplified and that the same basic assumptions are used within the design process and the normal supervision.

4.7.2 *Linkage with probabilistic analysis*

Within the design simulation the overall failure probability of several design parameters is determined. Within the probabilistic analysis, these design parameters will be used as input for the reliability analysis. The calculated design parameters can roughly be divided in: loading parameters, material parameters and geometric parameters. Only the geometric parameters and material characteristics are of importance for the probabilistic analysis. Loading parameters are separately determined in the probabilistic analysis as the real-time loading conditions are not depending of the loading conditions used in the design.

4.8 PROBABILISTIC ANALYSIS

The last step within the HRA method is to determine the probability of failure of the engineered structure. These probabilities are determined with basic probability analysis for the reliability on element level. For this analysis two things are of interest: the applied reliability function and the probabilistic procedure which is used to determine the probability of failure. These two aspects will be discussed in this section.

4.8.1 *Reliability function*

A reliability function is used in order to obtain a equation which describes success or failure within the probability analysis. The reliability is defined as the probability that a limit state is not exceeded, in which a limit state is defined as the state just before failure (CUR, 1997). The general form of a reliability function is:

$$Z = R - S \tag{7}$$

In which:

- R is the resistance to failure of the structure;
- S is the load acting on the structure.

Within this research, the reliability function is based on plastic limit state analysis. Within this analysis, a restriction is made by focussing on beam elements only. This method is based on physical non-linear and geometrical linear behaviour of the structure. Within this method failure is defined as loss of static equilibrium of the structure or any part of it (Vrouwenvelder, 2003).

The plastic limit state analysis consists of two consecutive parts: a upper bound analysis and a lower bound analysis. The reliability function is determined with the upper bound analysis. This analysis is easily to perform, however can be unsafe as it is not sure if the dominating failure mechanism is found. In order to investigate this, a lower bound analysis is performed. The advantage of a lower bound solution is that it is always at the safe side. If the lower bound coincides with the upper bound the correct failure mechanism is found, and the correct reliability function is defined.

The general formulation of the upper bound theorem is given by Vrouwenvelder (2003):

> Starting from an arbitrary mechanism, the corresponding equilibrium equation will provide an upper-bound solution for the limit load

The corresponding equilibrium equation is defined as a function of the virtual work done by the external loads and the virtual work done by the internal stresses:

$$\sum_{k=1}^{m} M_{pk}\vartheta_k = \lambda \sum_{i=1}^{q} F_i u_i \tag{8}$$

The lower bound theorem is formulated as follows (Vrouwenvelder, 2003):

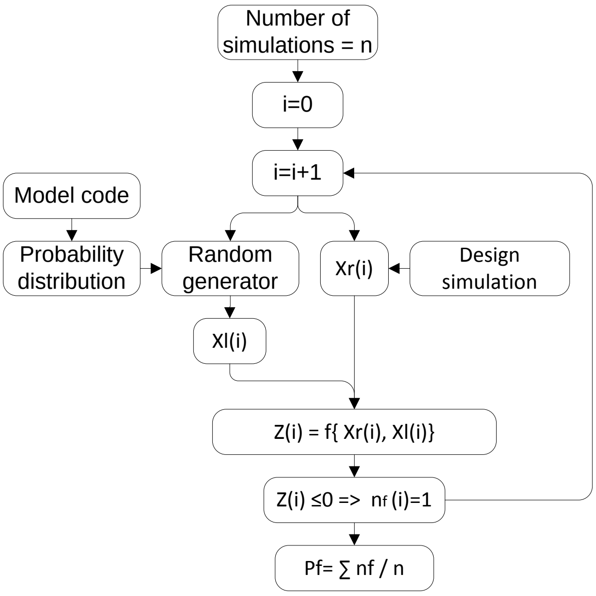
> Each arbitrary moment distribution, that is in equilibrium with the external load and for which nowhere the yield condition is violated, delivers a lower bound for the limit load.

Further information on the use of the upper- and lower bound is given in appendix G.

4.8.2 *Probabilistic procedure*

The calculations within the probabilistic analysis are performed by means of a Monte Carlo simulation procedure. This process is shown in its basic form in figure 28. The input for this simulation procedure consists of parameters obtained from the design simulation (the previous step in the HRA model) and parameters obtained from the probabilistic model code (JCSS, 2001). Parameters obtained from the design simulation are dominantly resistance parameters, while parameters originating from the probabilistic model are predominantly loading conditions. This is due to the fact that the loading conditions within the design simulation are not the real occurring loading conditions, but rather expected loading conditions. In order to approximate real loading conditions, probabilistic loading conditions from the probabilistic model code are adopted. Further information on the exact division of the two groups within the applied case study are given in chapter 5.

This input is used within the Monte Carlo simulation procedure as input for the reliability function (equation 7). These values are incorporated as deterministic values within each Monte Carlo iteration. Within each iteration, it is determined if Z is smaller then or equal to one. If this is the case, failure will occur.



Xr = resistance parameters
Xl = loading parameters

Figure 28: Monte Carlo procedure

The next step within the Monte-Carlo procedure is to run the simulation of the model. The probability of failure is estimated with the following formula:

$$P_f \approx \frac{n_f}{n} \tag{9}$$

In which n is the total number of simulations and n_f is the number of simulations for which $Z < 0$. By running a sufficient number of simulations a reliable result can be obtained. More technical details on the Monte-Carlo method and a procedure to check the results with a FORM analysis is presented in de Haan (2012).

4.9 CONCLUSION

Within this chapter a model for Human Reliability Assessment within structural engineering is proposed in order to answer sub-question 2:

> 2. *What is the configuration of a Human Reliability Assessment method specifically aimed towards quantifying the probability and consequences of human error in typical design processes within structural engineering?*

Basically the configuration of the proposed Human Reliability Assessment method consists of four distinctive steps. The first step is to direct the efforts towards processes which are vulnerable for human error (quantitative HRA analysis). The second step is to quantify Human Error probabilities (HEPs) and Error Magnitudes (EMs) on the basic task level (Human Error Quantification). The third step is to link these basic task level HEPs and EMs to the strength of a structure (Design Simulation). The final step is to determine a structural failure probability based on the structural strength properties and structural loading conditions.

Concerning the overall process, it can be concluded that the HRA model has the potential to quantify the effect of human error within carefully defined boundary conditions. However further research is required to increase the accuracy of the model and its practical use.

5 CASE STUDY

5.1 INTRODUCTION

Within chapter 4 a model for assessing the effects of human error within structural design processes is set-apart. This model is used within this chapter to investigate the consequences of human error within a predefined case. This case entails the detailed structural design of a reinforced concrete beam within an office building. These type of structures are relatively common within the Netherlands. The considered design process consists dominantly out of designing the structural dimensions of the beam. Al other structural design activities, such as selecting the structural layout, are incorporated as boundary conditions (e.g. no errors are occurring in these activities). This case study is not randomly chosen as will be discussed in section 5.2.

This chapter is structured on the same way as the previous chapter. Each of the sections 5.2 to 5.5 discusses the case study concerning the four steps within the HRA model, which is set-up as follows. The case study results concerning the qualitative HRA analysis is set apart in section 5.2. Section 5.3 discusses the results concerning the Human Error Quantification step. Section 5.4 sets apart the results within the design simulation procedure and section 5.5 discusses the final results obtained with the probabilistic analysis. The chapter is finally concluded in section 5.6.

5.2 QUALITATIVE ANALYSIS

The first step in the HRA model is to define the process of interest and its boundaries. This process consists of four steps: identify the process, identify the design context, select scenarios for further research and identify all tasks within the selected design process. These four steps will be discussed in the remainder of this section.

5.2.1 *Process identification*

The process of interest is a structural engineering process within a typical engineering company. Two restrictions are imposed on the boundaries of the process: only the design process is considered and a common structure is used as design object (office building). Furthermore with design process is meant the steps which are required to establish structural dimensions and other structural properties. Design activities left outside the research boundary are: selecting a structural type, establishing boundary conditions, site research, authority improvement, etc. These activities are of importance for finding the exact failure probability of a structure. However for demonstrating the use of the HRA model, restricting the case study to a few design tasks is sufficient.

5.2.2 *Design context*

The context of the process under consideration consists of two parts: the design object and the design organisation. Within the case study an imaginary design object and organisation are used which is set-apart in this section.

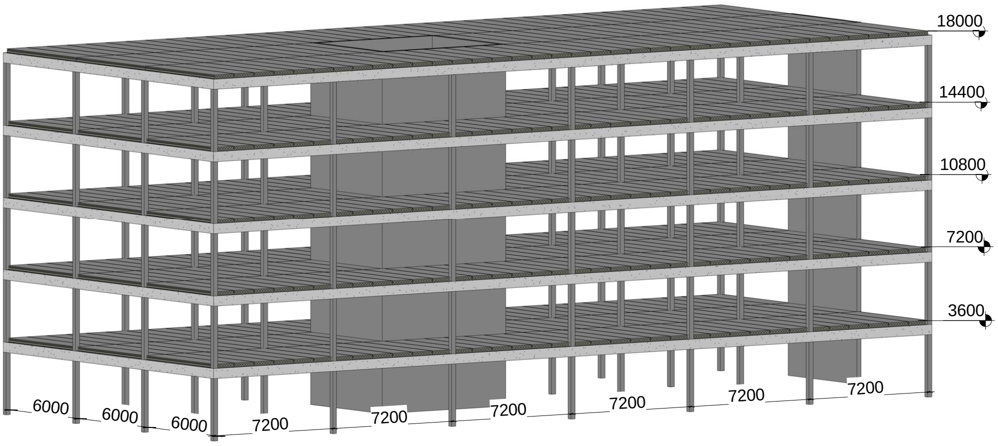


Figure 29: Overview of the office building used within the case study.

The design object is a beam element within an office building of the type shown in figure 29. This office building consists of a framework of concrete beams and column elements. The floor elements (which are supported by the beam elements) consist of hollow core slabs. The overall stability of the frame structure is ensured by means of a stabilizing core. A technical drawing of the office building is given in appendix A. The material properties, dimensions of the structure and loading conditions on the beam element are given in table 8. It should be noted that wind loads and other horizontal loads are not considered in the HRA as they are predominantly carried by the stabilizing core. Finally two distinctive beam types are considered: a statically determined beam and a statically undetermined beam within the frame structure of the office building.

The following assumptions are made concerning the design organization:

- The design is executed by a 'standard' engineering company within the Netherlands. The organization of the company is adequate and sufficient support is available.
- The design is performed by a professional engineer, capable of doing the particular design task.
- Detailed design of a single element within the design is performed by a single engineer, coordination and communication between several designers is required to design the whole structure.

Table 8: Basic design assumptions within the case study

Materials	Concrete	c35	
	Reinforcing steel	FeB 500	
Dimensions	Beam length	7,2	[m]
	Beams	250 x 500	[mm^2]
	Columns	250 x 250	[mm^2]
	Slab length	6,0	[m]
	Stabilizing walls	d = 250	[mm]
	floor slabs	d = 200 [a]	[mm]
	Column length	3,6	[m]
Loads	Dead load floors [b]	3,0	[kN/m^2]
	live load floors [c]	3,1	[kN/m^2] ($\psi = 0{,}5$)

[a] 150 mm hollow core slab and 50 mm finishing floor.
[b] Class B: office use.
[c] Hollow core slabs with finishing floor.

5.2.3 *Scenario identification*

Scenario analysis within this thesis is performed by conducting three consecutive elements. First a explorative FMEA is performed on the basic structural level to get some idea of the dominating failure modes within a building system. Secondly a explorative FTA is performed to determine the possible failure types within this failure mode. Finally a desk research is performed to investigate the probability of occurrence of the concerned failure mode/failure types. Based on these results, scenarios for further research within the remainder of the HRA are selected.

It should be noted that the FMEA and FTA are very basic, as they are meant to give a global idea about the elements affected by failure and the occurring failure types. The more elaborate desk research is subsequently used to select the scenarios for further research.

Failure Modes Effect Analysis

The basic FMEA is based on information from Mohr (1994). The analysis is presented in appendix A. A FMEA is an inductive or bottom up method, by determining all possible ways a system or process can fail (Mohr, 1994). There are two approaches for accomplishing an FMEA: the hardware approach (which lists individual hardware items) and the functional approach (which lists the outputs). Within this thesis a hardware approach is adopted, consisting of several (basic) construction elements. The considered elements are: beam elements, beam/column joints, column elements, slab elements, stability core, overall integrity and facade.

Based on personal judgement and information from the literature study a Risk Priority Number (RPN) for each failure mode is determined. The three most relevant failure modes are:

- Progressive collapse [1] of the structure due to incorrect design/insufficient coordination of the overall integrity.
- beam/joint/column/slab collapse by incorrect design.
- unwanted deformation/vibration of beam/slab elements caused by incorrect design.

The top risk identified is progressive collapse of a structure. The probability of occurrence of this failure is not very high, however the severity of failure (complete structure failure) is high and the detection possibility is low. These three properties result in a high RPN. The second risk identified is element failure due to incorrect design.

Failure on element level (second risk) is closely related to failure by overall integrity or progressive collapse failure (top risk). According to Val & Val (2006), providing safety in traditional design is achieved by designing structural components against specified limit states. However this approach does not exclude risk of local damage to a structure due to accidental events. One such an event (which is closely related to human error) is gross errors in design. This can be manifested by structural collapse on element level due to human error, consequently leading to impact loading on other parts of the structure and finally progressive collapse of the structure. From this perspective failure on element level leads to failure in the overall structural integrity.

Based on this, and the limitations of HRA for use within a very extensive process such as the overall integrity, failure on element level is selected as the dominant failure mode. The next step within the analysis would be to investigate the possibility of failure by means of progressive collapse. This is deemed to be outside the scope of this research and left for further research.

Fault Tree Analysis

The selected failure mode is element failure due to an incorrect design. A fault tree analysis (FTA) is performed to identify possible types of element failure. FTA is a failure analysis in which an undesired state event is analysed using boolean logic to combine a series of lower-level events (CUR, 1997). FTA is a deductive or top down method. The FTA is presented in appendix A.

---

[1] The spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or disproportionately large part of it.

Three main failure types are found: stability type of failure, shear force failure and moment force failure. Only moment force failure will be considered in the remainder of the research. All underlying failure types of this main failure type will be considered in the desk research (except failure types originating from the construction process).

Desk research

A desk research is performed to investigate the probability of occurrence of the failure modes and failure types found with the explorative FMEA and FTA. Eight papers which present quantitative information about the types of failures occurring throughout the world are used in this analysis. These papers are: Boot (2010), ABC-meldpunt (2011), Fruhwald et al. (2007), Matousek & Schneider (1976), Walker (1981), Eldukair & Ayyub (1991), Allen (1979) and Hadipriono (1985). It should be noted that Walker is cited from Fruhwald. This section summarises the result of this desk research. An elaborate description of the desk research methodology and the analysing methodology is given in appendix A.

To select relevant information, three research questions are selected for further research:

- What type of error did lead to the failure?
- How could these errors have occurred?
- Which building elements were involved in the failure?

The first two questions are closely related to the distinction in error classification given by Reason (1990). Reason differentiated three levels: the behavioural level consisting of the easy observable aspects of behaviour (question 1), the contextual level which also includes assumptions about causality (question 2) and the conceptual level which is based on the cognitive mechanisms involved in producing the error (this level is not considered in the available literature).

Type of error

The first research question is: 'What type of error did lead to the failure? '. This research question coincides with the failure types determined with the FTA. Within the analysis methodology (see appendix A), a subdivision in main category and sub-category is made. The three most relevant risks on main category level are in decreasing order:

1. Error in design (in general).
2. Error in communicating the design to others.
3. Error in system's schematics.

The seven most relevant risks on sub-category level are in decreasing order:

1. Error in mechanical schematization / force balance.
2. Calculation error.
3. Error in structural / mechanical system choice.
4. Error in document coordination among disciplines.
5. Error in drawing (wrong measurements etc.).
6. No calculation update or missing detailed calculation.
7. Error in determining loading scenarios.

From above main- and sub- category analysis it can be concluded that 'Error in design (in general)' is the most error prone activity in the design process. Errors within this main category are typically occurring due to schematization, calculation and coordination activities. Exploring design concepts and understanding the functional requirements (both main categories) is found to be of minor importance. Elements of the short list on sub-category level are returning in the FTA. Most of these errors are relevant for further research in the HRA.

Causes of error

The second research question is: 'How could these errors have occurred? '. The analysis method of this question is presented in appendix A. Based on this research question, the five most important error causes are in decreasing order:

1. Insufficient knowledge / education / qualification.
2. Ignorance.
3. Communication error.
4. Insufficient task division / overview.
5. Reliance on other parties.

Comparing this short list with similar results within the literature seems useful. One such a list is presented in chapter 3 based on findings from Vrouwenvelder (2011), van Herwijnen (2009) and Mans & Derkink (2009). This list is: professional knowledge, complexity of the task, physical and mental conditions, untried new technologies, adaptation of technology to human beings and social factors and organisation. The first category, insufficient knowledge, is directly mentioned. Communication errors and insufficient task division / overview is indirectly mentioned in the category 'completeness or contradiction of information'. The last two categories, ignorance and reliance on other parties, are not directly mentioned but originate from the category 'Social factors and organization'. From this considerations it can be concluded that the short list is not completely corresponding to the literature. However there is some correlation between both lists.

Finally the causes of error can be subdivided in errors on Micro level (knowledge, communication and ignorance) and on Meso level (Insufficient task division and reliance on other parties). This subdivision on levels is acknowledged, but will not be discussed further.

Elements affected by failure

The third research question is: 'Which building elements were involved in the failure? '. The analysis of this question is presented in appendix A. The research is based on categorization of building elements which are presented within the FMEA analysis. The five elements which were most affected by failure in a decreasing order are:

1. Beams and trusses
2. Slabs and plates
3. Vertical elements
4. Foundations
5. Connections

Failure in vertical elements (Columns and walls) is only causing approximately 12 % of the collapses, while failure in horizontal elements (beams, trusses, slabs and plates) cause approximately 44 % of the collapses (see appendix A). This is quite in line with the remark given by Vrouwenvelder (2011) based on other literature, concerning the triggering event to progressive collapse: "[...] the column failure is only responsible for about 10% of the structural failures [...]". Based on the research within this thesis, another more likely triggering event would be progressive collapse due to impact loading of failing beams/slabs. Within this research only the probability of occurrence of this impact load is considered.

5.2.4 *Conclusions scenario identification*

Within this section a desk research is performed to select particular scenarios for further research with the Human Reliability Assessment (HRA) method. Based on the results from the this research it can be concluded that failure of beam elements is the most frequent occurring single element failure. Based on these findings, the HRA is restricted to a the design of a single beam element.

A last step is to select relevant scenarios within these defined limits. As mentioned before, the information concerning the causes of failure is potentially the most powerful. This level of abstractness does go beyond the project boundary concerning its relevance. This makes the results of the scenario analysis on this level valuable for other design processes then the particular process concerned in the scenario. Furthermore the causes of failure are on a deeper cognitive level, which is beneficial for analyses of the real causes of failure.

Based on this, two 'causes of failure' are selected as scenarios for further research. The selection is based on relevance according to the desk research and the possibilities to model these scenarios with the HRA method. These scenarios are:

1. Level of professional knowledge
2. Level of design control

Professional knowledge

Professional knowledge is a property of the designer, based on skills, experience, nature and abilities. Within this research professional knowledge is limited to engineering knowledge, leaving out other types of knowledge such as communication- and social knowledge.

Professional knowledge is primarily based on the Micro-level or individual level, but is strongly influenced by aspects on the Meso-level such as organizational knowledge management. Another important aspect of the required knowledge within a design process is the cognitive demand level.

The link between professional knowledge on one hand and cognitive level on the other hand is not straight forward, and needs some clarification. Reason elaborates extensively on this subject in his book on Human Error (Reason, 1990). Reason distinguishes three levels on which a human mind is performing: skill-based, rule-based and knowledge-based level. Concerning the effect of expert knowledge on failure at the Knowledge-based level, Reason remarks (Reason, 1990, page 58):

> Experts, then, have a much larger collection of problem-solving rules than novices. They are also formulated at a more abstract level of representation. Taken to an unlikely extreme, this indicates that expertise means never having to resort to the Knowledge Based mode of problem solving. [...] the more skilled an individual is in carrying out a particular task, the more likely it is that his or her errors will take 'strong-but-wrong' forms at the Skill-based and Rule-based levels of performance.

Above citation does not directly provide information on the link between professional knowledge and the probability of failure. However knowledge influences the level on which a person executes a task. An expert will execute most engineering tasks on a rule-based level, while a young engineer entangles the engineering question for the first time, inevitable leading to a knowledge-based type of action. Knowledge-based actions have another cognitive demand profile in comparison to Rule-Based actions, leading to different probabilities of failure.

Internal control

One of the measures to prevent failures within a engineering firm is control. Due to the generally accepted assumption that humans are the 'weakest link' in the design of an engineered structure, engineers place a very high importance on error control measures (Stewart, 1993).

Within a design process several types of control can be distinguished. The level and profundity of control is process dependent, and differs widely. In an attempt to simplify this, three levels of control will be distinguished in accordance with the design supervision levels given in Annex B of NEN-EN-1990 (2002):

Self checking
Checking performed by the person who has prepared the design.

Normal supervision
Checking by different persons than those originally responsible and in accordance with the procedure of the organization.

Third party checking
Checking performed by an organization different from that which has prepared the design.

As this thesis focusses on human error within the organizational boundaries, no further attention will be paid to third party checking.

5.2.5 *Design process*

The proposed HRA model is based on failure probabilities within each basic design task. As such an overview of all tasks within the design process is required. The considered design process is the detailed design of a beam element. For this the design is subdivided in a global design phase and a detailed design phase. The global design phase provides information for the detailed design phase by means of communication, while the detailed design phase is the process which is considered in the case study. An flowchart of all design steps is shown in appendix B. This flow chart consists of design tasks and parameters which are obtained from the considered design tasks.

Based on the above mentioned assumptions it can be noted that the overall design process is not considered into depth. This is an boundary condition applied to the research in order to fit the research within its time limits. An interesting topic for further research is to model the decision process leading to an overall design.

5.3 HUMAN ERROR QUANTIFICATION

Within section 4.6 the Human Error Probabilities (HEP) and Error Magnitudes are introduced. These parameters are linked to the design process on the task level of the process, this is presented in appendix F. The first parameter (HEP) is coupled to the basic task level. The design activities consists of 111 basic tasks obtained from the design process described in appendix B. Each design activity is coupled to one of the seven basic tasks defined with the simplified HEP method. Furthermore a cognitive demand level is assigned to each basic task, based on the experience of the designer.

The second parameter EM, is coupled to the micro-task level. This is due to the fact that EMs must be coupled to a parameter in order to be of use. Each micro-task consists of several basic tasks which are required to obtain the parameter. The results of this coupling is shown in appendix F. This section will analyse the final results of the HEP-quantification process. This is done by discussing how often basic tasks are occurring within the selected structural design process and which differences are imposed on the cognitive demand levels for an experienced and inexperienced designer.

In total 111 basic design tasks are modelled for designing the reinforced concrete beam. The design tasks are presented in appendix F. Table 9 presents an overview of the division of these activities concerning the seven basic tasks specified within the simplified HEP method. The ‘calculate‘ task is by far the most occurring design activity, followed on a distance by the ‘determine‘, ‘derive‘ and ‘consult‘ design activities. The last three tasks: ‘Obtain‘, ‘insert‘ and ‘communicate‘ are occurring to a lesser extend within the design tasks. These results do comply to the expectations as one specific design activity is considered: the design of a simple beam element. On this detailed design level few communication is required. Furthermore most tasks consists of consulting the norm requirements, and applying them by means a calculation. If more parts of the overall design, or a more diverse design activity was selected, a more equivalent distribution among the basic tasks is expected.

Table 9: Occurrence of the basic tasks within the case study

Basic task	No. of design activities
consult	30
obtain	14
derive	21
determine	25
calculate	46
insert	7
communicate	12

Within the type of designer a difference is made between experienced and inexperienced designers. Based on this division, the 111 basic tasks are coupled to the three cognitive levels. An overview of the division of design activities as a function of the cognitive levels and professional knowledge is shown in table 10. It can be seen from this figure that an experienced engineer executes the engineering task on a lower cognitive level then an inexperienced engineer. A remarkable thing is that an experienced designer is almost not acting on the knowledge-based level, while a inexperienced designer does act on a skill-based level. This occurrence is a consequence of the fairly easy design task within the case study. If a more complicated design tasks was selected, these figures will shift towards a higher cognitive level.

Table 10: Applied cognitive level in the case study as a function of professional experience

Cognitive level	Experienced designer	Inexperienced designer
Skill-based	62	34
Rule-based	82	93
Knowledge-based	3	20

5.4 RESULTS DESIGN SIMULATION

The previous section discussed the results obtained on a basic task level. The next step is to combine these results into an human error probability distribution of the overall process. The underlying simulation procedure is discussed in section 4.7. This section discusses some basic results of this design simulation. Furthermore the effects of both scenarios on the overall process are discussed as well. It should be noted that the results of a case executed by an inexperienced designer are used in this section.

The first result obtained from the analysis is the result of a single micro-task, which is presented in figure 30. This figure presents the scatter in the beam height(Hb) by means of a histogram. This result is depending of two micro-tasks. It can clearly be seen that the result of this operation equals the correct results in most of the cases. Furthermore, the error rate [2] equals 0,05, which equals the sum of the HEP values of the considered micro-tasks.

The second result is the output of a series of micro-tasks. Depending on the number of micro-tasks required to obtain a certain parameter, the error probability will increase, as is presented in figure 31. This histogram presents the outcome of the micro-task to calculate the distributed load on the beam. The input from this micro-task is depending on 13 other micro-tasks, which is causing the scatter in the histogram. The error rate within the distributed load parameter is 0,35. It should be noted that most of the errors lie within an acceptable margin from the correct value.

One last thing to notice is that the human error magnitude is defined as the deviation from intend. This entails that the human error did lead to a deviation in the design, but it is not sure if this error will lead to an undesired situation: structural failure. For instance it can be seen from figures 31

---

[2] defined as the fraction of cases in which the design parameter deviates from the correct design value

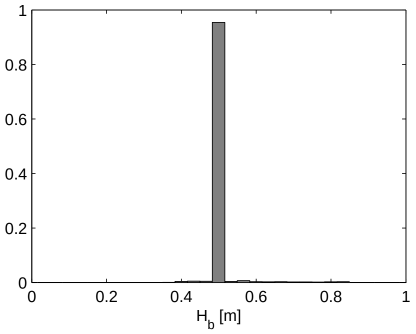


Figure 30: Histogram of the Beam height (Hb)

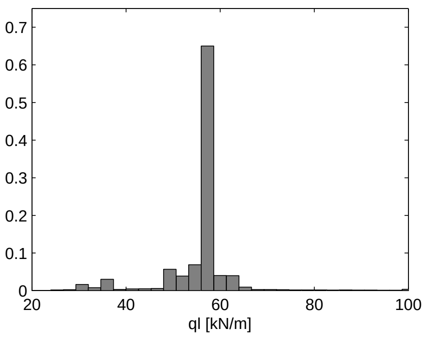


Figure 31: Histogram of the distributed load (ql)

that also positive errors are occurring and most errors are within a certain bandwidth. This is a consequence of the definition of the error magnitudes.

5.4.1 *Results control mechanisms*

Within this subsection the results concerning the level of control are presented. The designer checks regularly the correctness of a design parameter based on experience or logical assumptions. This process is termed self-checking. The effect of self-checking is presented in figure 32, which shows the top reinforcement area within the beam before and after self-checking. Also the final design check by the designer is included, which is also a self-checking mechanism. It can be seen from this figure that the error rate is reduced from 0,42 to 0,28. Also the scatter within the error is reduced somewhat. From this it can be concluded that self-checking is an important aspect of human error prevention.

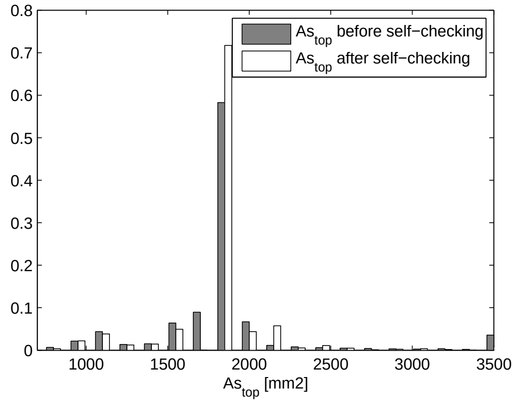


Figure 32: Histogram of the top reinforcement (As_{top}) before and after self-checking

Within the process, three checking mechanisms are incorporated: minimum reinforcement control, maximum reinforcement control and crack width control. If the design exceeds the calculated control values an action sequence is initiated in order to satisfy the control value. In case of the minimum reinforcement check, the minimum reinforcement is adopted. Within the maximum reinforcement check, the design is recalculated one iteration. Within the subsequent iterations the beam height is increased with 50 mm until the maximum reinforcement check is satisfied, or the beam height equals 800 mm. Within the crack with control the complete design is reconsidered one iteration. Within the subsequent iterations the reinforcement area is increased until the crack with is satisfied, or the maximum of three iterations is reached.

As an example of the usability of the control loops, the effect of checking the maximum allowable reinforcement is shown in a histogram in figure 33. It can be concluded that this control loop reduces the lowest beam heights (300 to 400 mm) with about 50 %. However this goes at a certain cost as the overall beam height is increased with 5 mm and the error rate is increased with 0,007 due to an error in the control loop. It should be noted that the Human Error Probability (HEP) value in figure 33 is increased with a factor 4. This is done in order to make visual interpretation of the results possible.

Overall the effect of minimum/maximum reinforcement checking does not have a major influence on error control. The reason for this is probably twofold:

- The minimum and maximum reinforcement values differentiate considerable from the correct reinforcement value. This makes is less suitable for error detection.
- The reinforcement checks are both based on parameters within the design process. An error in these parameters results in a comparable error in the minimum/maximum reinforcement value, hence the error will not be detected based on these values.

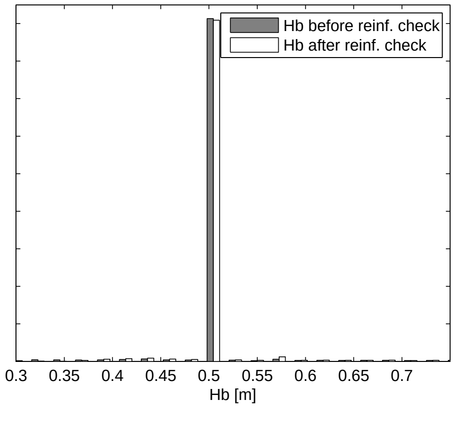


Figure 33: Histogram of the beam height (Hb) before and after maximum reinforcement control (distributions not on real scale)

After the design is finished by the designer an independent engineer checks the results. This is performed by reconsidering small parts of the design again and subsequently compare the results with the results of the designer. The effect of this process is shown in figure 34. The figure shows that the negative errors leading to a top reinforcement lower then 1000 mm are almost completely disappeared. Furthermore the error rate is reduced from 0,28 to 0,22.

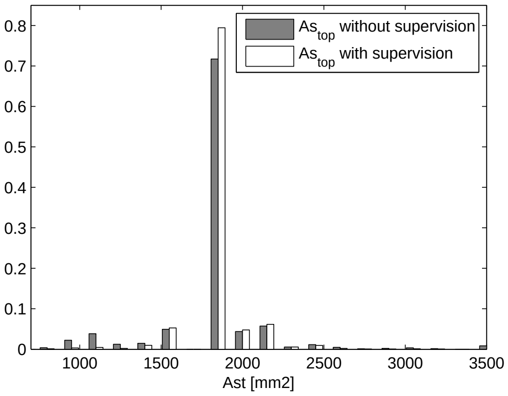


Figure 34: Histogram of the top reinforcement (As_{top}) before and after superior control

5.4.2 *Results professional knowledge*

Within this subsection the results concerning the level of professional knowledge are presented. This scenario is incorporated within the model by distinguishing two types of engineers: an experienced engineer and an inexperienced engineer. For each of these two types of engineers a cognitive demand level (skill-, rule- or knowledge based) is assigned to each basic task. This results in a different error probability distribution on the task level. In the figures 35 and 36 the effect of experience on the top reinforcement area is shown. It can be seen from these figures that experience has quite some effect on the error rate, which is reduced from 0,43 to 0,36. However one important thing to notice is that the error occurrence beneath a reinforcement area of 1500 mm is not decreased. This has a large effect on the final structural failure probability which will be discussed in section 5.5. This is due to the fact that these errors (which reduce the reinforcement area) decrease the structural resistance.

5.5 RESULTS PROBABILITY ANALYSIS

Within this section the results of the probabilistic analysis are discussed. Within section 4.8 it is set-apart that the probabilistic analysis is performed with a Monte Carlo simulation based on reliability functions, which are determined with plastic limit state analysis. This section will elaborate further on this by discussing the specific aspects of the probabilistic procedure which is used within the case study. Furthermore the results of the probabilistic analysis are discussed as well.

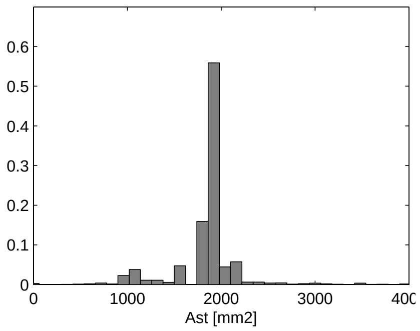


Figure 35: Histogram of the top reinforcement (As_{top}) if an Inexperienced designer performs the design

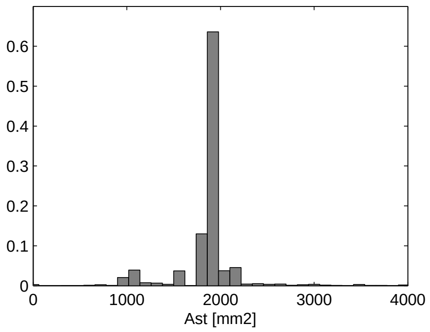


Figure 36: Histogram of the top reinforcement (As_{top}) if an experienced designer performs the design

5.5.1 *Probabilistic procedure*

Within the probabilistic analysis two construction types are considered. The first structural type is a prefab single beam element, which is modelled as a statically determined beam. The second structural type is a statically undetermined beam element. This element is envisioned as a beam within a frame structure supported by a concrete core. A schematic representation of this is given in figure 37. Both beam layouts are envisioned as an element of the office building presented in this chapter.

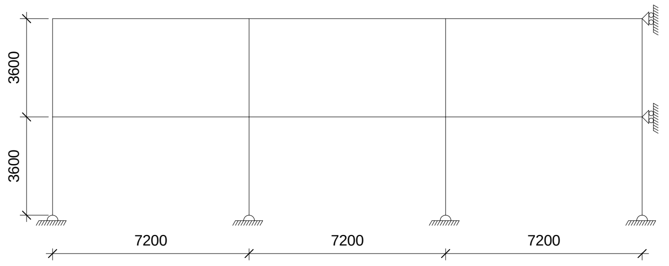


Figure 37: Basic layout of the frame structure

Some simplifications were required to analyse beam elements with the upper bound and lower bound analysis. The beam elements are modelled as a simple beam carrying a slab floor within an office building. The effect of tying reinforcement in the supports and positive effects of the slab floors are neglected. Furthermore errors within the shear reinforcement are not taken into account in the calculations.

The upper bound calculations are based on the mechanisms defined in appendix G. This analysis is based on 1-D beam elements loaded by distributed loads. Furthermore the lower bound check of the upper bound is presented in appendix G as well.

Within section 4.8 it was discussed that the reliability function consists in its basic form of two groups of input parameters: resistance parameters

(R) and loading parameters (S). Furthermore these two groups of parameters were used within the Monte Carlo procedure given in figure 28. In this procedure resistance parameters originate from the HRA simulation and loading parameters originate from the probabilistic model code (JCSS, 2001). This is the basic form of this methodology, however it requires some further refinement based on the particular case within this case study. This refinement is shown in figure 38, in which a subdivision is made in geometric properties, material characteristics and loading parameters. The parameters will be explained in the following three paragraphs.

The mean value of the geometric properties, such as beam dimensions and reinforcement layout, result from the HRA simulation process. It should be noted that these resistance parameters are not a fixed value as they are subjected to human error in the design. As a result they are presented by the probability functions given in section 5.4. Deviation in the geometric properties originating from construction activities are considered by using a standard deviation based on the probabilistic model code.

The material characteristics (f_y and f_c) are dominantly based on the probabilistic models given in JCSS (2001). Only the mean value of the concrete strength is based on the HRA simulation process. This is due to the common design practise that concrete strength is determined in the design phase, which is mostly adapted in the construction phase. As such, an error in the design phase will be adopted in the construction phase as well. Concerning reinforcement steel strength this is somewhat different. Due to the highly standardized steel strengths within especially normal applications, an error in design will probably not lead to an alteration in the strength of the steel in the construction. Based on this considerations, the choice is made to keep the reinforcement as a function of the probabilistic model code alone. It should be noted that deviation in the concrete strength due to construction activities is incorporated by using a standard deviation based on the probabilistic model code.

The loading conditions (self weight and distributed load) are functions of the distributions found in the model code. Loading conditions are also calculated in the design process. However these are the design parameters, and not the real occurring loading conditions. As such they are not relevant for the reliability analysis.

Loading conditions

The loading conditions of the structure are based on the action models defined in the probabilistic model code (JCSS, 2001). Only self weight and distributed loads are considered. Wind loads are not considered, as they are primarily of concern for the stability core in this particular structural design. Besides the loading conditions, the geometrical properties and material characteristics are partly based on the probabilistic model code. The probability of failure is calculated with a Monte Carlo procedure. Detailed information on the interpretation of the probabilistic model code within this thesis is presented in de Haan (2012). The resulting parameters of the

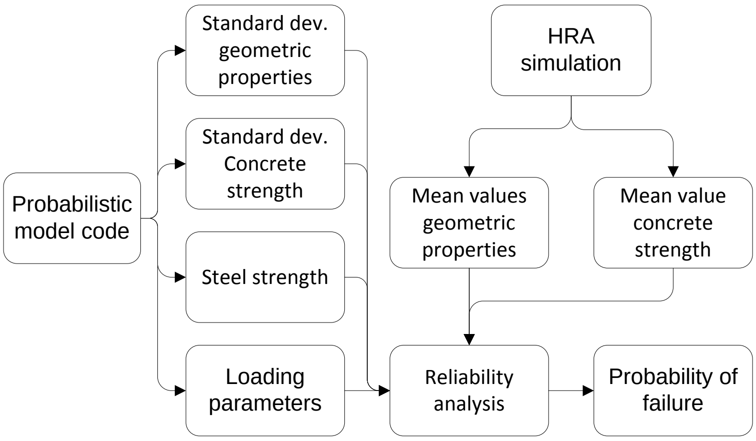


Figure 38: Division input parameters of the reliability function within the case study

model code are presented in table 11.

Table 11: Probabilistic models for the loading conditions and material properties (JCSS, 2001; Vrouwenvelder, 2002)

X	Parameter	Distr.	μ	V	λ	Unit
Hs	Slab height	Normal	160	0,004		[mm]
Hb	Beam height	Normal	HRA	0,004		[mm]
Bb	Beam width	Normal	HRA	0,004		[mm]
Hc/Bc	column dimensions	Normal	HRA	0,004		[mm]
ρ_c	Mass density concrete	Normal	2500	0,04		[kg/m^3]
f_c	concrete strength	Logn.	HRA	0,12		[N/mm^2]
α	long term reduction factor	Normal	0,85	0,10		[-]
f_y	yield strength	Normal	560	0,05		[N/mm^2]
q_{long}	Long term live load	Gamma	0,50	1,27	0,2/year	[kN/m^2]
q_{short}	Short term live load	Gamma	0,20	1,85	1,0/year	[kN/m^2]
m_R	Model factor resistance	Normal	1,0	0,05		[-]
m_E	Model factor load effect	Normal	1,0	0,10		[-]

HRA: Output variables of the design simulation process.

5.5.2 *Final results*

Within this subsection the final results of the probabilistic analysis will be presented for the statically determined and statically undetermined beam cases respectively.

Statically determined beam

Table 12: Dimensional parameters static determined beam in case of no error occurrence

X	Parameter	μ	Unit
Lx	Beam length	7,20	[m]
Hb	Beam height	0,75	[m]
Bb	Beam width	0,40	[m]
Asb	Bottom reinforcement	1570	[mm^2]
Ast	Top reinforcement	402	[mm^2]
Asshear	Shear reinforcement	335 (ø8-300)	[mm^2/m]

The first analysis concerns the case of a prefab beam modelled as a statically determined beam. The dimensional parameters in case of no error occurrence are presented in table 12. A visual representation of the results is given in figure 39. Within this figure the reliability function is simplified considerable in order to represent some characteristics of the function. Only two parameters are depicted (beam height and reinforcement area), while the other parameters are kept deterministically. Nevertheless figure 39 provides some useful insights into the results of the analysis and the used reliability function. The shape of the reliability function encompasses two important aspects of failure in reinforced concrete beams: a lower reinforcement ratio results in a higher collapse probability and the reinforcement ratio has an optimum due to brittle concrete failure.

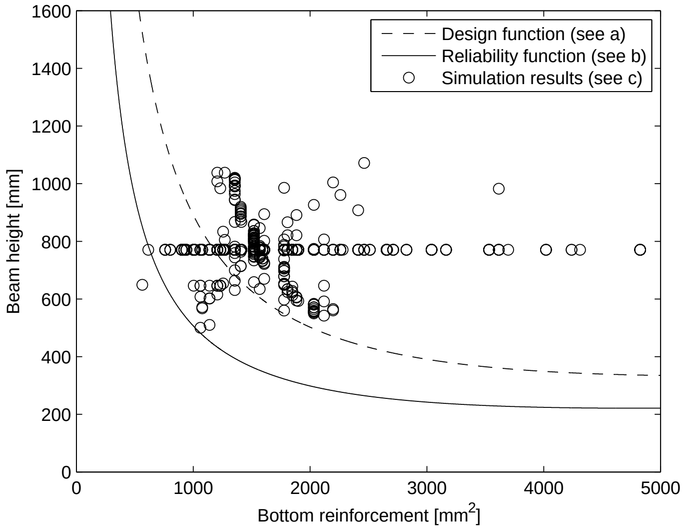
Within figure 39 two trends can be distinguished. Firstly, there is a horizontal line at a fixed beam height of 750 mm. This represents errors which only affect the reinforcement area, and not the beam dimensions. Secondly there is a trend-line parallel to the design function. This represents errors which affect both the beam height and reinforcement area. Both trend lines seem logical results of the simulation process.

The results of the Monte-Carlo simulation is presented in table 13. The results for a statically determined beam are not completely in agreement with the expectations. First of all, the failure probability decreases slightly if the design is executed by an experienced designer. This suggests that the experience of the designer has only a minor influence on the structural reliability. Secondly, the failure probability decreases with a factor of approximately 4,0 [3] if self-checking and normal supervision is applied instead of only self-checking.

Earlier analysis within the statically determined beam suggested somewhat other values. this is shown in table 13 as well. These values are based on other values within the self-checking and supervision loops. Comparison of the results of both analysis results in two conclusions. Firstly, the

---

[3] Factor is defined as SC/NS in which SC is the failure probability of a design with only self-checking and NS is the failure probability of a design with self-checking and normal supervision.



[a] Reliability function based on ULS partial factor method (elastic analysis).
[b] Reliability function based on plastic limit state analysis.
[c] Single simulation result out of a total of 20.000 runs.

Figure 39: Results of a statically determined beam simulation as a function of beam height and bottom reinforcement.

values of the reliability index differ too much. Secondly, the relative effect of the scenarios do not differ considerable (influence of experience is limited while control has a larger effect). From this it can be concluded that the final results should be used as relative results and not as absolute results.

Table 13: Results of the Monte-Carlo simulation of the statically determined beam.

Scenario	failure probability	Reliability index	Earlier analysis
Experienced designer with self-checking	$4,25 \cdot 10^{-3}$	2,63	3,02
Experienced designer with normal supervision	$9,00 \cdot 10^{-4}$	3,12	3,48
Inexperienced designer with self-checking	$5,00 \cdot 10^{-3}$	2,58	3,00
Inexperienced designer with normal supervision	$1,20 \cdot 10^{-3}$	3,04	3,35

Statically undetermined beam

The second analysis is a statically undetermined beam element. The dimensional parameters are presented in table 14.

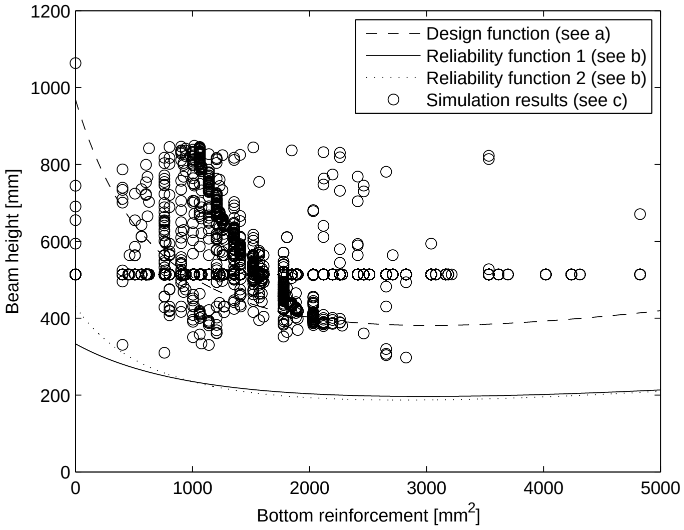
Table 14: Dimensional parameters of the statically undetermined beam in case of no error occurrence

X	Parameter	μ	Unit
Lx	Beam length	7,20	[m]
Hb	Beam height	0,50	[m]
Bb	Beam width	0,25	[m]
Asb	Bottom reinforcement	1520	[mm^2]
Ast	Top reinforcement	1808	[mm^2]
Asprac	Practical reinforcement	628	[mm^2]
Lc	Column length	3,60	[m]
Bc	Column width	0,25	[m]
Asc	Column reinforcement	1256 ($2 \cdot 628$)	[mm^2]
Asshear	Shear reinforcement	335 (ø8-300)	[mm^2/m]

A visual representation of the reliability function is given in figure 40. In this case there is not a single reliability function but two reliability functions as two failure mechanisms are governing the failure domain (see appendix G). The same properties as found in figure 39 for the statically determined beam are visible in this figure as well. Remarkable is that the effect of concrete crushing is becoming relevant at a lower reinforcement ratio. Furthermore it can be seen that the same two trend-lines are visible within the results (horizontal and parallel trend-line).

An interesting thing to mention is that the scatter within the statically undetermined beam is higher (in comparison to the statically determined case). It should be noted that the total number of simulations with an error however is almost similar. Due to this scatter increase, one should expect a higher failure probability in the statically undetermined beam case. However the failure is not decreased in the statically undetermined beam case, and is even somewhat lower in comparison to the statical determined beam case. From this two conclusions can be drawn. Firstly, a statically undetermined beam is more robust (which becomes visible in the lower reliability function). The second conclusion is of interest from an error causation perspective: the same error occurrence leads to another (lower) error consequence. This is in line with the non-linear behaviour of error causation discussed by Hudson (2010) and Ale et al. (2012).

The results from the probability analysis are depicted in table 15. Overall, the failure probabilities are lower in comparison to the statically determined case. The same results as within the statically determined case are found. Experience has only minor influence, an experienced engineer decreases the



[a] Reliability function based on ULS partial factor method (elastic analysis).
[b] Reliability function based on plastic limit state analysis.
[c] Single simulation result out of a total of 20.000 runs.

Figure 40: Results of a statically undetermined beam simulation as a function of beam height and bottom reinforcement.

structural failure probability with a factor 1,2 [4]. Design control has again quite some influence, as the failure probability decreases with a factor 2,5 [5] in case of normal supervision. Furthermore the earlier results deviate again in absolute values but they support the relative conclusions as well.

The conclusion from both beam types is that normal supervision has influence on the reliability of a structure while the effect of experience is somewhat smaller. Another point of interest is the use off the results. The absolute values of the calculations are not reliable, however the relative values seems reliable. This entails that the method is suitable for comparing different design process configurations.

5.6 CONCLUSION

Within this chapter, the HRA method is used to investigate the effect of human error within a predefined case in order to answer sub-question 3:

---

[4] Factor is defined as EXP/INEXP in which EXP is the failure probability of a design performed by an experienced designer and INEXP is the failure probability of a design performed by an inexperienced designer.

[5] Factor is defined as SC/NS in which SC is the failure probability of a design with only self-checking and NS is the failure probability of a design with self-checking and normal supervision.

Table 15: Results of the Monte-Carlo simulation of the statically undetermined beam

Scenario	failure probability	Reliability index	Earlier analysis
Experienced designer with self-checking	$1,50 \cdot 10^{-3}$	2,97	3,33
Experienced designer with normal supervision	$6,40 \cdot 10^{-4}$	3,22	3,55
Inexperienced designer with self-checking	$1,72 \cdot 10^{-3}$	2,93	3,09
Inexperienced designer with normal supervision	$7,2 \cdot 10^{-4}$	3,19	3,27

> *3. What are the consequences of human error within a design process of a typical structural engineering process on the structural reliability of a building structure?*

Selection of the case study is based on the qualitative analysis within the HRA method. Within this analysis the detailed design of a reinforced concrete beam element within an office building is selected. Furthermore two scenarios for further research are selected: the level of engineering knowledge and the level of design control. Within the first scenario two experience levels are defined: experienced and inexperienced. Within the second scenario two control mechanisms are defined: self-checking and normal supervision.

Based on the analysis performed in this chapter it can be concluded that both scenarios have influence on the failure probability of a structure. The strongest influence is found with the design control scenario. Both selected control mechanisms (self-checking and normal supervision) have quite some influence on the reliability of a building structure. It should be noted that self-checking is always occurring within a design process (mostly subconscious). Due to this, it is not a management choice to select a self-checking mechanisms. However self-checking can be influenced by managerial aspects, such as the level of support and the applied work pressure.

The second scenario is the level of professional knowledge of an engineer. The effect of a higher knowledge level is lower in comparison to design control. Despite this, it can be concluded that experience has also some influence on this simple design process. If more complicated design processes were selected, this effect will probably increase.

6

DISCUSSION RESULS

Within this chapter the used methodology is discussed concerning its relevance and usability. Firstly the used methodology is evaluated by considering the applicability of the model based on the model requirements (section 6.1). Secondly the reliability of the model is discussed in section 6.2. After that, the validity of the research is discussed by considering the internal and external validity (section 6.3). Finally the use of the model within a risk management process is discussed in section 6.4.

6.1 MODEL REQUIREMENTS

Within chapter 4, four categories of model requirements are stated: functional requirements, operational requirements, pre-conditions and points of departure. Within this section, the proposed HRA model will be evaluated based on these model requirements.

Functional requirements
Based on Ale et al. (2012) and Hudson (2010) five functional requirements were formulated. Evaluating the model on each of these five requirements results in the following:

- *Suitability model;* the suitability of the model for engineering tasks is demonstrated with a case study. From this it can be concluded that the model generates usable results, however further improvements are required to increase its practical use.

- *Error causation;* due to the non-deterministic character of error causation (Hudson, 2010) a fuzzy logic of error causation is adopted. Error is seen as a probability while the cause can be manifold. This method lacks the ability to identify a single cause, as it weakens the causal relation between cause and effect. On this manner, the problem of determining causality is eased a little in favour of increasing the adequacy to capture common effects (such as higher order causes and lower order barriers, Hudson, 2010).

- *Cognitive aspect;* the cognitive aspects of human error are incorporated by subdividing each design task into cognitive tasks, and link these into a cognitive demand profile. This method seems valid and is based on an existing HRA method (CREAM-method, Hollnagel, 1998).

- *Organizational context;* Organizational context is incorporated by introducing a weight factor (Common Performance Characteristics, CPC) within the HEP quantification based on a combined score which depends on the task context. This method is very basic, however seems reliable and useful.

- *Presentation results;* the results are presented by means of a probability distribution function. This is due to the non-linear and non-deterministic behaviour of human errors which cannot be presented reliable with a deterministic value (Hudson, 2010). This method is useful and meets the current level of HRA complexity.

Operational requirements
Two operational requirements are formulated concerning the use of the model within an engineering environment. Evaluation of the model on these two requirements results in:

- *Engineering use;* the HEP quantification method is subdivided in an extended and simplified method in order to increase the usability by engineers. Based on the experience within this research, the usability seems to be increased, however further research is required to verify this.
- *User friendly;* within this research only minor attention is given to the user friendliness of the model. Further efforts are required to increase its practical use. This is a consequence of the focus of this research on theoretical rather then on practical aspects.

Pre-conditions
The pre-conditions for the model commence from rules and regulations of the building process:

- *Use in engineering processes;* The model is demonstrated with a case study which is predominantly based on rules given in the Eurocodes. From this it is concluded that the model is suitable for use in processes defined by the current building rules and regulations.

Points of departure
The points of departure are imposed on the model in order to focus the research efforts. Departure points are: the model is aimed towards design tasks and the model is a diagnosis method. Based on the case study performed in this research it can be concluded that these restrictions do not hamper the validity of the research too much. It should be noted that these restrictions are departure points for further research.

6.2 RELIABILITY

The reliability of this thesis can be divided in two separate aspects. The first aspects is the reliability of the proposed model. The second aspect is the reliability of the case study.

The proposed Human Reliability Model is based on literature findings, discussions with university supervisors and personal contributions of the researcher. Reliability of the model is checked by conducting a case study, comparing the model with Human Reliability Models within the literature and review sessions with the university supervisors.

Based on this, it can be concluded that the model is crude and its reliability can be increased. This is a direct consequence of one of the research limitations: *the research is meant as an explorative research on the possibilities to quantify human error within structural engineering processes*. From this perspective, the reliability of the proposed model is sufficient for his intended use. Improvements of the model concerning its reliability are proposed in the conclusion (chapter 7).

The technical aspects of the case study (dimensions etc.) are based on a technical design mentioned in literature. Other aspects of the design process, such as the organizational situation in which the design is performed, are based on assumptions obtained from literature. The reliability of the results of the case study is checked by comparing the results with comparable results within the literature. More details on this are given in subsection 6.3. Due to time limits no extensive validation of the case study results is performed. Again this adopted method is the direct consequence of the explorative character of this research.

6.3 VALIDITY

A research method is valid if its usage is adequate to give an answer to the research question. Two types of validity are distinguished within this research: Internal and external validity. Furthermore the results are compared with comparable results within the literature.

6.3.1 *Internal validity*

Internal validity is the validity within the research for deriving logical conclusions from known information or assumed to be true (Verschuren & Doorewaard, 2007). Within this research internal validity concerns the derivation of structural failure probabilities from human errors occurring within the structural design process. This internal validity is evaluated by a discussion on the application of the model based on literature concerning failure causation. This internal validation is important from a scientific perspective as it indicates the deficits of most Human Reliability Assessment models to quantify human errors properly.

Non-linear character failure causation
An important deficit of Human Reliability Assessments concerning accident causation is mentioned by P. Hudson in his inaugural speech (Hudson, 2010). According to Hudson, failure causation must be regarded as both non-linear and non-deterministic. Within the presented model this is incorporated to a large extend. The non-linearity from organizational causes to effects is present in the focus of the proposed HRA model on the complex interactions between human cognition, rather then defining specific routes of human information processing. Furthermore the relation between error and consequence is based on a calculation sequence, in which numerous causal routes can be distinguished. Concerning the non-deterministic character of accident causation, the model represents the variables in terms of probability distributions rather then simple failure rates. This is in line with Hudson (2010) and the distributions used in the CATS [1] model (Ale et al.,

---

[1] CATS, or Causal model for Air Transport Safety, is developed by a research consortium in the Netherlands in the beginning of this century. CATS is a causal model for air transport safety. Its purpose is to establish in quantitative terms the risks of air transport.

2009, 2010). Finally concerning the internal validity the question remains if the proposed model is advanced enough to cope sufficiently with the non-linear and non-deterministic properties of accident causation. Further research is required on this topic.

active failures and latent conditions

Within chapter 3 the 'Swiss cheese' model was introduced. Holes in the defensive layers within this model were occurring due to active failures and latent conditions. Active failures are the unsafe acts committed, while latent conditions are unsafe conditions within a system. A HRA model should be able to represent both error provoking conditions. Within the proposed HRA model both aspects are incorporated as follows:

- *Active failures*; the model uses Human Error Probabilities (HEP) and Error Magnitudes (EM) on the basic-task / micro-task level to present the probability of occurrence of an active failure in the design process.
- *Latent conditions*; the model uses the design context and the overall design layout to present latent conditions. Latent conditions have large impacts on the conditions in which a design is performed, which is presented by a weighting factor depending of the design context. Furthermore, latent conditions within the overall design process are for instance incomplete control mechanisms within the organization (which can be modelled with a design sequence).

The first question arising from this is if all active failures are incorporated in the model. This is not the case, for instance extraneous acts and errors of intent cannot be modelled adequately. This deficit is a consequence of the focus of the model on tasks and within those tasks error probabilities from literature. As within the literature errors of intent are not quantified, a structural failure probability caused by intentional actions cannot be obtained.

The second question is if all latent conditions are taken into account, and if the relation between latent condition and consequence is correct. It is very hard to detect all latent conditions, and quantify there influence. Representing this relation by means of a weighting factor and the process layout is very basic, but is a useful approximation.

6.3.2 *Comparison results*

Within the literature study a paper (Stewart, 1993) is discussed which simulates the effect of human error on the design and construction of a reinforced concrete beam (simply supported, without compressive and shear reinforcement). This case is comparable with the case study for the statically determined beam presented in this thesis. Stewart (1993) distinguishes two control measurements: 'designer checking' and 'design check'. These are comparable with 'self-checking' and 'normal supervision' defined in this research. A comparison of the results is given in table 16.

Comparing the results shows that the results of Stewart are considerable lower. Furthermore supervision is slightly more effective within the model

Table 16: Comparison results Stewart (1993) and the case study

	Stewart (1993)	Case study
Self-checking	$0,381 \cdot 10^{-3}$	$4,3 \cdot 10^{-3}$
Normal supervision	$0,586 \cdot 10^{-4}$	$9,0 \cdot 10^{-4}$

of Stewart. Despite these numerical differences, there is quite an agreement in the general picture of the results: normal supervision has quite an influence of the structural reliability. The numerical differences can be explained by the large margins on the failure probabilities in any Human Reliability Assessment. from this, and the analysis in the case study, it can be concluded that the results of the HRA model are only valuable as relative results. This is in line with the shortcomings of HRA formulated by Swain (1990) (presented in chapter 3.4) and the conclusions made in chapter 5.

6.3.3 *External validity*

External validity is the extent to which the results of this thesis can be generalized to other situations (Verschuren & Doorewaard, 2007). For this two aspects are distinguished: the use of the model within structural design processes and the use of the results of the model outside its boundaries. The proposed Human Reliability Assessment is meant for structural engineering processes within the design process, for which it can be used in principle within each of these processes. However due to the explorative character of this research only a single case study is considered. This hampers the external validity of this research on this perspective. As such further research is required to investigate the applicability of the model in other situations then the case study.

The second aspect is the use of the results of the model. Due to the fact that the obtained results can only be used in a relative manner, this use is somewhat restricted. The results can only be used relative to results of processes which are also evaluated with the model. This entails for instance that the model cannot be used to establish reliability indexes for direct use within design codes. Its intended use is to compare different structural design process layouts with each other concerning there error proneness. Furthermore, it can also be used to asses different design codes on there effects on human error.

6.4 MANAGEMENT FOLLOW UP

Within this thesis a model for Human Reliability Assessment (HRA) within typical structural engineering tasks is proposed. Despite necessary improvements, the model has shown its applicability for quantifying the effect of human error within a typical building structure. The question remaining is how this model can be used within human error management.

The proposed HRA method is basically a risk management support tool. It is typically aimed towards low probability - high consequence risks, occurring due to gross errors as a consequence of human malfunction. The tool allows evaluation of the potential effect of human actions. Based on a comparable risk management support tool (Ale et al., 2012), it can be stated that the proposed tool enhances the possibilities of a company to allow the evaluation of the present and future vulnerabilities to catastrophic events. These evaluations can then be used to steer management towards controlling rare disasters that individual managers are unlikely to see.

This enhances the possibility of a safety-critical organization to pro-actively evaluate and manage the safety of their activities. According to Hollnagel & Woods (2006) and Reiman & Pietikainen (2011) the challenge of this is in being able to anticipate on vulnerabilities rather than merely react to them when they occur.

The question remaining is which actions should be taken after the HRA method has distinguished vulnerabilities within the organizational process. Assessing this in detail lies outside the scope of this research, as this research is focussing on proposing a human error diagnosis method rather then an human error management method. Nevertheless it is deemed necessary to discuss human error management application shortly, in order to place the diagnosis model in a larger perspective.

One such a risk management support tool is proposed by Ale et al. (2012), which describes the influence of management on safety functions. This model is depicted in figure 41. The model distinguishes four tasks: to provide, use, maintain and monitor the risk control measures that need to operate to keep the system safe. For these tasks seven deliveries are distinguished: procedures, technology, interface, availability, competence, communication, commitment. They are called deliveries because they are risk controls, instructions and resources that management should deliver to the tasks.

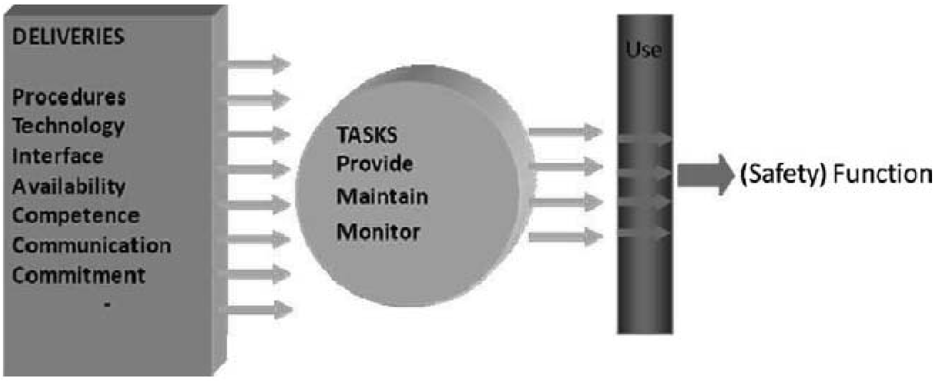


Figure 41: Deliveries and tasks of the management system (Ale, 2006, as cited from Priemus & Ale, 2010)

The management system shown in figure 41 is very useful for showing the use of the proposed HRA model in this research. Considering the four management tasks, the proposed model is mainly focussing on monitoring the risk control measures. This is due to the empathy of the model to assess a vulnerable situation in order to pinpoint possible weaknesses. It does not directly provide tools for use within risk management. As such it is not aimed towards the provide, use and maintain tasks within the risk management system.

In this light, the research has 'monitored' two indicators which are of interest for the risk control system within an engineering firm. These indicators are the effect of professional knowledge and the effect of design control. From the analysis it is become clear that design control has quite an influence on the final results. The effect of professional knowledge was also positive, however less clear cut. Based on these findings, engineering companies and building contractors can alter there design process in order to incorporate the findings of the HRA. For this, managers can use the seven deliveries distinguished in figure 41.

From above considerations it can be concluded that the proposed HRA model is meant as a helpful tool for use within the risk management system of an engineering company or building contractor. Based on the management system provided in figure 41, its use within risk management systems is further demonstrated.

7

CONCLUSIONS AND RECOMMENDATIONS

This research considers the effect of human error within structural engineering. The objective of this research is to investigate the effect of human error within the design process on the reliability of building structures. In this chapter conclusions and recommendations for further research are presented. The main research question is defined as:

> *What are the consequences of human error within the structural design process on the structural reliability of a typical building structure?*

To answer the main research question, a Human Reliability Assessment (HRA) method for structural design tasks is proposed. This model is subsequently used to investigate the consequences of human error within the detailed design of a reinforced concrete beam in a building structure.

The HRA model basically encompasses four steps, which are presented in figure 42. The model starts with a general idea about the particular engineering task, of which insights on the effect of human error is required. Through the four HRA steps a failure probability of the engineered structure is obtained.

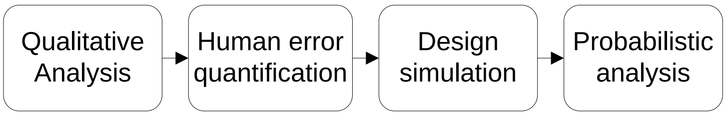


Figure 42: Basic steps within the HRA model

7.1 CONCLUSIONS

The qualitative analysis is used to determine the context of the situation. Furthermore a prior analysis (scenario selection) is used to select potential hazardous design tasks, on which a HRA analysis should be performed. The following conclusion is formulated concerning this step:

- It is found that using the HRA model for a complete design process is unrealistic. To tackle this, minimizing the HRA to the most hazardous design steps is required.

Within the human error quantification, a Human Error Probability (HEP) and an Error Magnitude (EM) is calculated for each task within the design. These parameters present the occurrence probability and consequence of a human error in a single design task. For the HEP quantification two methods are proposed: an extended and a simplified HEP method. Concerning this part of the HRA process, the following conclusions are stated:

- Quantifying HEPs within design is sensitive to subjectivity due to the inherent aspect to assess possible human failure modes. In order to minimize these negative effects, careful selection of the boundary conditions and starting points is required.

- The extended HEP quantification method has the potential to analyse a non-standard structural design process. This process however requires extensive efforts and sufficient human factors knowledge.
- Based on a small survey it is concluded that HEP quantification is not reliable, if conducted by an engineer without prior extensive training.
- The simplified HEP quantification method can be used to analyse a standard design process. This process is applicable for use by engineers as it relies on engineering judgement rather then on psychological aspects.

The next step, design simulation, is used to derive an error probability on the structural element level. This simulation process is based on a task step analogy of the design process. Within this analogy, a task HEP and EM is combined in a so called micro-task. All micro-tasks combined form the design process. Besides this, design control is modelled with an algorithm where some or all prior micro-tasks are re-evaluated if the initial results are not within 'reasonable' limits. This analysis resulted in the following conclusions:

- The micro-task analogy is useful for modelling human error in design. Two important elements of a design process are encompassed in the model: a task is depending on a finite number of previous design steps and errors are modelled as a deviation from intend. This latter deviates from the simple success-failure notion often used in HRA.
- the control loop analogy is useful, however very crude. This entails that further research is required to increase the accuracy of control loops in design. Despite this it encompasses the ability to check the results based on previous experience.

The last step is to determine the failure probability on element level. This analysis is performed with a probabilistic Monte-Carlo method. The error probabilities found in the previous step combined with probabilistic loading conditions are used to determine the structural failure probability. This process is deemed useful for determining structural failure probabilities based on human error probabilities.

Concerning the overall process, it can be concluded that the HRA model has the potential to quantify the effect of human error within carefully defined boundary conditions. However further research is required to increase the accuracy of the model and its practical use.

Case study

The HRA model is used to analyse a simple design process, consisting of the design of a reinforced concrete beam element within a building structure. For this analysis two scenarios are selected: the level of design control and the level of professional knowledge of the designer. Furthermore two beam types are considered: a statical determined and a statical undetermined beam. Conclusions based on the performed case study are:

- Human error has the potential to reduce the reliability index of a beam element from 3,8 to approximately 3,5 to 2,5.
- The influence of design experience on the structural failure probability is limited. The failure probability decreases slightly if an experienced designer performs the design instead of an inexperienced designer.
- There is quite some effect of normal supervision on the structural failure probability. In comparison to a process with only self-checking, the effect is about a factor 2,4 to 4,0.
- A design process without design supervision (self-checking and normal supervision) results in an unrealistic failure probability. Due to the inherent presence of (mostly subconscious) self-checking within design, this is deemed an unrealistic design practice.
- The results are only usable as relative results. This entails that the method can only be used to compare different design configurations defined within the HRA. Comparison with results outside the HRA is doubtful due to the lack of real time validation.

7.2 RECOMMENDATIONS

In accordance with the conclusions, recommendations for project/process managers with regards to Human Error management can be made:

- The model can be used as a diagnosis method. It is aimed towards monitoring structural design processes on there human error proneness and monitoring the effect of risk control measurements.
- The effect of human error within structural engineering processes is significant. A manager should be aware of this and take sufficient pre-cautionary measurement to prevent human error from occurring or/and mitigate the negative consequences.
- An effective measurement is introducing control mechanisms within the process. An important aspect of this control mechanism is its design. A pit fall concerning this is a control mechanism which uses information from the design process to control the same design process.

7.3 OPPORTUNITIES FOR FURTHER RESEARCH

The conducted research is an explorative research concerning the use of Human Reliability Assessment methods within structural engineering design. Based on this, several opportunities for further research are formulated.

Verification and calibration of the model

The proposed Human Reliability Assessment method is only worked out in basic form. A important step is to verify and calibrate the model with a real-time structural engineering process. Based on this, the model can be improved and altered for practical use.

Improvement of the Human Error probabilities
The Human Error Probabilities (HEPs) are primarily based on values available within literature. A deficit of these values is that they are primarily based on operational types of actions. Further research is required to verify the applicability of the HEPs or to find reliable and applicable HEPs.

Improvement of the Error Magnitude
The Error Magnitude (EM) within design tasks is only vaguely known. These EMs are required together with the HEPs to obtain a probability distribution of the effects of human error within a single design task. Research is required to attain EMs of professionals conducting relevant engineering tasks, which can be used as realistic input within the model.

Control mechanisms
The control mechanisms within the process are modelled on a very basic manner within the proposed HRA-method. They are only depending of the knowledge of the engineer and the person's level of control over the design parameter. This simple model is deemed to be to crude for use within realistic applications. As such, modifications of this is required. Improvements can be made by incorporating the available control time, task complexity and designer experience on a more sophisticated manner.

Learning effects
The effect of learning (single loop, double loop) is an important part of human interaction. Incorporation of this within the model would increase the applicability and accuracy of the model.

Non-linear character failure causation
Within the literature (Hudson, 2010) it is discussed that accident causation must be regarded as both non-linear and non-deterministic. A Human Reliability Assessment method must cope with these properties in order to estimate failure probabilities accurately. It is discussed that the presented model comprises some features to model these non-linear and non-deterministic aspects. However further research is required to investigate the limitations of the proposed model on these aspects and to propose improvements to the model.

Safety barriers
Within the design process more (often subconscious) safety barriers are present. Furthermore safety barriers are often interrelated caused by common organizational factors. This could mean that barriers might fail after an incident much easier al of a sudden. Within the model this is applied on a basic manner. Investigation on these safety barriers and the effect of the interrelation between these barriers is required to pinpoint there effect on human error prediction

Model for construction tasks
The HRA model is designed for typical design tasks within structural engineering. Expansion of the model with typical construction tasks would increase the applicability of the model for use within basic engineering.

8

DEFINITIONS

8.1 LIST OF DEFINITIONS

Cognitive process	A group of mental processes by which input is transformed, reduced, elaborated, stored, recovered and used.
Construction process	The process by which resources such as manpower, material and equipment is used to construct a facility or product based on the design plan.
Design process	The process (often iterative) in which a plan or scheme is created for the realization of a stated objective to create a product.
error rate	The fraction of cases in which the performance deviates from the limits of performance defined by the system.
Failure	In general defined as the unsuitability of the structure to serve the purpose where it was built for, regardless of cause. Within this thesis narrowed to failure caused by the collapse of (parts of) a building.
Human error	Any member of a set of human actions or activities that exceeds some limit of acceptability, i.e. an out of tolerance action, or failure to act, where the limits of performance are defined by the system.
Limit state	The state just before failure occurs.
Micro-task	A task sequence consisting of one or more cognitive activities to acquire one single design parameter.
Non-deterministic	The relation between two values is not deterministic, e.g. it is not sure that every time when A occurs, B will occur as well.
Non-linearity	The causal effects are not simplified to a single chain, but represented by an ever-increasing tree of binary or more combinations.
Reliability	The probability that the limit state is not exceeded.
Progressive collapse	The spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or disproportionately large part of it.
Risk	The combination of the probability of occurrence of a defined hazard and the magnitude of the consequences of the occurrence.

Robustness	The ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause.
Structural safety	The absence of harm due to an unexpected chance of failure due to structural collapse of (part of) the building.

8.2 LIST OF ABBREVIATIONS

APJ	Absolute Probability Judgement
BCF	Basic Cognitive Function
CATS	Causal Model for Air Transport Safety
CPC	Common Performance Condition
CCA	Critical Cognitive Activity
CFF	Cognitive Function Failure
CREAM	Cognitive Reliability and Error Analysis Method
EM	Error Magnitude
EPC	Error Producing Condition
FORM	First Order Reliability Method
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GEMS	Generic Error Modelling System
GTT	General Task Type
HEART	Human Error Assessment and Reduction Technique
HEP	Human Error Probabilities
HEQ	Human Error Quantification
HRA	Human Reliability Assessment
IA	Impact Assessment
JHEDI	Justification of Human Error Data Information
NEP	Nominal Error Probability
PC	Paired Comparisons
PRA	Probabilistic Risk Assessment
PSF	Performance Shaping Factor
RPN	Risk Priority Number
SLIM	Success Likelihood Index Methodology
THERP	Technique for Human Error Rate Prediction
VSS	Vulnerable System Syndrome

BIBLIOGRAPHY

ABC-meldpunt (2009). Abc meldpunt - registratie en analyse van bouwfouten. periode 1: 15 maart tot 17 november 2009. Technical report, TNO Bouw en Ondergrond, Delft.

ABC-meldpunt (2011). Abc meldpunt- registratie en analyse van bouwfouten. periode 5: 1 januari 2011 - 15 juni 2011. Technical report, TNO Bouw en Ondergrond, Delft.

Ale, B. J. M. (2006). The occupational risk model. Technical report, TU Delft/TBM, Delft.

Ale, B. J. M., Bellamy, L. J., Cooke, R., Duyvis, M., Kurowicka, D., & Lin, P. H. (2009). Causal model for air transport safety. final report. Technical report, Ministry of transport, directorate general for air transport and maritime affairs, The Hague, Netherlands.

Ale, B. J. M., Bellamy, L. J., van der Boom, R., Cooper, J., Cooke, R. M., Goossens, L. H. J., Hale, A. R., Kurowicka, D., Morales, O., Roelen, A. L. C., & Spouge, J. (2010). Further development of a causal model for air transport safety (cats): building the mathematical heart. *Reliability engineering and system failure*, *94*, 1433–1441.

Ale, B. J. M., Hanea, D., Sillen, S., Lin, P. H., Gulijk, C., & Hudson, P. (2012). Modelling risk in high hazard operations: integrating techical, organisational and cultural factors. Unpublished: Department of safety science, Delft university of technology.

Allen, D. E. (1979). Errors in concrete structures. *Canadian journal of civil engineering*, *6*(3).

Apostolakis, G. (1982). Data analysis in risk assessments. *Nuclear engineering and design*, *71*, 375–381.

Baker, J. W., Schubert, M., & Faber, M. H. (2008). On the assessment of robustness. *Structural safety*, *30*, 253–267.

Boot, W. (2010). Constructieve schade, een onderzoek naar de constructieve schade in bouwwerken en de wijze waarop wet- en regelgeving een rol spelen bij het waarborgen van de constructieve veiligheid. Master's thesis, Technical University Delft, Delft.

Busker, H. Faalkosten aanhoudend probleem in de bouw- en installatiesector. received from http://www.bouwkosten.nl/media/86351/faalkosten.pdf.

Busker, H. (2010). Faalkosten door de jaren heen. received from http://www.bouwkosten.nl/media/86351/faalkosten.pdf.

CUR (Ed.). (1997). *Probability in civil engineering, part 1: the theory of probabilistic design*. Gouda: CUR Bouw en Infra. CUR publication 190.

CUR (Ed.). (2010). *Falende constructies. case-onderzoek naar structurele oorzaken van falen en maatregelen die dat tegengaan*. Gouda: CUR Bouw en Infra. CUR publication C232.

de Haan, J. (2012). Human error in structural design. Master's thesis, Technical University Delft. Not yet published.

DiMattia, D. G., Khan, F. I., & Amyotte, P. R. (2005). Determination of human error probabilities for offshore platform musters. *Journal of Loss Prevention in the Process Industries*, *18*, 488–501.

El-Shahhat, A. M., Rosowsky, D. V., & Chen, W. F. (1995). Accounting for human error during design and construction. *Journal of architectural engineering*, *84*, 84–92.

Eldukair, Z. A. & Ayyub, B. M. (1991). Analysis of recent u.s. structural and construction failures. *Journal of performance of constructed facilities*, *5*(1).

Ellingwood, B. R. (1987). Design and construction error effects on structural reliability. *Journal of Structural Engineering*, *113*(2), 409–422.

Ellingwood, B. R. & Dusenberry, D. O. (2005). Building design for abnormal loads and progressive collapse. *Computer-Aided Civil and Infrastructure Engineering*, *20*, 194–205.

Ellingwood, B. R. & Kanda, J. (Eds.). (2005). *Structural safety and its quality assurance*. Reston (Virginia): American Society of Civil Engineers.

Epaarachchi, D. C. & Stewart, M. G. (2004). Human error and reliability of multistory reinforced-concrete building construction. *Journal of performance of constructed facilities*, *18*(1), 12–20.

Everdij, M. H. C. & Blom, H. A. P. (2006). Safety methods database. Technical report, National Aerospace Laboratory (NLR). retrieved from: http://www.nlr.nl/documents/flyers/SATdb.pdf.

Everdij, M. H. C., Blom, H. A. P., & Kirwan, B. (2006). Development of a structured database of safety methods. 8th International conference on probabilistic safety assessment and management. retrieved from: http://www.nlr.nl/id 9276/l en.pdf.

Fruhwald, E., Serrano, E., Toratti, T., Emilsson, A., & Thelandersson, S. (2007). Design of safe timber structures- how can we learn from structural failures in concrete steel and timber? Technical report, Lund Institute of Technology, Lund (Sweden).

Grozdanovic, M. & Stojiljkovic, E. (2006). Framwork for human error quantification. *Philosophy, Sociology and Psychology*, *5*(1), 131–144.

Hadipriono, F. C. (1985). Analysis of events in recent structural failures. *Journal of structural engineering*, *111*(7).

Harrison, M. (2004). Human error analysis and reliability assessment. 46th IFIP WG10.4 Workshop on Human Computer Interaction and Dependability (Siena, Italy). retrieved from: http://www2.laas.fr/TSF/IFIPWG/WorkshopsMeetings/46/05-Harrison.pdf.

Hollnagel, E. (1993). Modelling of cognition: procedural prototypes and contextual control. *Le travail humain*, *65*(1), 27–51.

Hollnagel, E. (1998). *Cognitive reliability and error analysis method*. Oxford: Elsevier Science Ltd.

Hollnagel, E. & Woods, D. D. (2006). Epilogue: resilience engineering precepts. In E. Hollnagel, D. D. Woods, & N. Leveson (Eds.), *Resilience engineering: concepts and precepts*. Aldershot: Ashgate.

Hudson, P. (2010). Safety science: It's not rocket science, it's much harder. Repository TU Delft. received from http://repository.tudelft.nl/view/ir/uuid

Hyatt, N. (2006). *Incident investigation and accident prevention in the process and allied industries*, chapter Appendix H: Human error assessment and reduction technique (HEART), (pp. H1–H12). Ontario (Canada): Richmond Hill.

JCSS (2001). *Probabilistic Model Code*. Joint Committee on Structural Safety. Received from: http://www.jcss.byg.dtu.dk/Publications/Probabilistic-Model-Code.aspx ISBN 978-3-909386-79-6.

Kaminetzky, D. (1991). *Design and construction failures: Lessons from forensic investigations*. New York: McGraw-Hill.

Kempen, P. M. & Keizer, J. A. (2000). *Advieskunde voor praktijkstages. Organisatie verandering als leerproces*. Groningen: Wolters-Noordhoff.

Kirwan, B. (1994). *A guide to practical human reliability assessment*. London: Taylor and Francis.

Kirwan, B. (1996). The validation of three human reliability quantification techniques - therp, heart and jhedi: Part 1- technique descriptions and validation issues. *Applied ergonomics*, *27*(6), 359–373.

Kirwan, B., Kennedy, R., Taylor-Adams, S., & Lambert, B. (1997). The validation of three human reliability quantification techniques- therp, heart and jhedi: Part 2 - results of validation exercise. *Applied ergonomics*, *28*(1), 17–25.

Mans, D. G. & Derkink, M. (2009). Faalkosten en constructieve veiligheid: een verkenning naar financiele prikkels om constructieve veiligheid te realiseren. Received from http://www.platformconstructieveveiligheid.nl /upload/documents/ Faalkosten20en20contstructieve20veiligheid.pdf.

Mans, D. G., Rings, L., van den Brand, R., & Derkink, M. (2009). Evaluation of the risk management of structural safety in 15 building projects. In *IABSE Symposium: Sustainable infrastructure - environment friendly, safe and resource efficient*, (pp. 85–93).

Matousek, M. & Schneider, J. (1976). Untersuchungen zur struktur des sicherheitsproblems bei bauwerken. Technical report, Institut fur baustatik und konstruktion ETH Zurich, Zurich.

Melchers, R. E. (1984). Human error in structural reliability assessments. *Reliability engineering*, *7*, 61–75.

Melchers, R. E. (1989). Human error in structural design tasks. *Journal of structural engineering*, *115*(13), 1795–1807.

Melchers, R. E. & Harrington, M. V. (1984). Human error in structural reliability-i: investigation of typical design tasks. Technical report, Monash University, department of Civil Engineering, Australia. Research report No. 2/1984.

Meshkati, N. (1991). Human factors in large-scale technological systems accidents. *Industrial crisis quarterly*, *5*, 131–154.

Mohr, R. R. (1994). Failure modes and effects analysis. Presentation. 8th edition.

NASA (2002). Fault tree analysis. Presentation. NASA Lewis Research Center.

NEN-EN-1990 (2002). *Eurocode - Basis of structural design*. Delft: Nederlands Normalisatie Instituut.

Nowak, A. S. & Carr, R. I. (1985). Sensitivity analysis for structural errors. *Journal of structural engineering*, *111*, 1734–1746.

OED (2012). Oxford english dictionary. digital version.

OVV (2012). Instorten van het dak van de aanbouw van het stadion van fc twente, te enschede. de Onderzoeksraad voor Veiligheid. Received from http://www.onderzoeksraad.nl-docs/rapporten-Rapport-Grolsch-Veste-web-def-260612.pdf.

Priemus, H. & Ale, B. (2010). Construction safety: an analysis of systems failure. the case of the multifunctional bos and lommerplein estate, amsterdam. *Safety Science*, *48*, 111–122.

Reason, J. T. (1990). *Human error*. Cambridge: Cambridge University Press.

Reason, J. T. (2000). *Managing the risks of organizational accidents*. London: Ashgate.

Reason, J. T., Carthey, J., & de Leval, M. R. (2001). Diagnosing 'vulnerable system syndrome': an essential prerequisite to effective risk management. *Quality in Health Care*, *10*(Suppl II), ii21–ii25.

Reiman, T. & Pietikainen, E. (2011). Leading indicators of system safety. monitoring and driving the organizational safety potential. *Safety science*, *50*, 1993–2000.

Rouse, W. B. (1983). Models of human problem solving: detection, diagnosis, and compensation for system failures. *Automatica*, *19*(6), 613–625.

Sanvido, V. E., Khayyal, S. A., Guvenis, M. M., Norton, K. J., Hetrick, M. S., Al-mualllem, M., Chung, E. K., Medeiros, D. J., Kumara, S. R. T., & Ham, I. (1990). An integrated building process model. Technical report, The Pennsylvania State University.

SCIA (2012). *Reference guide, Nemetschek SCIA*. SCIA Engineer. received from http://www.nemetschek-scia.com/webhelp/esa.htm.

Stamatelatos, M. (2000). Probabilistic risk assessment: what is it and why is it worth performing it? NASA office of safety and mission assurance. Received from http:// www.hq.nasa.gov /office/codeq/ qnews/pra.pdf.

Stewart, M. G. (1992a). Modelling human error rates for human reliability analysis of a structural design task. *Reliability engineering and system safety*, *36*, 171–180.

Stewart, M. G. (1992b). Simulation of human error in reinforced concrete design. *Research in engineering design*, *4*, 51–60.

Stewart, M. G. (1993). Structural reliability and error control in reinforced concrete design and construction. *Structural safety*, *12*, 277–292.

Stewart, M. G. & Melchers, R. E. (1988). Checking models in structural design. *Journal of structural engineering*, *115*(6), 1309–1324.

Storbakken, R. (2002). An incident investigation procedure for use in industry. Master's thesis, University of Wisconsin-Stout.

Swain, A. D. (1990). Human reliability analysis: need, status, trends and limitations. *Reliability Engineering and System Safety*, *29*, 301–313.

Swain, A. D. & Guttmann, H. E. (1983). A handbook of human reliability analysis with emphasis on nuclear power plant applications. Technical report, Sandia National Labs, Albuquerque (USA).

USNRC (2009). Three mile island accident. received from http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.pdf. United States Nuclear Regulatory Commission.

Val, D. & Val, E. G. (2006). Robustness of frame structures. *Structural Engineering International*, *2*, 108–112.

van Herwijnen, F. (2009). *Leren van instortingen*. Zoetermeer: Bouwen met staal.

Verschuren, P. & Doorewaard, H. (2007). *Het ontwerpen van een onderzoek*. Den Haag: LEMMA.

Vrouwenvelder, A. C. W. M. (2002). Developments towards full probabilistic design code. *Structural safety*, *24*, 417–432.

Vrouwenvelder, A. C. W. M. (2003). *The plastic behaviour and the calculation of beams and frames subjected to bending*. Technical University Delft. Lecture book.

Vrouwenvelder, A. C. W. M. (2011). Probabilistic modelling of exposure conditions for robustness. In *Taller, Longer, Lighter - Meeting growing demand with limited resources, IABSE-IASS 2011 London Symposium Report*, (pp. 593–602).

Vrouwenvelder, A. C. W. M., Holicky, M., & Sykora, M. (2009). Modelling of human error. Joint workshop of COST actions TU0601 and E55 in Ljubljana (Slovenia).

Walker, A. C. (1981). Study and analysis of the first 120 failure cases. *Structural failure in buildings*.

Williams, J. C. (1986). Heart - a proposed method for assessing and reducing human error. In *Proceedings: 9th advances in reliability technology symposium*, Bradford, United Kingdom. National centre of systems reliability.

Williams, J. C. (1988). A data-based method for assessing and reducing human error to improve operational performance. In *Proceedings of the IEEE 4th conference on human factors in power plants*, Monterey (California). IEEE.

Williams, R. (2009). This one will bring the house down. ICE IStructE HSE SCOSS Prestige Lecture, Institution of Civil Engineers. Received from: http://www.scoss.org.uk/publications/rtf/SC09.039

Part II

APPENDICES

A

SCENARIO IDENTIFICATION

Contents

INTRODUCTION

This appendix consists of four parts. The first part elaborates on the research methodology within the desk research. Within the second part the results of the desk research are presented. The third part represent the Failure Mode and Effect Analysis (FMEA) and the Fault Tree Analysis (FTA) used within this research. Finally a technical drawing of the case study is presented.

DESK RESEARCH METHODOLOGY

Scenario identification is based on analysis of failure information available within the literature. Eight papers which present quantitative information about the types of failures occurring throughout the world are used in this analysis. These papers are selected on the basis of availability and relevance. Some papers were recommended by the thesis supervisors, while others were found by analysing the references of the available papers. These papers are: Boot (2010), ABC-meldpunt (2011), Fruhwald et al. (2007), Matousek & Schneider (1976), Walker (1981), Eldukair & Ayyub (1991), Allen (1979) and Hadipriono (1985). It should be noted that Walker is cited from Fruhwald.

Some of the characteristics of these investigated literature is presented in table 17. From this table it can be seen that the literature is mainly focussing on building structures (in contrast to civil structures). Further more, the researches are conducted from quite recently (2011) to about 35 years ago (1976). Also the type of material differs considerable and the investigated region is worldwide. From this it can be concluded that the investigated literature has quite a broad basis within failures of building structures.

It should be noted that the numbers given in this desk research can only be used as a broad indication, as the number of surveys is limited, the scope of these researches differ and background information is lacking. However they can still be useful in order to select relevant scenarios for further research.

INVESTIGATED ASPECTS

Three research questions are selected for further research:

- *question 1;* What type of error did lead to the failure?
- *question 2;* How could these errors have occurred?
- *question 3;* Which building elements were involved in the failure?

ANALYSIS METHOD QUESTION 1 (ERROR TYPE)

The first research question is: ‘What type of error did lead to the failure? ‘. Analysing this question is performed in several steps. First a list of risks of

Table 17: Characteristics of investigated failure literature

Author	Year	No. of cases	Type of structures	Type of material	Country or Region
Boot	2010	151	Buildings[a]	Various	Netherlands
Nelisse and Dieteren	2011	189	buildings[a]	Various	Netherlands
Fruhwald et al.	2007	127	Buildings	Timber	Scandinavia [c]
Matousek and Schneider	1976	295	Buildings	Various	Europe
Walker[b]	1981	120	Unknown	Unknown	Unknown
Eldukair and Ayyub	1991	604	Various	Various	United States
Allen	1979	188	Various	Concrete	Canada
Hadipriono	1985	150	Various	Various	The world

[a] Mainly buildings, varying from 90 to 95 %
[b] Cited from Fruhwald et al.
[c] Also some worldwide cases.

each activity within the design process is composed. This list is based on the 'design facility' model proposed by Sanvido, Khayyal, Guvenis, Norton, Hetrick, Al-mualllem, Chung, Medeiros, Kumara & Ham (1990), and consists of six main risks which are subsequently subdivided in sub-groups. Secondly each error mentioned in the literature is classified according to this list. Finally the results are analysed with the help of three parameters:

- Numbers of authors which mention the risk category
- Ranking of error categories on sub-group level.
- Ranking of risk categories on main-group level.

Ranking of both the sub- and main categories is based upon a formula depending of the number of authors which mentioned the risk and the corresponding percentages. Ranking varies from 1 for the highest score to 5 or 10 for the lowest score. This formula is given in equation 10.

$$R = N \cdot \sum_{1}^{8} P_i \tag{10}$$

N number of authors which mention the risk category
P_i percentage of cases which mentioned the risk category within each research

There are six main categories identified, which were all mentioned within the literature. There are 36 sub-categories identified, of which 14 categories are mentioned within the literature.

analysis method question 2 (causes of error)

The second research question is: ‘How could these errors have occurred? ’. For analysing this question a slightly different approach is used. The list of risks are not based on the ‘design facility’ model of Sanvido et al. (1990). Instead, the list is composed out of categories mentioned in the eight investigated researches. Ranking of the categories is based on the same formula as presented in the analysis method of question 1 (equation 10). There are 12 categories identified within the literature.

analysis method question 3 (affected elements)

The third research question is: ‘Which building elements were involved in the failure? ’.

The research is based on categorization of building elements which are present within a standard building type, such as an office building. Ranking of the categories is based on equation 10. Within this question 8 categories identified, complemented with a category unknown for cases where no information about the type of affected element was provided.

If ranking was not applied but a percentage of the total number of cases, a slight different order would occur. This is caused by the fact that slabs and plates are not mentioned by Fruhwald et al. (2007), which is quite logical as this research is based on timber structures. However this does not have large consequences for the conclusion.

Type of errors occurring		Boot (2010)		Nelisse & Dieteren		Fruhwald et al. (2007)[a]		Matousek & Schneider (1976)		Walker (1981)[b]		Eldukair & Ayyub (1991)		Allen (1979)[c]		Hadi-priono (1985)		Analyse		
		[No.	%]	[No.	[%]	[No.]	[%]	[No.]	[%]	[No.	[%]	[No.]	[%]	[No.	[%]	[No.	[%]	No. of authors[1]	Ranking sub groups[2]	Ranking main groups[3]
	Number of cases	151		189		127		295		120		604		188		150				
1	**Error in understanding functional requirements**							15	7									1		**5**
1 1 1	Error in analysing information																			
1 1 2	Error in defining requirements and limits																			
1 2 1	Error in selecting Objectives							15	7									1		
1 2 2	Conflicting objectives																			
1 3 1	Insufficient cost, schedules and quality demands																			
1 3 2	Conflicting cost, schedules and quality demands																			
2	**Error in exploring concept**			2	1													1		**4**
2 1 1	Error in design code reviews																			
2 1 2	Conflicting code requirements			2	1													1		
2 2 1	poor investigation of different system types																			
2 2 2	Poor investigation of material types																			
2 3 1	Poor concept coordination																			
2 4 1	Wrong selection of concepts																			
3	**Error in System's schematics**	33	38					134	50					9	5			3		**3**
3 1 1	Error in structural/mechanical system choice	33	38					100	34									2	3	
3 1 2	Error in technical parameters (ground etc.,)							34	16					9	5			2	8	
3 2 1	Poor coordination on system's schematics																			
3 2 2	Conflicts within system's schematics																			
3 3 1	Poor documentation of coordinated schemes																			
3 4 1	Poor selection of system's schematics																			
4	**Error in design (in general)**	46	53	91	48	90 d	71	100	34	60	50	299	50	103	55	43	29	8		**1**
4 1 1	Error in material selection																			
4 1 2	Error in analysing quality/quantity material			2	1									3	2			2		

Type of errors occurring	Boot (2010)		Nelisse & Dieteren		Fruhwald et al. (2007)[a]		Matousek & Schneider (1976)		Walker (1981)[b]		Eldukair & Ayyub (1991)		Allen (1979)[c]		Hadi-priono (1985)		Analyse		
	[No.	[%]	[No.	[%]	[No.]	[%]	[No.]	[%]	[No.	[%]	[No.]	[%]	[No.	[%]	[No.	[%]	No. of authors[1]	Ranking sub groups[2]	Ranking main groups[3]
4 2 1 Calculation error	46	53	3	2					8	7	15	3	2	1			5	2	
4 2 2 Error in determining loading scenarios			20	11									22	12			2	7	
4 2 3 Error in mechanical schematization/force balance			45	24					52	43	284	47	27	14			4	1	
4 2 4 No calculation update or missing/error in detailed calculation			3	2									25	13	15	10	3	6	
4 3 1 Error in calculation documentation																			
4 4 1 Design does not meet code requirements			18	10									1	1			2	10	
4 4 2 Design does not meet owner requirements																			
5 Error in communicating design to others	7	8	22	12			56	19	11	9	274	45					5		**2**
5 1 1 Error in drawing (wrong measurements etc.)	7	8	5	3			56	19									3	5	
5 2 1 Error in defining contract responsibilities											142	24					1	9	
5 3 1 Error in document coordination among disciplines			17	9					11	9	132	22					3	4	
5 4 1 Insufficient Regulatory control on design																			
6 Error in maintaining design information / models									5	4							1		
6 1 1 Error in data collection																			
6 2 1 Data storage error																			
6 3 1 Insufficient awareness of available knowledge																			
6 4 1 Error in updating information																			
6 5 1 Error in information delivery									5	4							1		

Legend:

[a] Only timber structures considered.

[b] Cited from Fruhwald et al. (2007).

[c] the groups 'bridge decks and pile or pier are left outside this table.

[d] Sum of the failure categories Design (mechanical loading) and Design (environmental loading), respectively 54,3 and 16,5 percent of the failures,

[1] The number of authors which identified the concerned risk as a cause of failure (N)

[2] and [3] Ranking based on N · ∑ Pi. Pi is percentage of errors in the considered case in which the type of error occurred.

Scaling from 1 (most important) to 5 or 10 (less important)

	Causes of errors	Boot (2010)		Nelisse & Dieteren		Fruhwald et al. (2007)[a]		Matousek & Schneider (1976)		Walker (1981)[b]		Eldukair & Ayyub (1991)		Allen (1979)[c]		Hadi-priono (1985)		Analysis		
		[No.	%]	[No.	%]	[No.]	[%]	[No.]	[%]	[No.	%]	[No.]	[%]	[No.	%]	[No.	%]	No. of authors [1]	Percentage[2]	Ranking groups[3]
	Number of cases	151		189		127		295		120		604		188		150				
1	Communication errors	12	48									224	37					2	12,9	3
2	Insufficient task division/overview			20	11							199	33					2	12,0	4
3	Lack of authority/guidance											274	45					1	15,0	7
4	Reliance on other parties							21	10			175	29					2	10,8	5
5	Insufficient knowledge/education/qualification	3	12	53	28			76	36			403	67					4	29,3	1
6	Insufficient time	2	8	1	1													2	0,2	10
7	Ignorance	2	8					30	14			495	82					3	28,9	2
8	Mistakes / lapses /slips							28	13									1	1,5	
9	Underestimation (of for instance influences											436	72					1	23,9	6
10	Frugality	5	20					2	1									2	0,4	8
11	Error in software			9	5													1	0,5	
12	Unknown situations											201	33					1	11,0	9
13	Unknown																			

Legend:

[a] Only timber structures considered.

[b] Cited from Fruhwald et al. (2007).

[c] the groups 'bridge decks and pile or pier are left outside this table.

[1] The number of authors which identified the concerned risk as a cause of failure (N)

[2] and [3] Ranking based on $N \cdot \sum Pi$. Pi is percentage of errors in the considered case in which the type of error occurred.
Scaling from 1 (most important) to 5 or 10 (less important)

	Building elements affected by error	Boot (2010)		Nelisse & Dieteren (2011)		Fruhwald et al. (2007)[a]		Matousek & Schneider (1976)		Walker (1981)[b]		Eldukair & Ayyub (1991)		Allen (1979)[c]		Hadipriono (1985)		Analyse		
		[No.]	[%]	[No.]	[%]	[No.]	[%]	[No.]	[%]	[No.]	[%]	[No.]	[%]	[No.]	[%]	[No.]	[%]	No. of authors [1]	Percentage[2]	Ranking main groups[3]
	Number of cases	151		189		127		295		120		604		188		150				
1	**Foundation (soil, raft footings)**	20	13	44	23							37	6	13	7			4	9,0	**4**
1 1	Foundation pile			9	5													1	0,7	
1 2	Foundation beam			12	6													1	1,0	
1 3	Strip footing			3	2													1	0,2	
2	**Vertical elements**	22	15	43	23	5	4					64	11	18	10			5	12,1	**3**
2 1	columns	1	1	23 [d]	12	5	4							10	5			4	3,1	
2 2	piles																			
2 3	walls	21	14	20 [d]	11									8	4			3	3,9	
3	**Beams and trusses**	10	7	25	13	116	91					65	11	23	12			5	19,0	**1**
3 1	Beams	7	5	25 [d]	13	60	47							23	12			4	9,1	
3 2	Trusses	3	2			43	34											2	3,7	
3 3	Frames & Arches					13	10											1	1,0	
4	**Slabs and plates**	17	11	49 [d]	26							206	34	41	22			4	24,9	**2**
5	**Stability elements**			30	16	37	29											2	5,3	
5 1	Bracings			3	2	37	29											2	3,2	
5 2	Stability construction			27 [d]	14													1	2,1	
6	**Roof structures**	27	18	9	5													2	2,9	
7	**Connections**	3	2			29	23					53	8,8	28	15			4	9,0	**5**
8	**Finishing structures**	27	18	12 [d]	6													2	3,1	
9	**Unknown**	23	15	9 [d]	5							204	34					3	18,8	

Legend:

[a] Only timber structures considered.

[c] the groups 'bridge decks and pile or pier are left outside this table.

[d] Subdivision within research is altered for use in this report.

[1] The number of authors which identified the concerned risk as a cause of failure (N)

[2] The percentage of cases which mentioned the error as a function of the total number of cases

[2] and [3] Ranking based on $N \cdot \sum Pi$. Pi is percentage of errors in the considered case in which the type of error occurred.

System: Office building
Phase: Design
type: Explorative FMEA

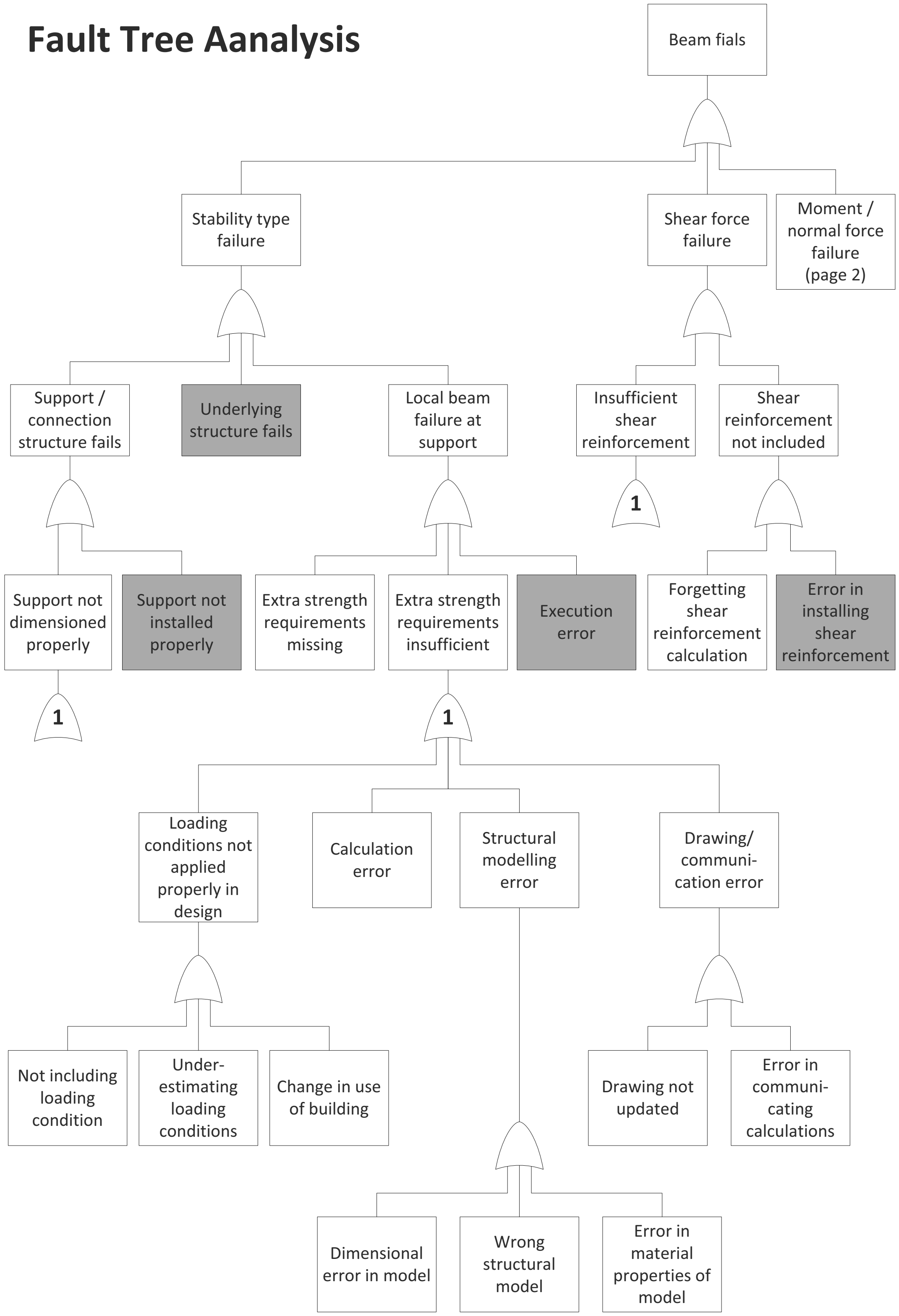
Failure Mode & Effect Analysis

No.	item	Failure mode	Failure cause	Failure effect	Prob. of occurrence[1]	Severity[2]	Detection[3]	Risk priority
1	Beam elements	Beam fails	Incorrect design	Element collapse	3	3	3	27
2			Design (partly) omitted		1	3	2	6
3		Insufficient beam strength	Incorrect design	Strong deformations/ vibrations	4	2	3	24
4			Design (partly) omitted		2	2	2	8
5	B/C joints	Joint fails	Incorrect design	Element collapse	3	3	3	27
6			Design (partly) omitted		1	3	2	6
7	Column elements	Column fails	Incorrect design	Element collapse	3	3	3	27
8			Design (partly) omitted		1	3	2	6
9	Slab elements	Slab fails	Incorrect design	Element collapse	3	3	3	27
10			Design (partly) omitted		1	3	2	6
11		Insufficient slab strength	Incorrect design	Strong deformations/ vibrations	4	2	3	24
12			Design (partly) omitted		2	2	2	8
13	Stability core	Stability core fails	Incorrect design	Overall structural collapse	2	5	2	20
14			Design (partly) omitted		1	5	1	5
15		Insufficient strength stab. core	Incorrect design	Strong deformations/ vibrations	4	2	3	24
16			Design (partly) omitted		2	2	2	8
17	Overall integrity	Progressive collapse structure	Incorrect design	Progressive collapse	2	5	3	30
18			Insufficient coordination		2	5	3	30
19			Design (partly) omitted		2	5	2	20
20	Façade	Façade fails	Incorrect design	Element collapse	3	3	2	18
21			Design (partly) omitted		2	3	2	12

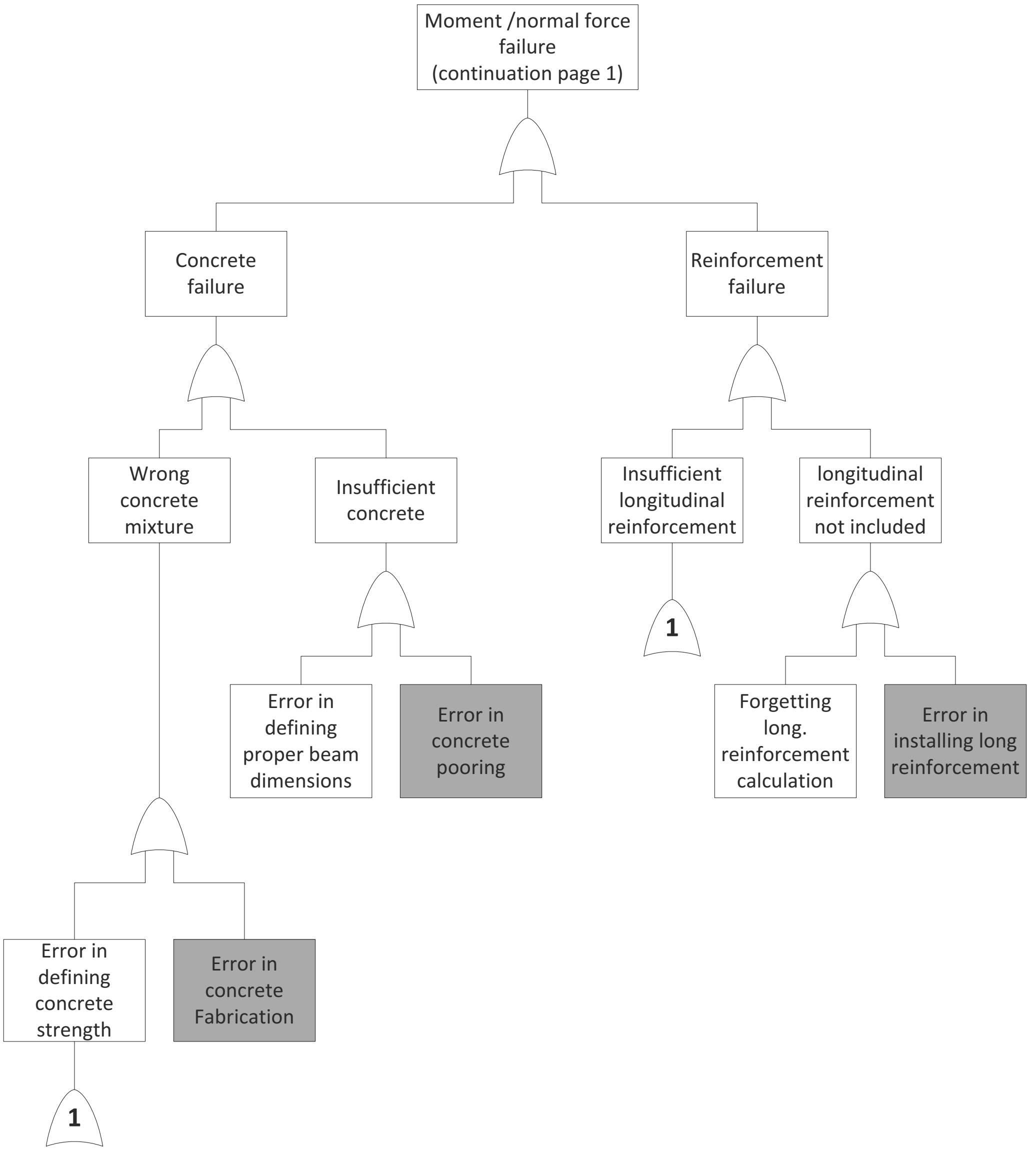
[1] Ranked from 1 (low probability of occurrence) to 5 (high probability of occurrence)
[2] Ranked from 1 (low severity) to 5 (high severity)
[3] Ranked from 1 (high possibility of detection) to 5 (low possibility of detection)

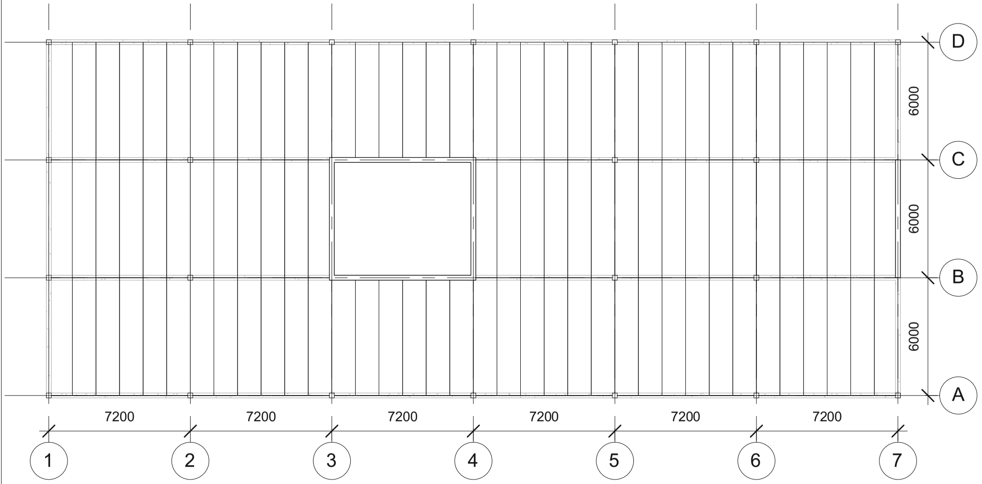
Extra notes:
[4] Coordination failure within detailed design is not considered
[5] Deliberate design errors are left outside the scope

Fault Tree Aanalysis

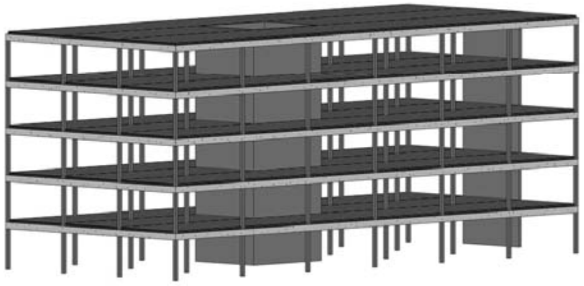


Fault Tree Aanalysis

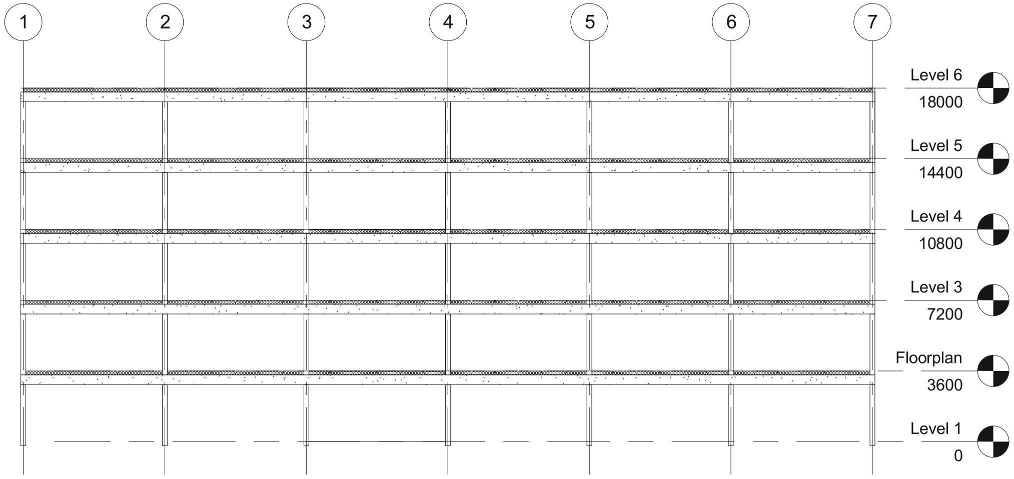




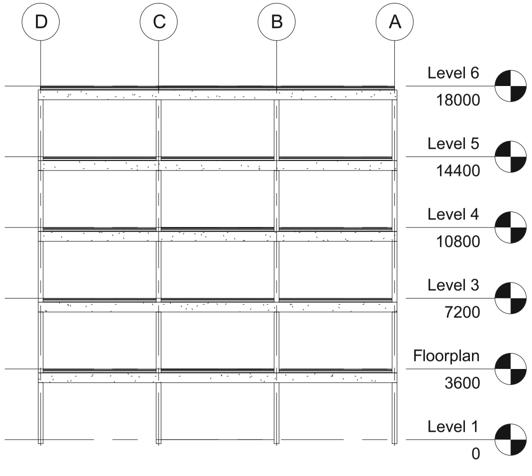
Floorplan



Isometry 2



Front view



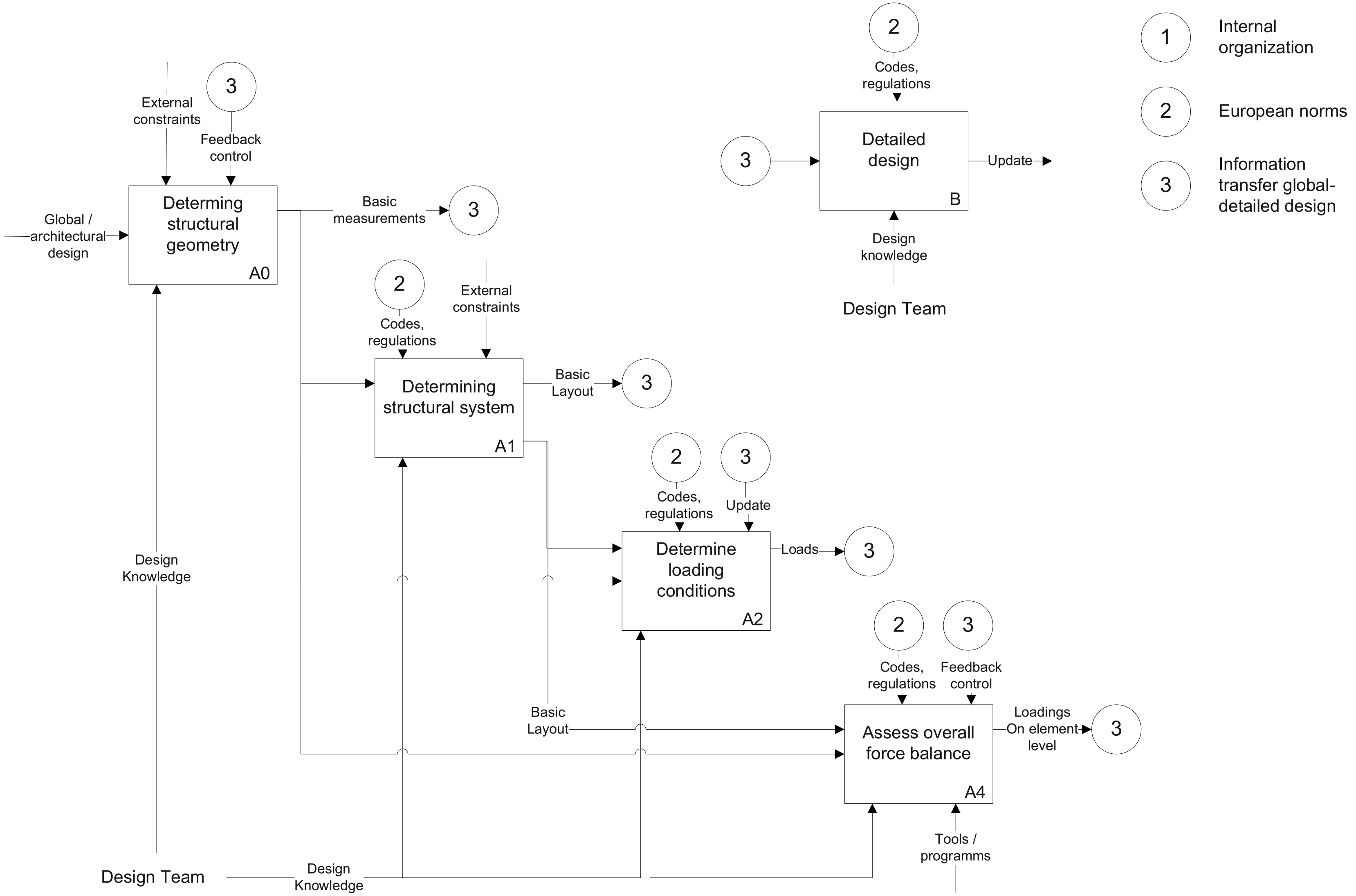
Right view

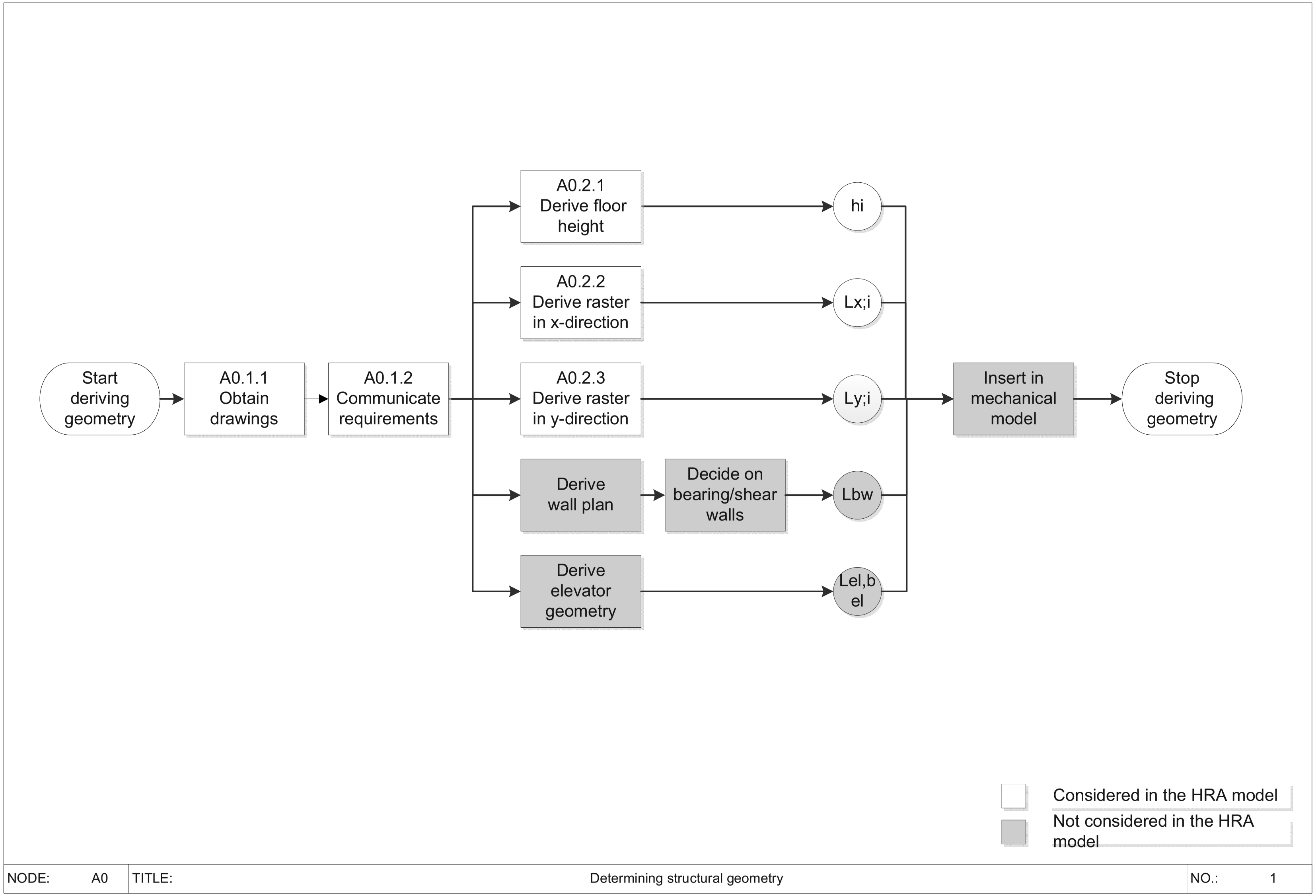
B

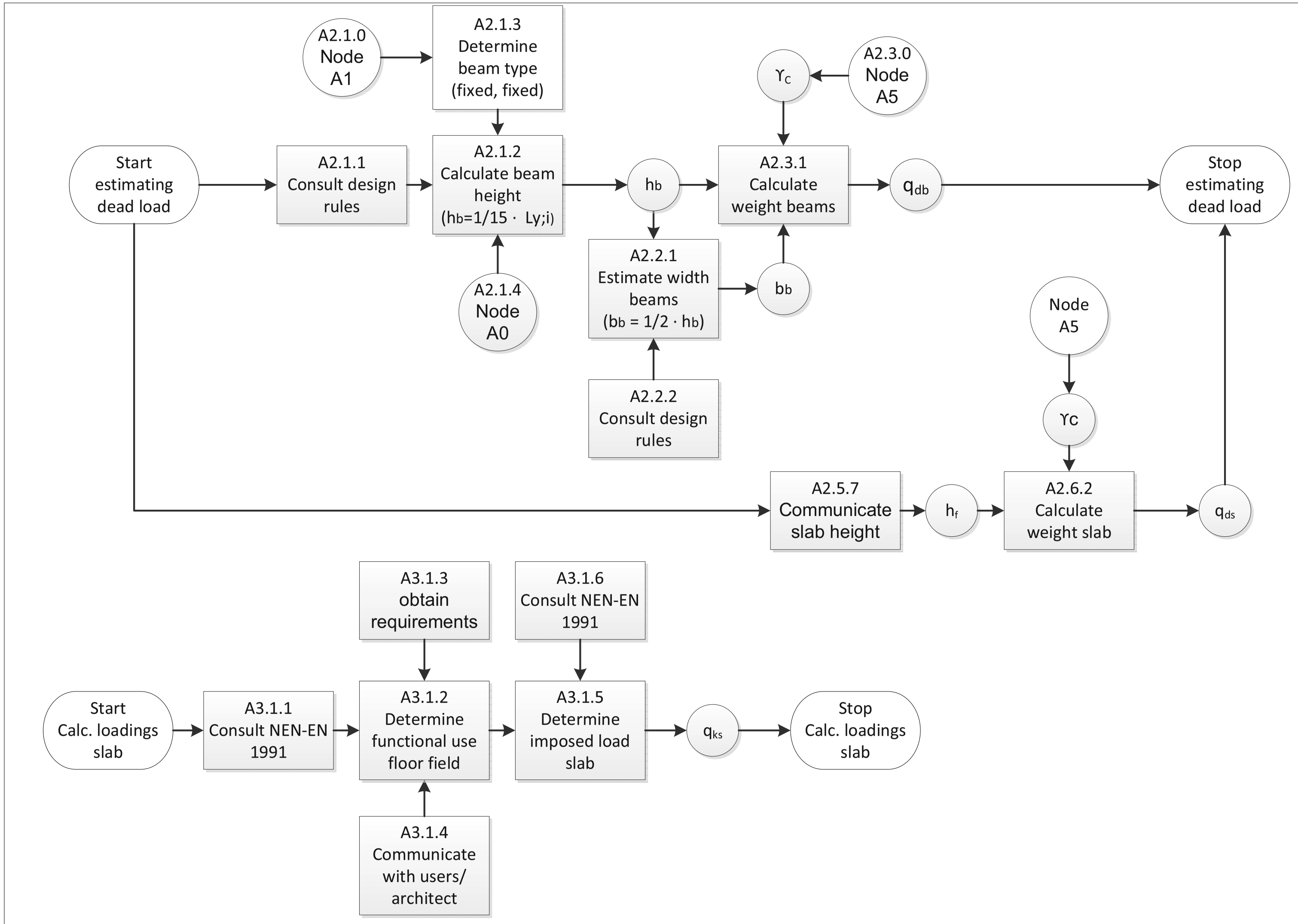
DESIGN PROCESS

Contents

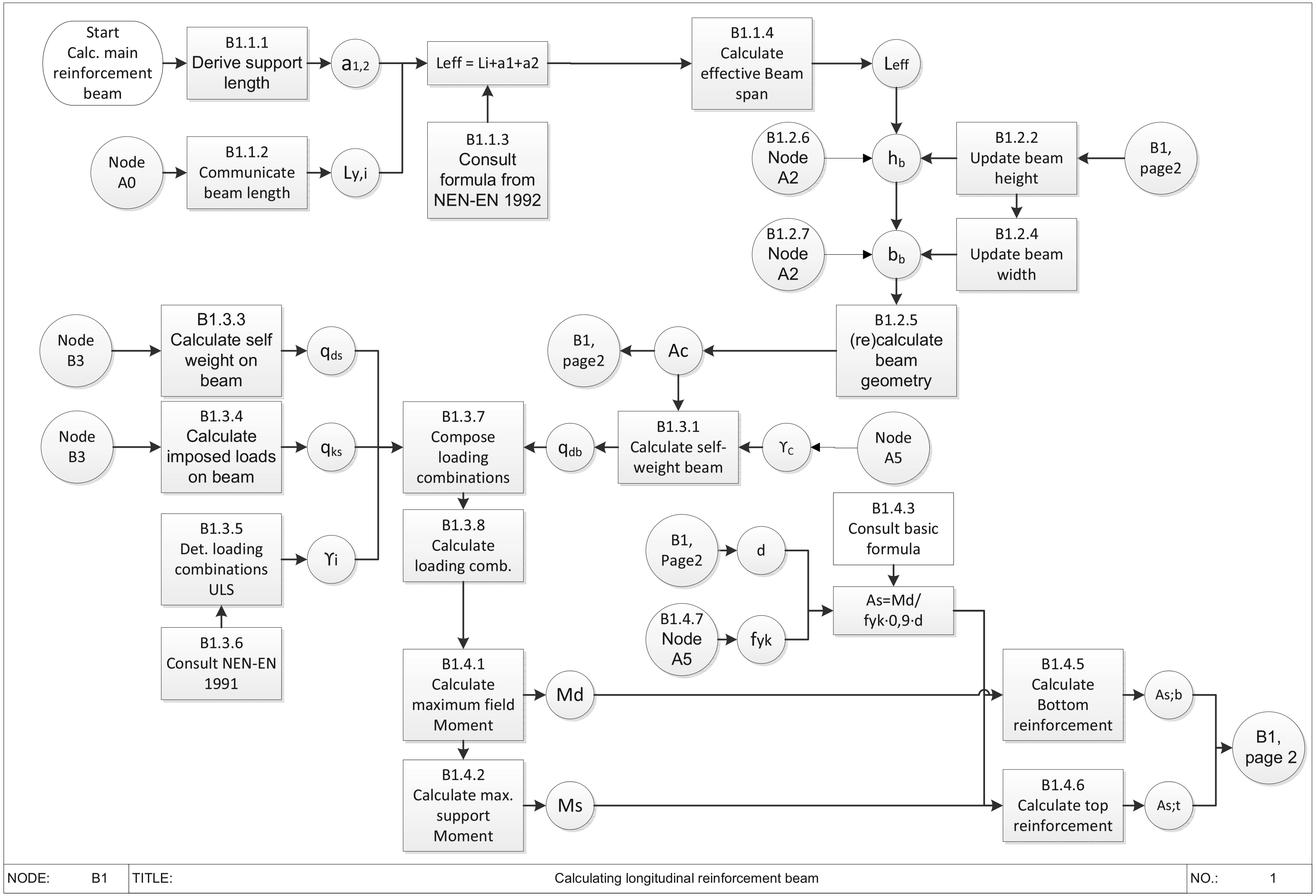
Global design (abbreviated)

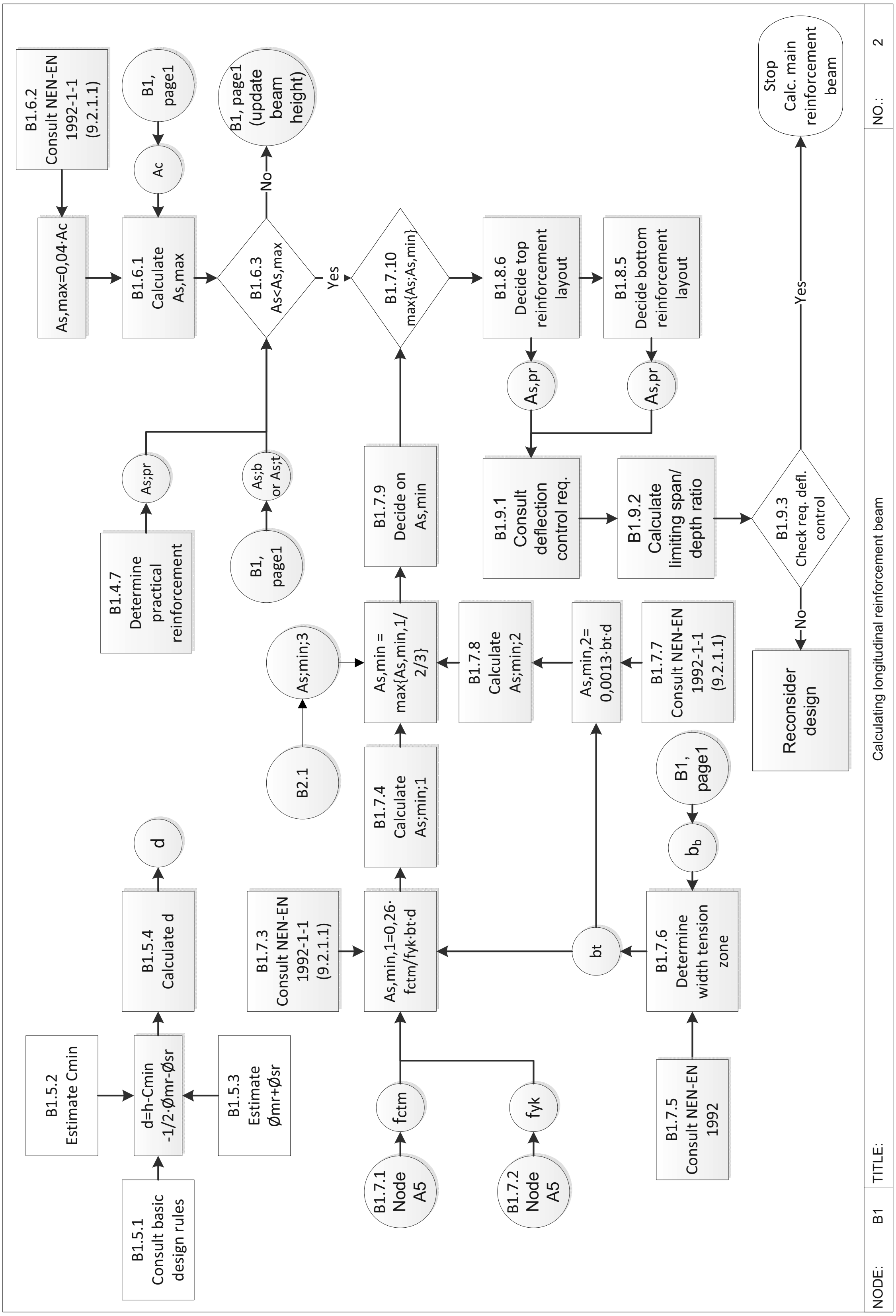


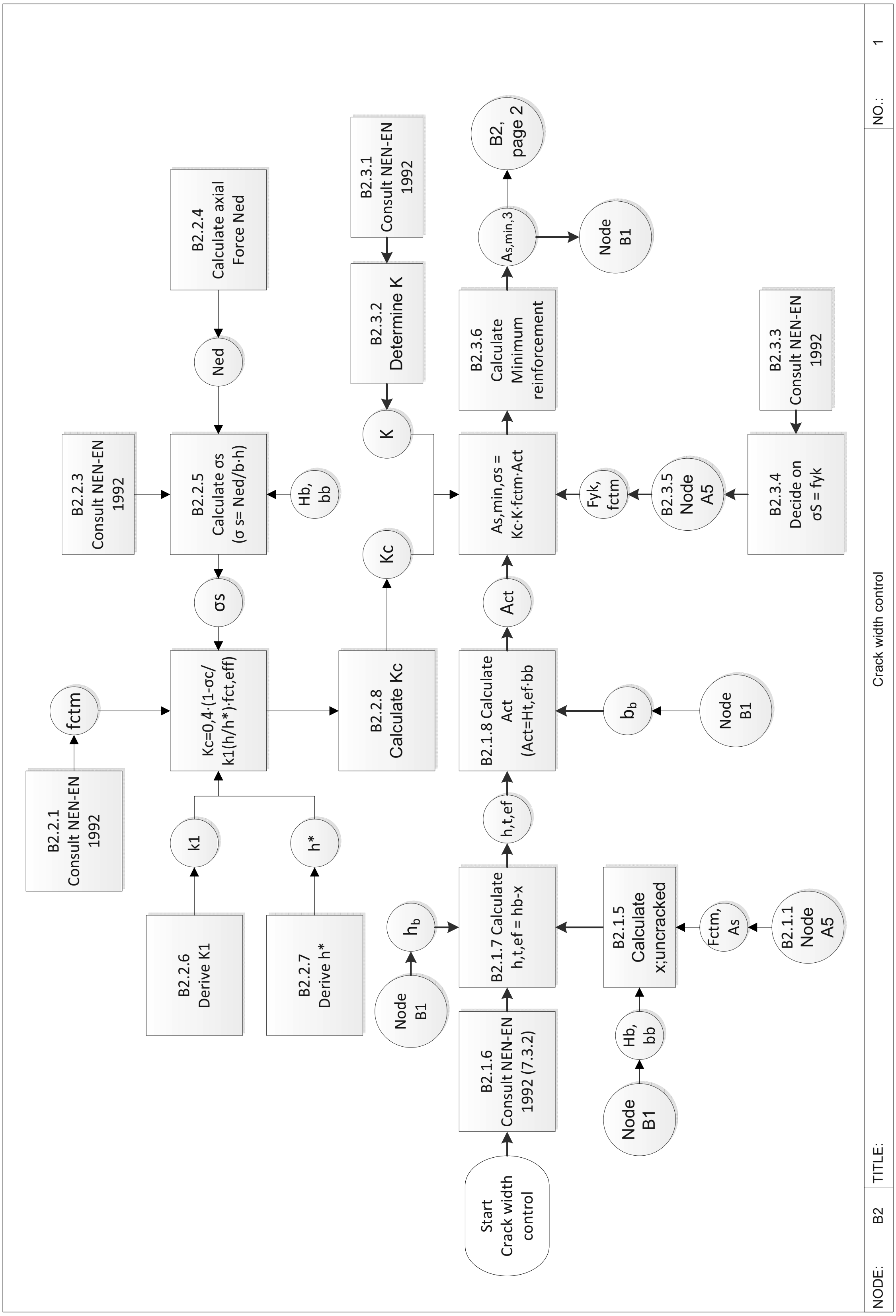

Start deriving geometry
A0.1.1 Obtain drawings
A0.1.2 Communicate requirements
A0.2.1 Derive floor height
A0.2.2 Derive raster in x-direction
A0.2.3 Derive raster in y-direction
Derive wall plan
Decide on bearing/shear walls
Derive elevator geometry
hi
Lx;i
Ly;i
Lbw
Lel,bel
Insert in mechanical model
Stop deriving geometry
Considered in the HRA model
Not considered in the HRA model
NODE: A0
TITLE: Determining structural geometry
NO.: 1

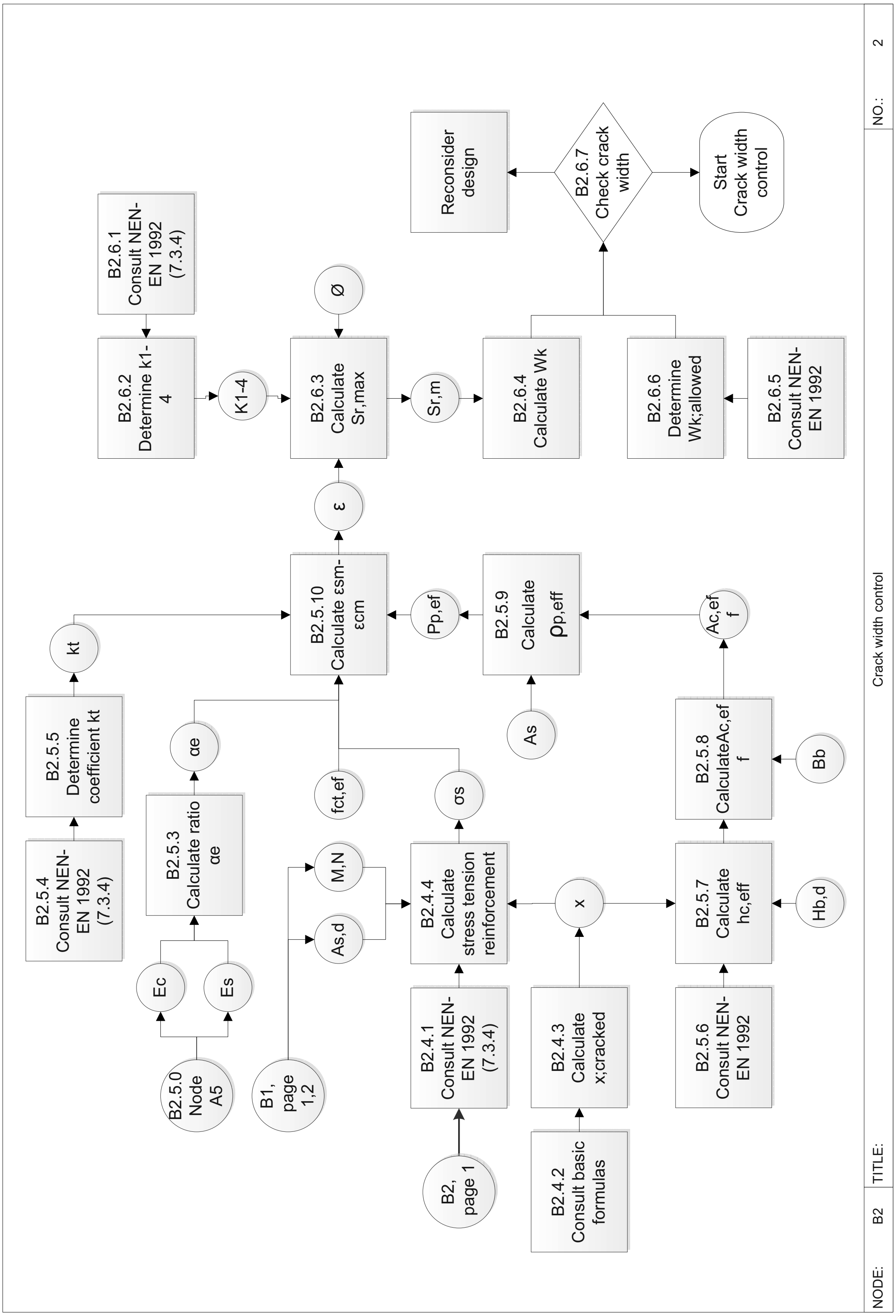


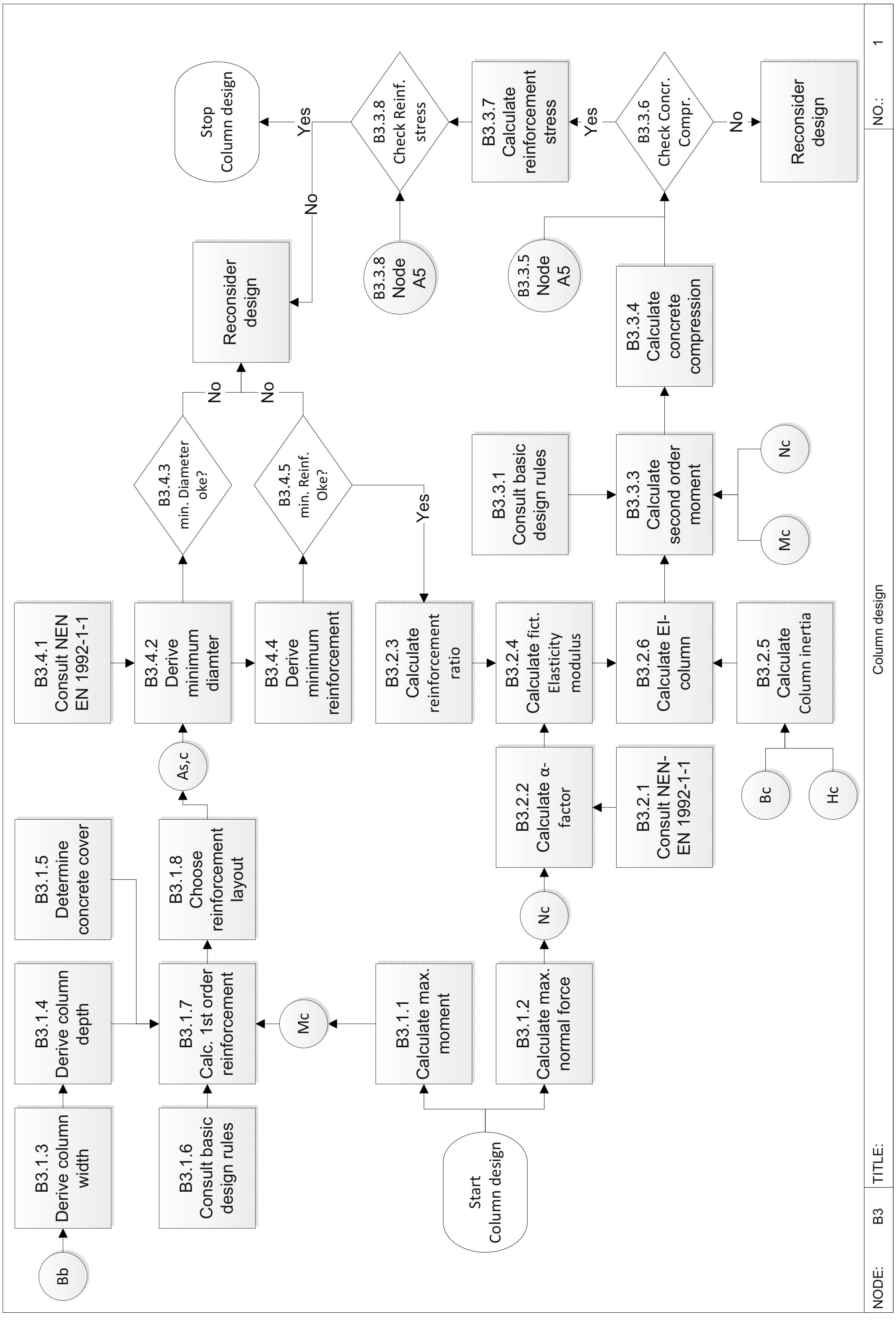
NODE:	A2	TITLE:	Determine distributed loads	NO.:	1

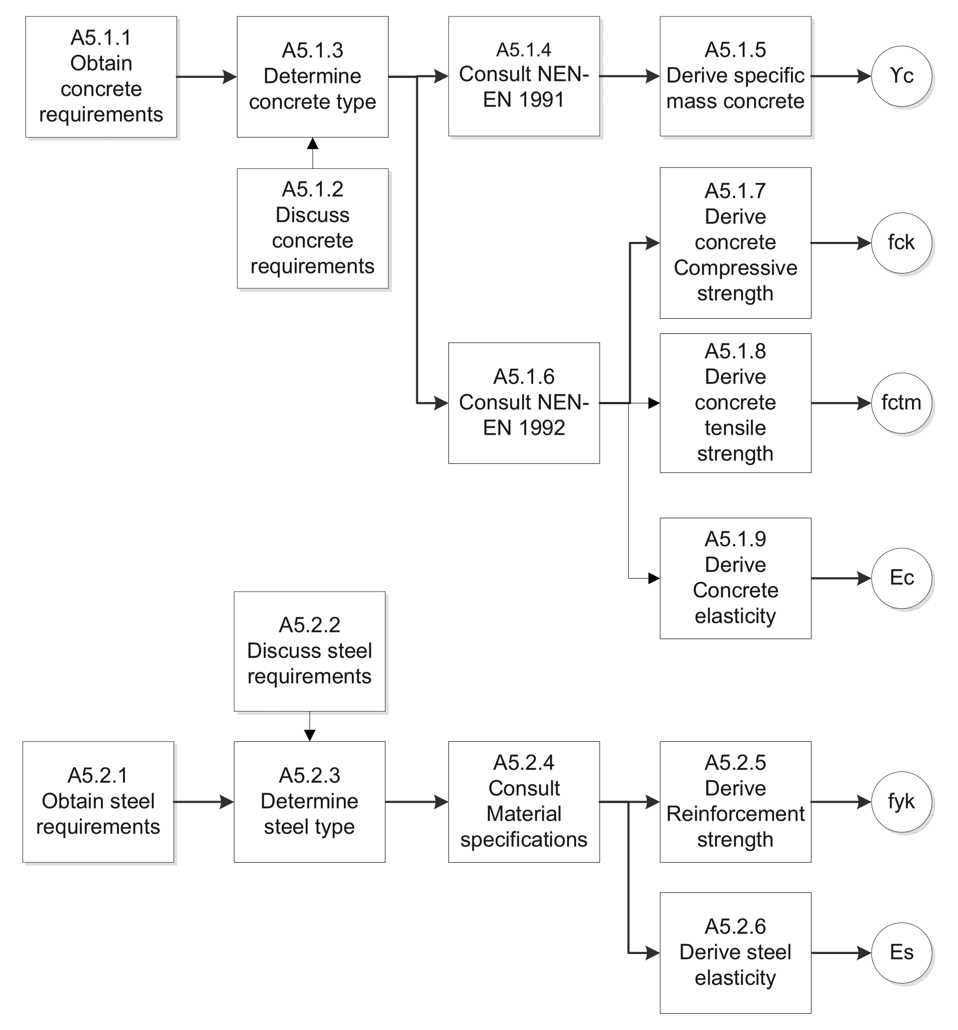

Start
Calc. main reinforcement beam
B1.1.1 Derive support length
$a_{1,2}$
Node A0
B1.1.2 Communicate beam length
Ly,i
Leff = Li+a1+a2
B1.1.3 Consult formula from NEN-EN 1992
B1.1.4 Calculate effective Beam span
Leff
B1.2.6 Node A2
h_b
B1.2.2 Update beam height
B1, page2
B1.2.7 Node A2
b_b
B1.2.4 Update beam width
B1.2.5 (re)calculate beam geometry
B1, page2
Ac
Node B3
B1.3.3 Calculate self weight on beam
q_{ds}
Node B3
B1.3.4 Calculate imposed loads on beam
q_{ks}
B1.3.7 Compose loading combinations
q_{db}
B1.3.1 Calculate self-weight beam
γ_c
Node A5
B1.3.5 Det. loading combinations ULS
γ_i
B1.3.8 Calculate loading comb.
B1.3.6 Consult NEN-EN 1991
B1, Page2
d
B1.4.3 Consult basic formula
B1.4.7 Node A5
fyk
As=Md/ fyk·0,9·d
B1.4.1 Calculate maximum field Moment
Md
B1.4.5 Calculate Bottom reinforcement
As;b
B1, page 2
B1.4.2 Calculate max. support Moment
Ms
B1.4.6 Calculate top reinforcement
As;t
NODE: B1
TITLE: Calculating longitudinal reinforcement beam
NO.: 1


B1.5.1 Consult basic design rules
B1.5.2 Estimate Cmin
d=h-Cmin -1/2·Ømr-Øsr
B1.5.3 Estimate Ømr+Øsr
B1.5.4 Calculate d
d
B1.7.1 Node A5
fctm
B1.7.2 Node A5
fyk
B1.7.3 Consult NEN-EN 1992-1-1 (9.2.1.1)
As,min,1=0,26·fctm/fyk·bt·d
B1.7.4 Calculate As;min;1
B1.7.5 Consult NEN-EN 1992
B1.7.6 Determine width tension zone
bt
B1, page1
bb
B2.1
As;min;3
As,min = max{As,min,1/2/3}
B1.7.8 Calculate As;min;2
As,min,2= 0,0013·bt·d
B1.7.7 Consult NEN-EN 1992-1-1 (9.2.1.1)
Reconsider design
B1.4.7 Determine practical reinforcement
As;pr
B1, page1
As;b or As;t
B1.7.9 Decide on As,min
B1.9.1 Consult deflection control req.
B1.9.2 Calculate limiting span/ depth ratio
B1.9.3 Check req. defl. control
No
Yes
B1.6.2 Consult NEN-EN 1992-1-1 (9.2.1.1)
As,max=0,04·Ac
B1, page1
Ac
B1.6.1 Calculate As,max
B1.6.3 As<As,max
No
B1, page1 (update beam height)
Yes
B1.7.10 max{As;As,min}
B1.8.6 Decide top reinforcement layout
B1.8.5 Decide bottom reinforcement layout
As,pr
As,pr
Stop Calc. main reinforcement beam
NODE:
B1
TITLE:
Calculating longitudinal reinforcement beam
NO.:
2


NODE: B2
TITLE: Crack width control
NO.: 1
Start Crack width control
B2.1.6 Consult NEN-EN 1992 (7.3.2)
B2.1.7 Calculate h,t,ef = hb-x
Node B1
h_b
B2.1.5 Calculate x;uncracked
Node B1
Hb, bb
Fctm, As
B2.1.1 Node A5
h,t,ef
B2.1.8 Calculate Act (Act=Ht,ef·bb
b_b
Node B1
Act
As,min,σs = Kc·K·fctm·Act
Fyk, fctm
B2.3.5 Node A5
B2.3.4 Decide on σS = fyk
B2.3.3 Consult NEN-EN 1992
B2.3.6 Calculate Minimum reinforcement
As,min,3
Node B1
B2, page 2
B2.3.1 Consult NEN-EN 1992
B2.3.2 Determine K
K
Kc
B2.2.8 Calculate Kc
B2.2.1 Consult NEN-EN 1992
fctm
Kc=0,4·(1-σc/ k1(h/h*)·fct,eff)
B2.2.6 Derive K1
k1
B2.2.7 Derive h*
h*
σS
B2.2.3 Consult NEN-EN 1992
B2.2.5 Calculate σs (σ s= Ned/b·h)
Hb, bb
Ned
B2.2.4 Calculate axial Force Ned


NODE: B2
TITLE: Crack width control
NO.: 2
B2, page 1
B2.4.1 Consult NEN-EN 1992 (7.3.4)
B2.4.2 Consult basic formulas
B2.4.3 Calculate x;cracked
B2.4.4 Calculate stress tension reinforcement
x
B1, page 1,2
As,d
M,N
σs
fct,ef
B2.5.0 Node A5
Ec
Es
B2.5.3 Calculate ratio αe
αe
B2.5.4 Consult NEN-EN 1992 (7.3.4)
B2.5.5 Determine coefficient kt
kt
B2.5.6 Consult NEN-EN 1992
B2.5.7 Calculate hc,eff
Hb,d
B2.5.8 CalculateAc,eff
Bb
Ac,eff
As
B2.5.9 Calculate ρp,eff
Pp,ef
B2.5.10 Calculate εsm-εcm
ε
B2.6.1 Consult NEN-EN 1992 (7.3.4)
B2.6.2 Determine k1-4
K1-4
B2.6.3 Calculate Sr,max
Ø
Sr,m
B2.6.4 Calculate Wk
B2.6.5 Consult NEN-EN 1992
B2.6.6 Determine Wk;allowed
B2.6.7 Check crack width
Reconsider design
Start Crack width control


Start
Column design
B3.1.1
Calculate max.
moment
B3.1.2
Calculate max.
normal force
Mc
Nc
B3.1.3
Derive column
width
Bb
B3.1.4
Derive column
depth
B3.1.5
Determine
concrete cover
B3.1.6
Consult basic
design rules
B3.1.7
Calc. 1st order
reinforcement
B3.1.8
Choose
reinforcement
layout
As,c
B3.4.1
Consult NEN
EN 1992-1-1
B3.4.2
Derive
minimum
diamter
B3.4.3
min. Diameter
oke?
B3.4.4
Derive
minimum
reinforcement
B3.4.5
min. Reinf.
Oke?
No
No
Yes
Reconsider
design
B3.2.1
Consult NEN-
EN 1992-1-1
B3.2.2
Calculate α-
factor
B3.2.3
Calculate
reinforcement
ratio
B3.2.4
Calculate fict.
Elasticity
modulus
B3.2.5
Calculate
Column inertia
Bc
Hc
B3.2.6
Calculate EI-
column
B3.3.1
Consult basic
design rules
B3.3.3
Calculate
second order
moment
Mc
Nc
B3.3.4
Calculate
concrete
compression
B3.3.5
Node
A5
B3.3.6
Check Concr.
Compr.
No
Reconsider
design
Yes
B3.3.7
Calculate
reinforcement
stress
B3.3.8
Check Reinf.
stress
B3.3.8
Node
A5
Yes
Stop
Column design
No
Reconsider
design
NODE:
B3
TITLE:
Column design
NO.:
1



NODE:	A5	TITLE:	Determine material characteristics	NO.:	1

C

EXTENDED HEP METHOD

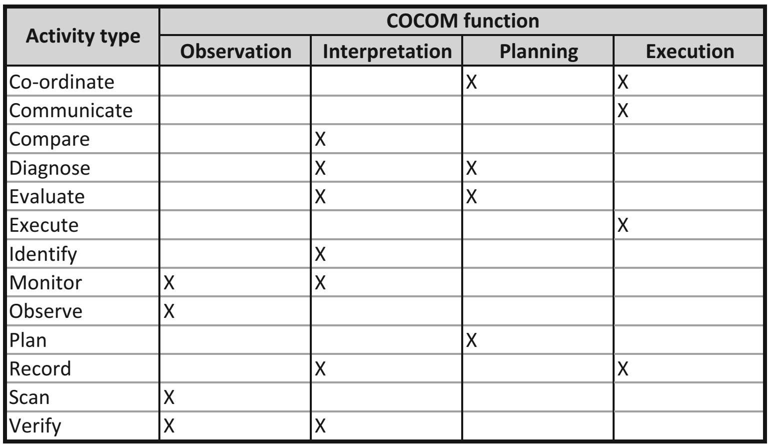
Contents

Within this appendix the classification diagrams used within the extended HEP-method are set-apart. These diagrams are obtained from Hollnagel (1998, chapter 9). The list of characteristic cognitive activities is shown in table 18. This list is a altered version of the list of characteristic cognitive activities presented by the CREAM method. This alteration was deemed necessary in order to adapt the model for structural design tasks. The actual cognitive demand profile is based on a table of the cognitive functions associated with each of the cognitive activities (the cognitive activity by cognitive demand profile). This is shown in figure 43. The second step of the CREAM method is to identify the likely Cognitive Function Failures (CFF). These function failures are presented in figure 44. The accompanying nominal values (NEP) for each cognitive function failure is presented in figure 45. The third step is to assess the effects of Common Performance Conditions (CPC) on the NEP values. Appropriate weighting factors for all cognitive function failures are defined in figure 46.

Table 18: List of critical cognitive activities. Based on the table presented by Hollnagel (1998) on page 246.

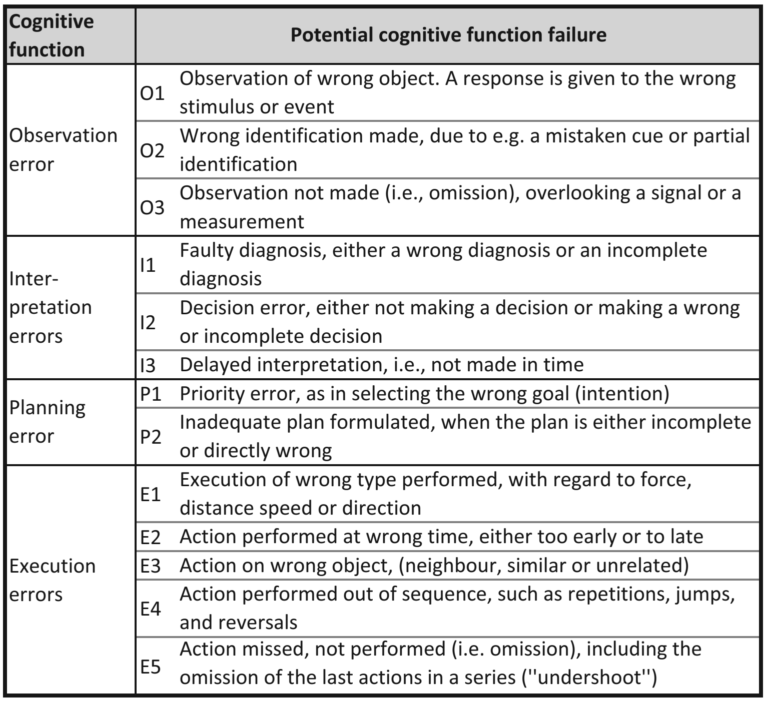
Cognitive activity	General definition
Coordinate	Bring design state and/or control configurations into the specific relation required to carry out a task or task step. Allocate or select resources in preparation for a task/job, etc.
Communicate	Pass on or receive person-to-person information needed for system operation by either verbal, electronic or mechanical means. Communication is an essential part of management.
Compare	Examine the qualities of two or more entities (measurements) with the aim of discovering similarities or differences. The comparison may require calculation.
Diagnose	Recognise or determine the nature or cause of a condition by means of reasoning about signs or symptoms or by the performance of appropriate tests. “diagnose“ is more thorough than “identify“.
Evaluate	Appraise or assess an actual or hypothetical situation, based on available information without requiring special operations. Related terms are “inspect“ and “check“.
Execute	Perform a previously specified action or plan.
Identify	Establish the state of a design or sub-design. This may involve specific operations to retrieve information and investigate details. “identify“ is more thorough than “evaluate“.
Monitor	Keep track of the design process, or follow the development of a set of parameters
Observe	Read specific design information or check specific design indicators.
Plan	Formulate or organise a set of actions by which a goal will be successfully achieved. Plans may be short term or long term.
Record	Write down design parameters, measurements, etc.
Scan	Quick or speedy review of information sources in order to obtain a general idea of the design action.
Verify	Confirm the correctness of a design parameter by inspection or test.

Figure 43: Cognitive-activity-by-cognitive-demand matrix. Based on the table presented by Hollnagel (1998) on page 248.



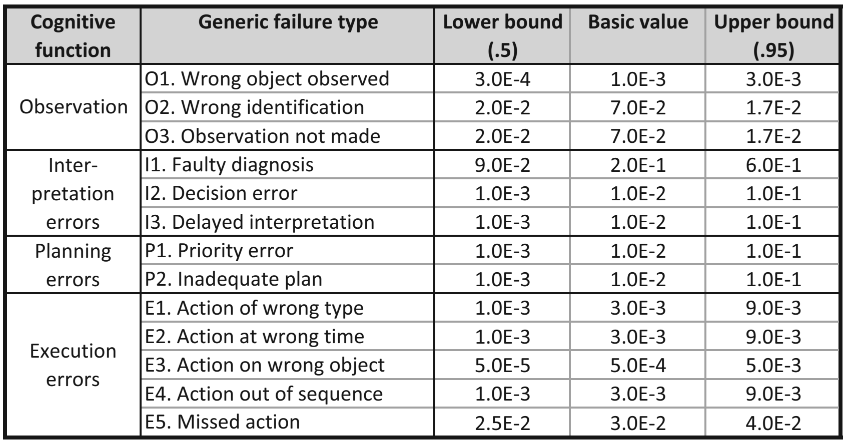
Activity type	COCOM function			
	Observation	Interpretation	Planning	Execution
Co-ordinate			X	X
Communicate				X
Compare		X		
Diagnose		X	X	
Evaluate		X	X	
Execute				X
Identify		X		
Monitor	X	X		
Observe	X			
Plan			X	
Record		X		X
Scan	X			
Verify	X	X		

Figure 44: Generic Cognitive Function Failures (CFF). (Hollnagel, 1998, page 250)



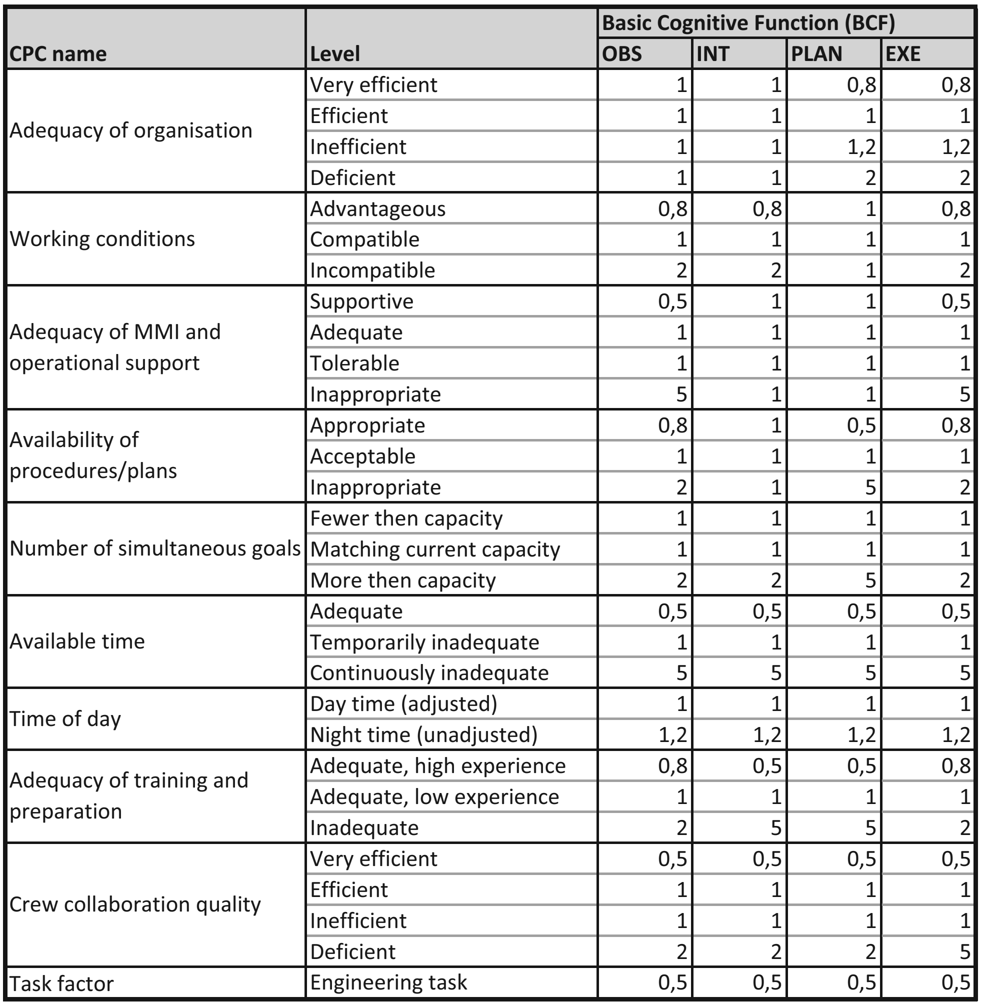
Cognitive function	Potential cognitive function failure	
Observation error	O1	Observation of wrong object. A response is given to the wrong stimulus or event
	O2	Wrong identification made, due to e.g. a mistaken cue or partial identification
	O3	Observation not made (i.e., omission), overlooking a signal or a measurement
Inter-pretation errors	I1	Faulty diagnosis, either a wrong diagnosis or an incomplete diagnosis
	I2	Decision error, either not making a decision or making a wrong or incomplete decision
	I3	Delayed interpretation, i.e., not made in time
Planning error	P1	Priority error, as in selecting the wrong goal (intention)
	P2	Inadequate plan formulated, when the plan is either incomplete or directly wrong
Execution errors	E1	Execution of wrong type performed, with regard to force, distance speed or direction
	E2	Action performed at wrong time, either too early or to late
	E3	Action on wrong object, (neighbour, similar or unrelated)
	E4	Action performed out of sequence, such as repetitions, jumps, and reversals
	E5	Action missed, not performed (i.e. omission), including the omission of the last actions in a series (''undershoot'')

Figure 45: Nominal values (NEP) and uncertainty bounds for cognitive function failures (Hollnagel, 1998, page 252)



Cognitive function	**Generic failure type**	**Lower bound (.5)**	**Basic value**	**Upper bound (.95)**
Observation	O1. Wrong object observed	3.0E-4	1.0E-3	3.0E-3
	O2. Wrong identification	2.0E-2	7.0E-2	1.7E-2
	O3. Observation not made	2.0E-2	7.0E-2	1.7E-2
Inter-pretation errors	I1. Faulty diagnosis	9.0E-2	2.0E-1	6.0E-1
	I2. Decision error	1.0E-3	1.0E-2	1.0E-1
	I3. Delayed interpretation	1.0E-3	1.0E-2	1.0E-1
Planning errors	P1. Priority error	1.0E-3	1.0E-2	1.0E-1
	P2. Inadequate plan	1.0E-3	1.0E-2	1.0E-1
Execution errors	E1. Action of wrong type	1.0E-3	3.0E-3	9.0E-3
	E2. Action at wrong time	1.0E-3	3.0E-3	9.0E-3
	E3. Action on wrong object	5.0E-5	5.0E-4	5.0E-3
	E4. Action out of sequence	1.0E-3	3.0E-3	9.0E-3
	E5. Missed action	2.5E-2	3.0E-2	4.0E-2

Figure 46: Weighting fators for Common Performance Conditions CPCs (Hollnagel, 1998, page 255)



		Basic Cognitive Function (BCF)			
CPC name	**Level**	**OBS**	**INT**	**PLAN**	**EXE**
Adequacy of organisation	Very efficient	1	1	0,8	0,8
	Efficient	1	1	1	1
	Inefficient	1	1	1,2	1,2
	Deficient	1	1	2	2
Working conditions	Advantageous	0,8	0,8	1	0,8
	Compatible	1	1	1	1
	Incompatible	2	2	1	2
Adequacy of MMI and operational support	Supportive	0,5	1	1	0,5
	Adequate	1	1	1	1
	Tolerable	1	1	1	1
	Inappropriate	5	1	1	5
Availability of procedures/plans	Appropriate	0,8	1	0,5	0,8
	Acceptable	1	1	1	1
	Inappropriate	2	1	5	2
Number of simultaneous goals	Fewer then capacity	1	1	1	1
	Matching current capacity	1	1	1	1
	More then capacity	2	2	5	2
Available time	Adequate	0,5	0,5	0,5	0,5
	Temporarily inadequate	1	1	1	1
	Continuously inadequate	5	5	5	5
Time of day	Day time (adjusted)	1	1	1	1
	Night time (unadjusted)	1,2	1,2	1,2	1,2
Adequacy of training and preparation	Adequate, high experience	0,8	0,5	0,5	0,8
	Adequate, low experience	1	1	1	1
	Inadequate	2	5	5	2
Crew collaboration quality	Very efficient	0,5	0,5	0,5	0,5
	Efficient	1	1	1	1
	Inefficient	1	1	1	1
	Deficient	2	2	2	5
Task factor	Engineering task	0,5	0,5	0,5	0,5

D

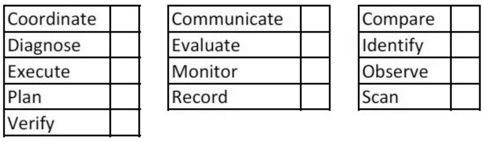
SURVEY EXTENDED HEP METHOD

Contents

This small survey is part of a graduation thesis. The questions are related to human behaviour within typical engineering tasks. The survey consists of four questions. Within the first two questions, activities should be selected from a list of basic activities which is shown beneath.

Basic activity	Definition
Coordinate	Coordinate activities within a task.
Communicate	Pass on or receive person-to-person information.
Compare	Compare two objects to find similarities.
Diagnose	Determine the cause of an (unwanted) condition.
Evaluate	Assess an actual or hypothetical situation, based on available information without requiring special operations.
Identify	Asses and actual or hypothetical situation, involving specific operations to retrieve information.
Execute	Perform a previously specified action or plan.
Monitor	Keep track of the development of a set of parameters.
Observe	Look for or read specific values or indicators.
Plan	Formulate a set of actions by which a goals will be successfully achieved.
Record	Write down events, measurements, etc.
Scan	Quick review of information sources to obtain a general impression of the state of the activities.
Verify	Confirm the correctness of measurements.

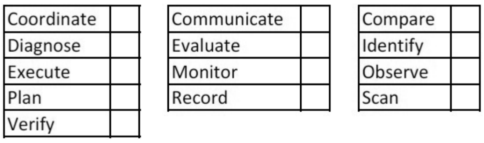
Question 1 You are asked by your supervisor to find him a particular design parameter in a technical design code. In order to complete this task, you must complete several basic activities. Select the basic activities you think are applicable for this task from the list below.



Coordinate	☐	Communicate	☐	Compare	☐
Diagnose	☐	Evaluate	☐	Identify	☐
Execute	☐	Monitor	☐	Observe	☐
Plan	☐	Record	☐	Scan	☐
Verify	☐				

Question 2 You are asked to calculate the cross section of a hexagon. In order to complete this task, you must complete several basic activities. Select the basic activities you think are applicable for this task from the list

below.



Coordinate	
Diagnose	
Execute	
Plan	
Verify	

Communicate	
Evaluate	
Monitor	
Record	

Compare	
Identify	
Observe	
Scan	

Question 3 You are asked by your supervisor to select the ψ_0 value of an office area (category B) from the table below. However an error has occurred, leading to an incorrect answer. Number the causes below from 1 (most realistic reason) to 3 (most unrealistic reason).

You missed your supervisor saying ‘office building‘, as a consequence you select a wrong category	
You accidentally select the ψ_1 value instead of the ψ_0 value.	
You did not understand the table very well, resulting in a interpretation error	

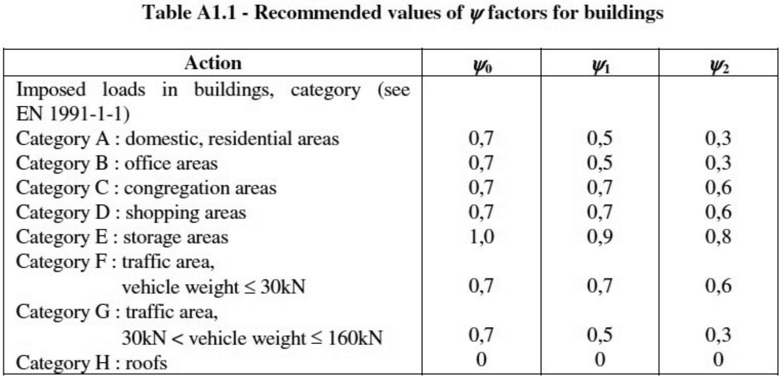


Table A1.1 - Recommended values of ψ factors for buildings

Action	ψ_0	ψ_1	ψ_2
Imposed loads in buildings, category (see EN 1991-1-1)			
Category A : domestic, residential areas	0,7	0,5	0,3
Category B : office areas	0,7	0,5	0,3
Category C : congregation areas	0,7	0,7	0,6
Category D : shopping areas	0,7	0,7	0,6
Category E : storage areas	1,0	0,9	0,8
Category F : traffic area, vehicle weight ≤ 30kN	0,7	0,7	0,6
Category G : traffic area, 30kN < vehicle weight ≤ 160kN	0,7	0,5	0,3
Category H : roofs	0	0	0

Question 4 You are asked to compare two drawings and identify the errors in one of them. However you were not able to find all errors. Number the causes of this error below from 1 (most realistic reason) to 3 (most unrealistic reason).

You were not able to understand the drawing very well, which makes it hard to find all errors	
You observed an error but did not identify it as an error.	
You were not able to scan the whole drawing within the specified time limits.	

The first question is: “You are asked by your supervisor to find a particular design parameter in a technical design code. In order to complete this task, you must complete several basic activities. Select the basic activities you think are applicable for this task from the list below“. The results of the first question is presented in figure47. The vertical axis shows the results of each respondent while the horizontal axis shows the results on each cognitive activity.

Cogn. Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	T**
Coordinate	X		X												X	3
Communicate	X	X	X		X	X		X	X				X		X	9
Compare		X							X							2
Diagnose							X								X	2
Evaluate					X		X			X						3
Identify						X			X							3
Execute	X	X	X					X	X	X			X	X		8
Monitor		X								X						2
Observe	X		X	X	X	X	X	X	X		X	X	X	X	X	13
Plan		X					X									2
Record	X						X		X				X			4
Scan	X	X		X		X		X	X	X		X				8
Verify		X	X		X					X					X	5
HEP Value*	0,019	0,059	0,032	0,014	0,031	0,037	0,029	0,018	0,058	0,036	0,007	0,014	0,011	0,028	0,051	

* HEP value is determined by using a standard function failure for each cognitive activity.

** Sum of respondents which mentioned the activity

Figure 47: Results of question 1 within the survey

If we analyse the task of question 1, realistic cognitive activities involved would be to communicate with the supervisor, obtain the design code (execute) observe the particular design code and select the particular design parameter (identify/diagnose/record). Communication is recognised by 9 of the respondents, execute by 8 respondents, observe by 13 respondents and identify/diagnose/record by 7 respondents. Only one respondent identified the four cognitive activities communicate/execute/observe/record.

From this it becomes clear that the results show a vague agreement with the expected outcome. Furthermore it becomes clear that the activity ‘decide which parameter to select‘ is not very well recognised within the methodology, as three activities (identify/diagnose/record) could cover this activity. Hollnagel (1998) wrote about this on page 168: “in CREAM, interpretation is assumed to include decision making as well as prediction [...] consequently, there is no specific group for decision making.“ This is quite confusing for a engineer to interpret, as interpretation cannot be directly selected (it is one of the four basic cognitive functions).

The results of each respondent is used to determine a Human Error Probability (HEP). For this standard failure types are selected. It can be seen from figure 47 that the HEP values vary from 0,007 to 0,059. The HEPs are plotted in a histogram in figure 48 together with a fitted Normal distribution. It can be seen from this figure that there is quite a scatter in the results and the Normal distribution does not fit the result very well. From this it

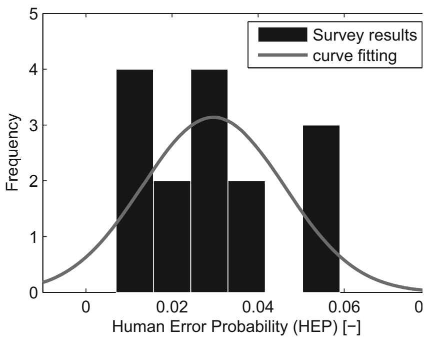


Figure 48: Distribution of the HEP values found with question 1 of the survey

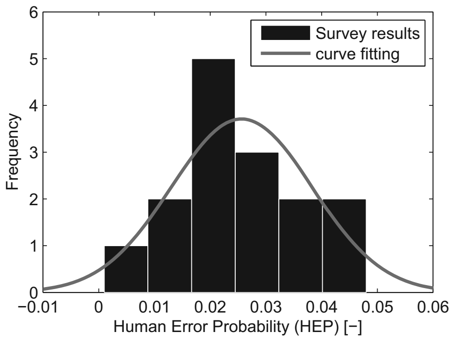
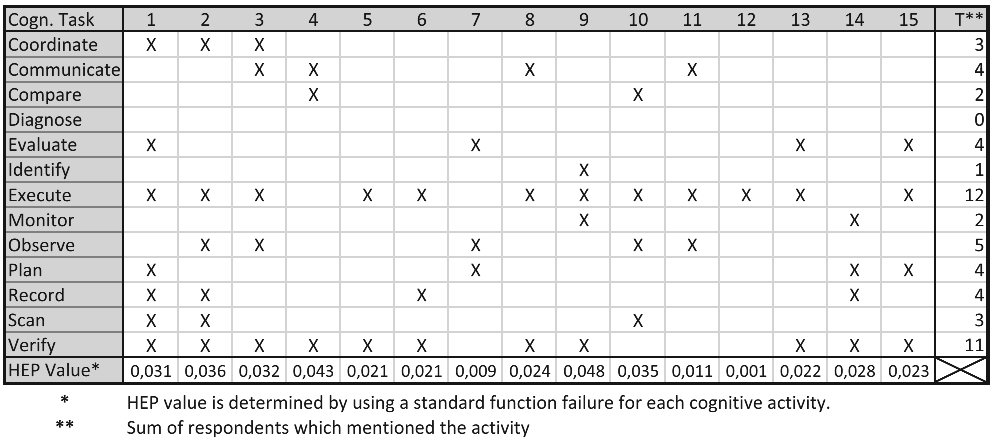


Figure 49: Distribution of the HEP values found with question 2 of the survey

can be concluded that there is to much scatter in the final HEP value.

The second question is: "You are asked to calculate the cross section of a hexagon. In order to complete this task, you must complete several basic activities. Select the basic activities you think are applicable for this task from the list below". The results of the first question is presented in figure 50. The axis are the same as in figure 47.



Cogn. Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	T**
Coordinate	X	X	X													3
Communicate			X	X				X			X					4
Compare				X						X						2
Diagnose																0
Evaluate	X						X						X		X	4
Identify									X							1
Execute	X	X	X		X	X		X	X	X	X	X	X		X	12
Monitor									X					X		2
Observe		X	X				X			X	X					5
Plan	X						X							X	X	4
Record	X	X				X								X		4
Scan	X	X								X						3
Verify	X	X	X	X	X	X		X	X				X	X	X	11
HEP Value*	0,031	0,036	0,032	0,043	0,021	0,021	0,009	0,024	0,048	0,035	0,011	0,001	0,022	0,028	0,023	

* HEP value is determined by using a standard function failure for each cognitive activity.

** Sum of respondents which mentioned the activity

Figure 50: Results of question 2 within the survey

Typical cognitive tasks involved in this task is calculating the hexagon (execute) and verifying the results. Other relevant cognitive tasks are communicate (getting the assignment) and planning the calculation task. It can be seen from figure 50 that execute (12) and verify (11) are by far the most recognised cognitive activities. Communicating and planning is almost not recognised as required cognitive activities. It can be concluded that the scatter in this task is less then the task in question one. However not one respondent has selected the expected outcome.

Te HEP values found with question two vary from 0,001 to 0,048 which is comparable with the results found in question one. The fitted Normal curve is however more realistically then the curve found at the HEP values of question one. From this it can be concluded that a somewhat simpler task also results in more reliable result.

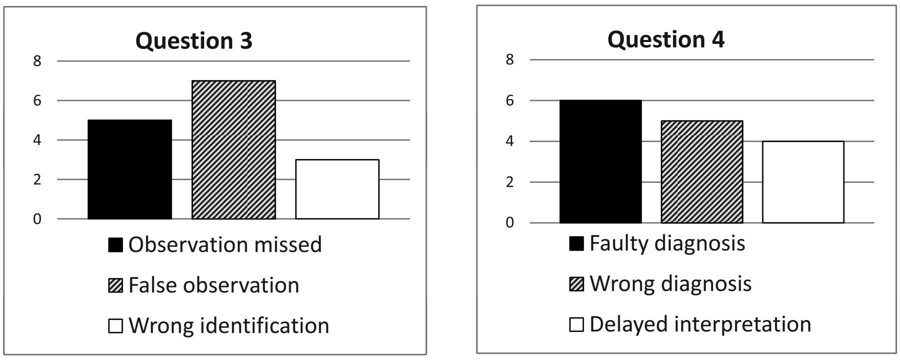


Figure 51: Survey results of questions three and four (selected cognitive function failures)

Question three and four of the survey are focussing on identifying likely cognitive function failures (of which a list is given in appendix C). Within both questions it was asked to rank the causes of an error. The difference between both questions is the focus on the type of function failure. Question three focusses on an ‘observation‘ function failure while question four focusses on an ‘interpretation‘ function failure. The results of question three and four are presented in figure 51. Concerning question three it can be concluded that there is a small trend towards selecting ‘false observation‘ as the cause of an error. Furthermore ‘missed observation‘ is also recognised as relevant. In question four no significant trend is visible. Despite this it is visible that ‘faulty diagnoses‘and ‘wrong diagnoses‘ are dominating over ‘delayed interpretation‘. From this it can be concluded that selecting function failures is very hard for engineers, as the scatter within both results is considerable.

E

SIMPLIFIED HEP METHOD

Contents

Selected Common Performance Conditions (CPC) within the case study

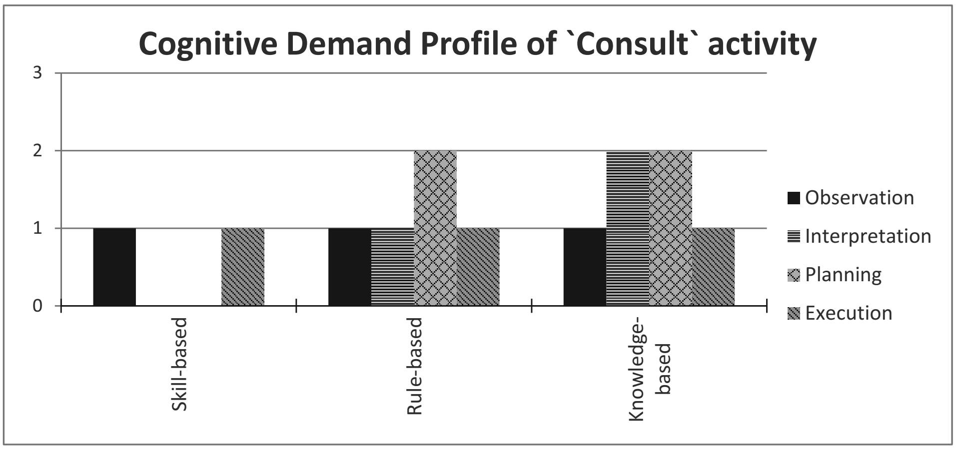
CPC name	Level	O	I	P	E
Adequacy of organization	Very efficient	1	1	0,8	0,8
Working conditions	Advantageous	0,8	0,8	1	0,8
Adequacy of MMI	Supportive	0,5	1	1	0,5
Procedures plans	Appropriate	0,8	1	0,5	0,8
Number of goals	Fewer then capacity	1	1	1	1
Available time	Adequate	0,5	0,5	0,5	0,5
Time of day	Day time (adjusted)	1	1	1	1
Training & preparation	Adequate, high experience	0,8	0,5	0,5	0,8
Crew collaboration	Very efficient	0,5	0,5	0,5	0,5
Task factor	Engineering task	0,5	0,5	0,5	0,5
Influence Common Performance Conditions (weight factors)		0,0320	0,0500	0,0250	0,0256

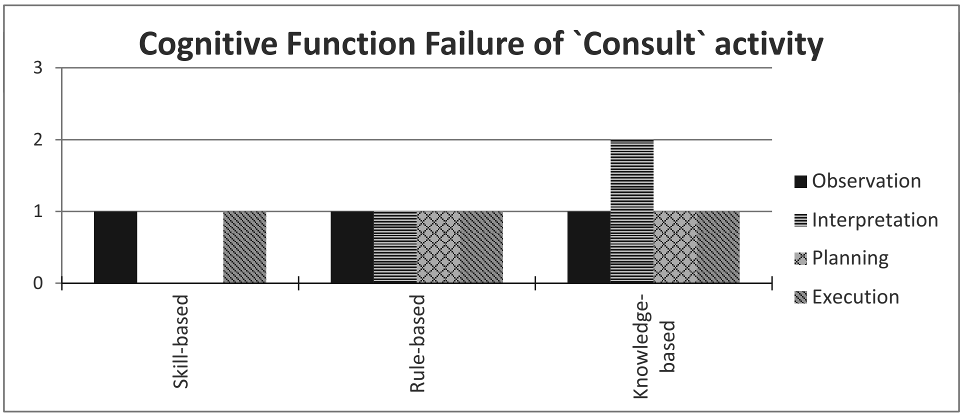
	Cognitive activities in the basic task: `consult`				BCF[1]				Credible Cognitive Function Failure (CFFs)													Failure Probabilities		
	Basic Cognitive Activity	Task #	Goal	Critical Cognitive Activity (CCA)	Observation	Interpretation	Planning	Execution	Obser-vation			Inter-pretation			Plan-ning		Execution					NEP[2]	Weigh-ting factors[3]	Adjus-ted NEP
									O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5			
Skill-based	Consult	# 1 1	Read text/drawing	Observe	X					X												0,07	0,032	0,0022
	Record	# 1 2	Record info/parameters	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Skill-based level																					Fully dependent		2,24E-03
																						Independent		2,25E-03
Rule-based level	Define activity	# 2 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Consult	# 2 2	Read text/drawing	Observe	X					X												0,07	0,032	0,0022
		# 2 3	Assess information	Diagnose		X	X					X										0,2	0,05	0,01
	Record	# 2 4	Record info/parameters	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Rule-based level																					Fully dependent		1,00E-02
																						Independent		1,25E-02
Knowledge-based level	Define activity	# 3 1	Asses task	Plan			X									X						0,01	0,025	0,0003
	Consult	# 3 2	Read text/drawing	Observe	X						X											0,07	0,032	0,0022
		# 3 3	Interpret text	Identify		X						X										0,2	0,05	0,01
		# 3 4	Deduce required info	Diagnose		X	X					X										0,2	0,05	0,01
	Record	# 3 5	Record info/parameters	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Knowledge-based level																					Fully dependent		1,00E-02
																						Independent		2,24E-02

[1] BCF: Basic Cognitive Functions

[2] NEP: Nominal Error Probability

[3] Depending of the context, or Common Performance Conditions (CPC)


Cognitive Demand Profile of `Consult` activity
3
2
1
0
Skill-based
Rule-based
Knowledge-based
Observation
Interpretation
Planning
Execution

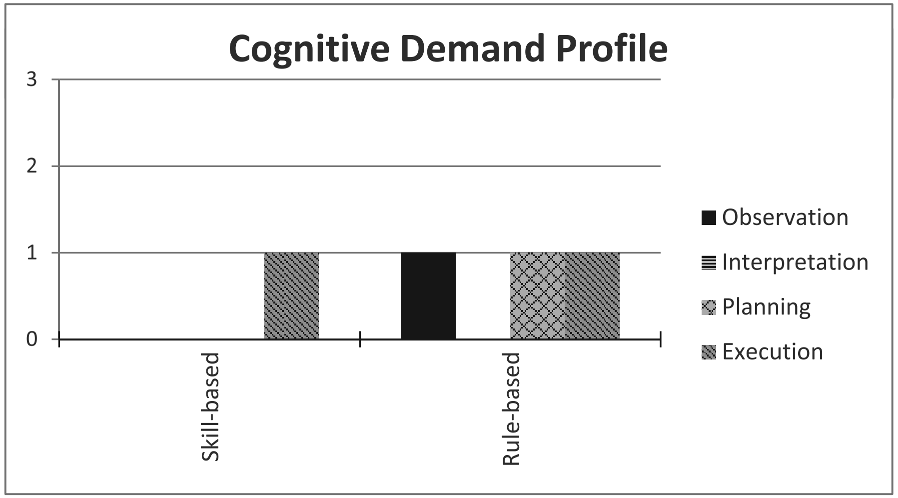

Cognitive Function Failure of `Consult` activity
3
2
1
0
Skill-based
Rule-based
Knowledge-based
Observation
Interpretation
Planning
Execution

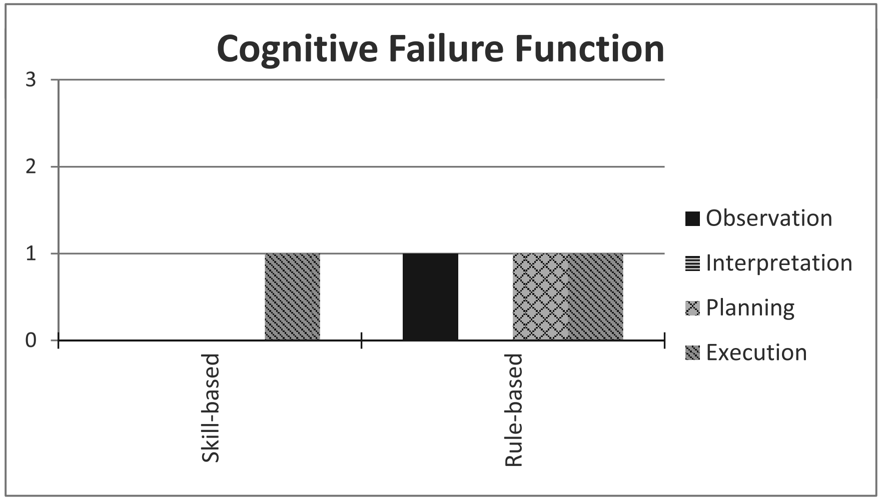
	Cognitive activities in the task: `obtain`				BCF[1]				Credible Cognitive Function Failure (CFFs)													Failure Probabilities		
	Basic Cognitive Activity	Task #	Goal	Critical Cognitive Activity (CCA)	Observation	Interpretation	Planning	Execution	Observation			Interpretation			Planning		Execution					NEP[2]	Weighting factors[3]	Adjusted NEP
									O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5			
Skill-based	Obtain	# 1 1	Obtain information	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Skill-based level																	Fully dependent						1,28E-05
																		Independent						1,28E-05
Rule-based level	Define activity	# 2 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Obtain	# 2 2	Observe information	Observe	X					X												0,07	0,032	0,0022
		# 2 3	Obtain information	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Rule-based level																	Fully dependent						2,24E-03
																		Independent						2,50E-03

[1] BCF: Basic Cognitive Functions

[2] NEP: Nominal Error Probability

[3] Depending of the context, or Common Performance Conditions (CPC)



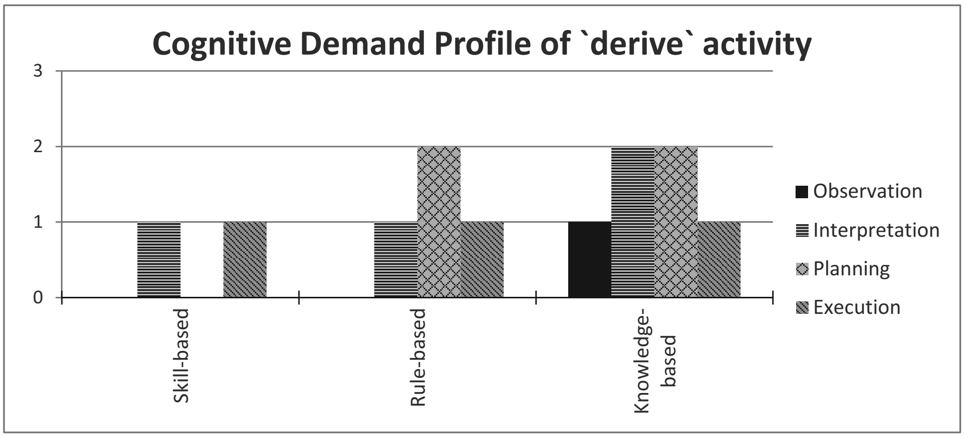


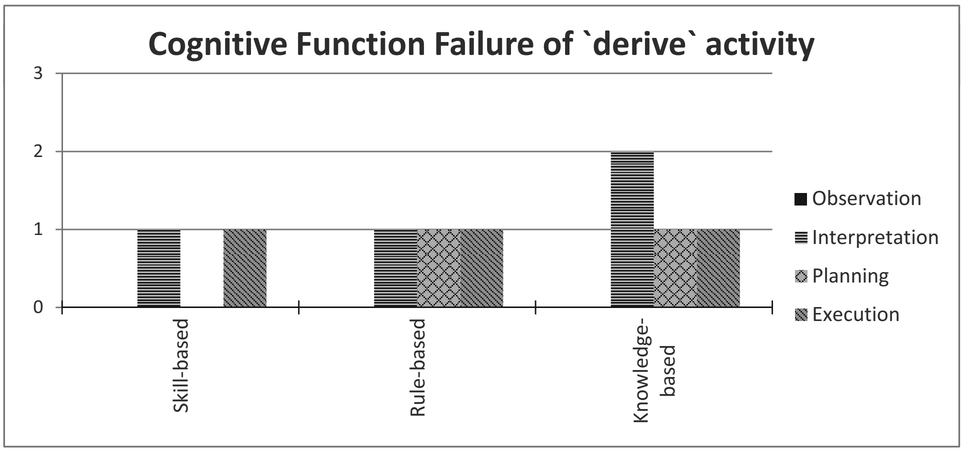
	Cognitive activities in the task: `derive`				BCF[1]				Credible Cognitive Function Failure (CFFs)													Failure Probabilities		
	Basic Cognitive Activity	Task #	Goal	Critical Cognitive Activity (CCA)	Observation	Interpretation	Planning	Execution	Obser-vation			Inter-pretation			Plan-ning		Execution					NEP[2]	Weigh-ting factors[3]	Adjus-ted NEP
									O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5			
Skill-based	Derive	# 1 1	Derive parameter/info	Identify		X							X									0,01	0,05	0,0005
	Record	# 1 2	Record parameter/info	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Skill-based level																					**Fully dependent** **Independent**		**5,00E-04** **5,13E-04**
Rule-based level	Define activity	# 2 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Derive	# 2 2	Derive parameter/info	Diagnose		X	X						X									0,01	0,05	0,0005
	Record	# 2 3	Record parameter/info	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Rule-based level																					**Fully dependent** **Independent**		**5,00E-04** **7,63E-04**
Knowledge-based	Define activity	# 3 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Derive	# 3 2	Observe information	Observe	X					X												0,07	0,032	0,0022
		# 3 3	Interpret information	Identify		X						X										0,2	0,05	0,01
		# 3 4	Derive parameter/info	Diagnose		X	X					X										0,2	0,05	0,01
	Record	# 3 5	Record parameter/info	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Knowledge-based level																					**Fully dependent** **Independent**		**1,00E-02** **2,24E-02**

[1] BCF: Basic Cognitive Functions

[2] NEP: Nominal Error Probability

[3] Depending of the context, or Common Performance Conditions (CPC)


Cognitive Demand Profile of `derive` activity
3
2
1
0
Skill-based
Rule-based
Knowledge-based
Observation
Interpretation
Planning
Execution

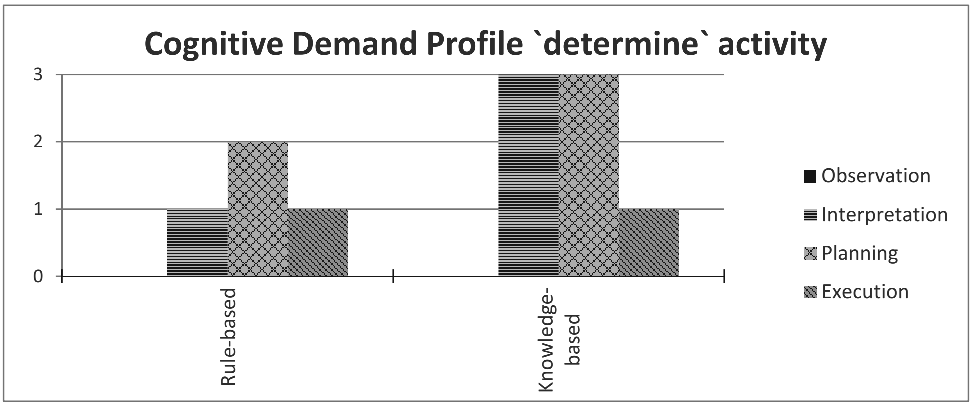

Cognitive Function Failure of `derive` activity
3
2
1
0
Skill-based
Rule-based
Knowledge-based
Observation
Interpretation
Planning
Execution

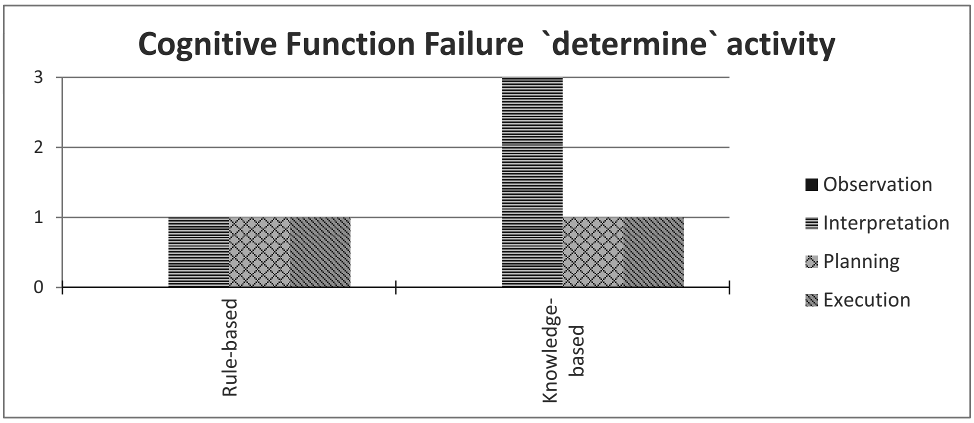
	Cognitive activities in the task: `determine`				BCF[1]				Credible Cognitive Function Failure (CFFs)													Failure Probabilities		
									Obser-vation			Inter-pretation			Plan-ning		Execution							
	Basic Cognitive Activity	Task #	Goal	Critical Cognitive Activity (CCA)	Observation	Interpretation	Planning	Execution	O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5	NEP[2]	Weigh-ting factors[3]	Adjus-ted NEP
Skill-based	Determine	# 1 1	Determine	Identify		X							X									0,01	0,05	0,0005
	Record	# 1 2	Record decision	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Skill-based level																					**Fully dependent** **Independent**		**5,00E-04** **5,13E-04**
Rule-based level	Define activity	# 2 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Determine	# 2 2	Determine	Diagnose		X	X					X										0,2	0,05	0,01
	Record	# 2 3	Record decision	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Rule-based level																					**Fully dependent** **Independent**		**1,00E-02** **1,03E-02**
Knowledge-based level	Define activity	# 3 1	Assess task	Plan			X									X						0,01	0,025	0,0003
		# 3 2	Identify problem	Identify		X						X										0,2	0,05	0,01
	Determine	# 3 3	Find higher level analogy	Diagnose		X	X					X										0,2	0,05	0,01
		# 3 4	Determine	Diagnose		X	X					X										0,2	0,05	0,01
	Record	# 3 5	Record decision	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Knowledge-based level																					**Fully dependent** **Independent**		**1,00E-02** **3,00E-02**

[1] BCF: Basic Cognitive Functions

[2] NEP: Nominal Error Probability

[3] Depending of the context, or Common Performance Conditions (CPC)


Cognitive Demand Profile `determine` activity
3
2
1
0
Rule-based
Knowledge-based
Observation
Interpretation
Planning
Execution

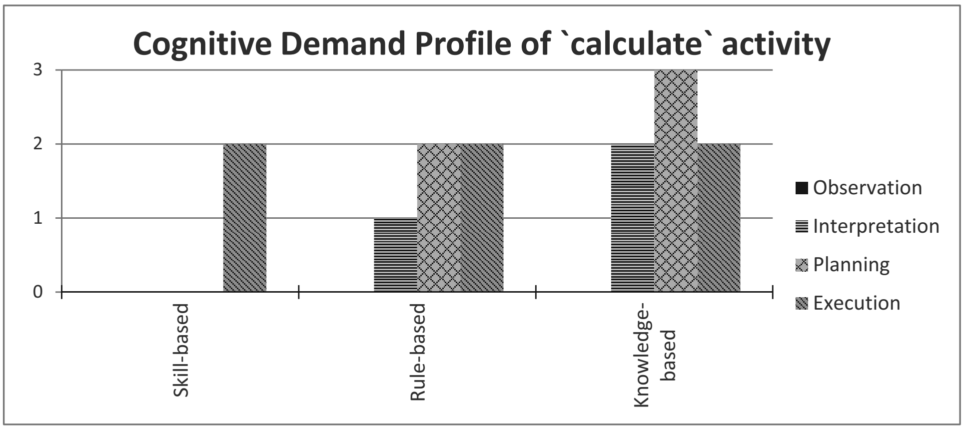

Cognitive Function Failure `determine` activity
3
2
1
0
Rule-based
Knowledge-based
Observation
Interpretation
Planning
Execution

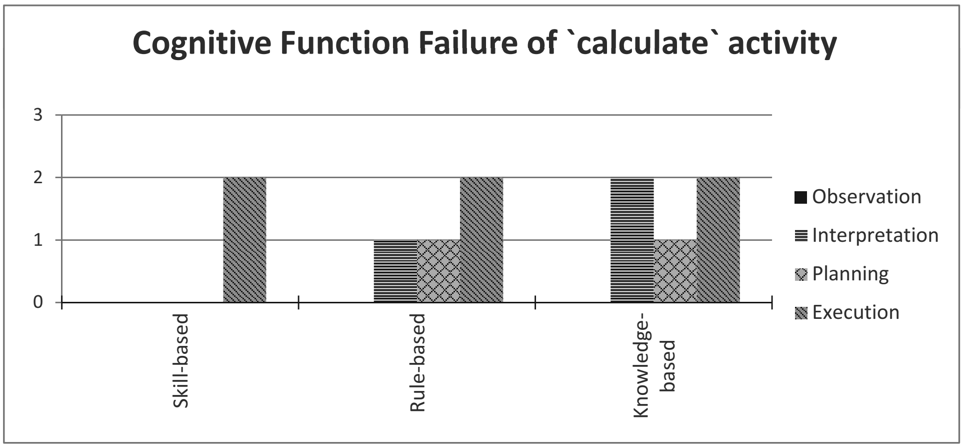
	Cognitive activities in the task: `calculate`				BCF[1]				Credible Cognitive Function Failure (CFFs)													Failure Probabilities		
	Basic Cognitive Activity	Task #	Goal	Critical Cognitive Activity (CCA)	Observation	Interpretation	Planning	Execution	Obser-vation			Inter-pretation			Plan-ning		Execution					NEP[2]	Weighting factors[3]	Adjusted NEP
									O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5			
Skill-based	Calculate	# 1 1	Execute calculation	Execute				X											X			0,0005	0,0256	1E-05
	Record	# 1 2	Record outcomes	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Skill-based level																					**Fully dependent**		**1,28E-05**
																						Independent		**2,56E-05**
Rule-based level	Define activity	# 2 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Calculate	# 2 1	Apply basic rule	Evaluate		X	X						X									0,01	0,05	0,0005
		# 2 3	Execute calculation	Execute				X											X			0,0005	0,0256	1E-05
	Record	# 2 4	Record outcomes	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Rule-based level																					**Fully dependent**		**5,00E-04**
																						Independent		**7,75E-04**
Knowledge-based level	Define activity	# 3 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Calculate	# 3 2	Diagnose calculation	Diagnose		X	X					X										0,2	0,05	0,01
		# 3 3	Find higher level analogy	Diagnose		X	X					X										0,2	0,05	0,01
		# 3 4	Execute calculation	Execute				X											X			0,0005	0,0256	1E-05
	Record	# 3 5	Record outcomes	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Knowledge-based level																					**Fully dependent**		**1,00E-02**
																						Independent		**2,02E-02**

[1] BCF: Basic Cognitive Functions

[2] NEP: Nominal Error Probability

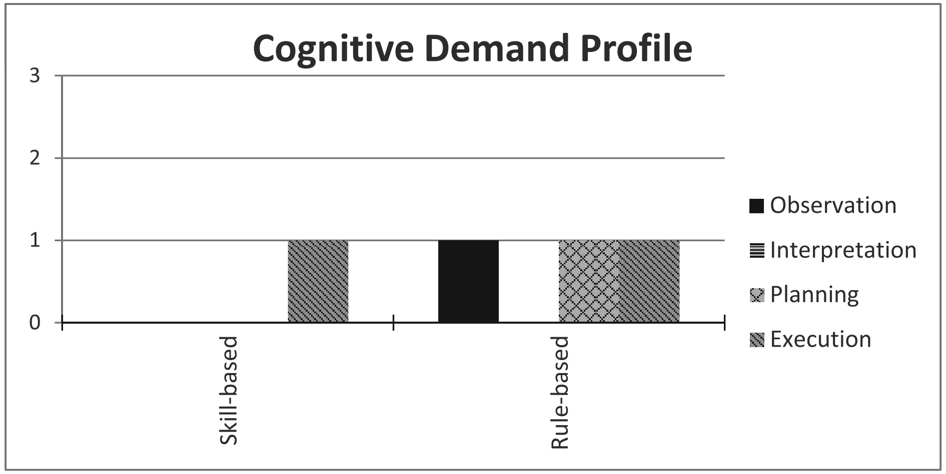
[3] Depending of the context, or Common Performance Conditions (CPC)

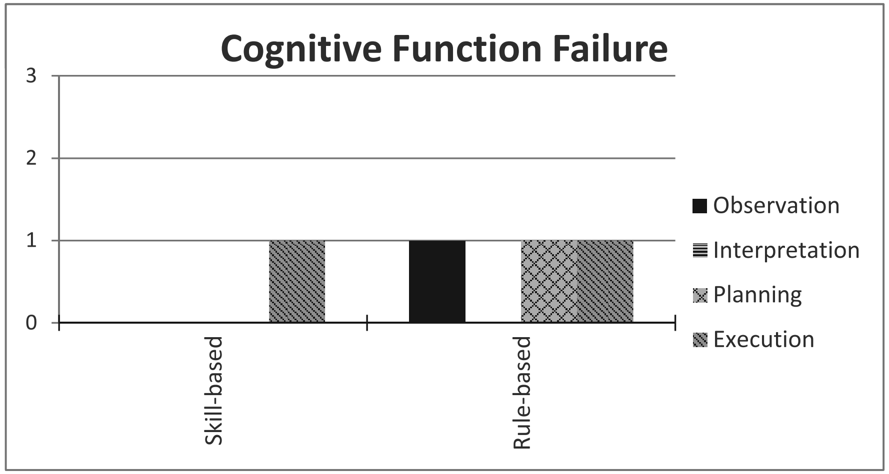

Cognitive Demand Profile of `calculate` activity
3
2
1
0
Skill-based
Rule-based
Knowledge-based
■ Observation
≣ Interpretation
▨ Planning
▧ Execution


Cognitive Function Failure of `calculate` activity
3
2
1
0
Skill-based
Rule-based
Knowledge-based
■ Observation
≣ Interpretation
▨ Planning
▧ Execution

	Cognitive activities in the task: `Insert`				BCF[1]				Credible Cognitive Function Failure (CFFs)													Failure Probabilities		
	Basic Cognitive Activity	Task #	Goal	Critical Cognitive Activity (CCA)	Observation	Interpretation	Planning	Execution	Observation			Interpretation			Planning		Execution					NEP[2]	Weighting factors[3]	Adjusted NEP
									O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5			
Skill-based	Insert	# 1 2	Insert information	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Skill-based level																					**Fully dependent** **Independent**		**1,00E+00** **1,28E-05**
Rule-based level	Define activity	# 2 1	Assess task	Plan			X									X						0,01	0,025	0,0003
	Insert	# 2 2	Observe information	Observe	X					X												0,07	0,032	0,0022
		# 2 3	Insert information	Execute				X											X			0,0005	0,0256	1E-05
	Human Error Probability (HEP) of basic task execution on Rule-based level																					**Fully dependent** **Independent**		**2,24E-03** **2,50E-03**

[1] BCF: Basic Cognitive Functions [2] NEP: Nominal Error Probability [3] Depending of the context, or Common Performance Conditions (CPC)



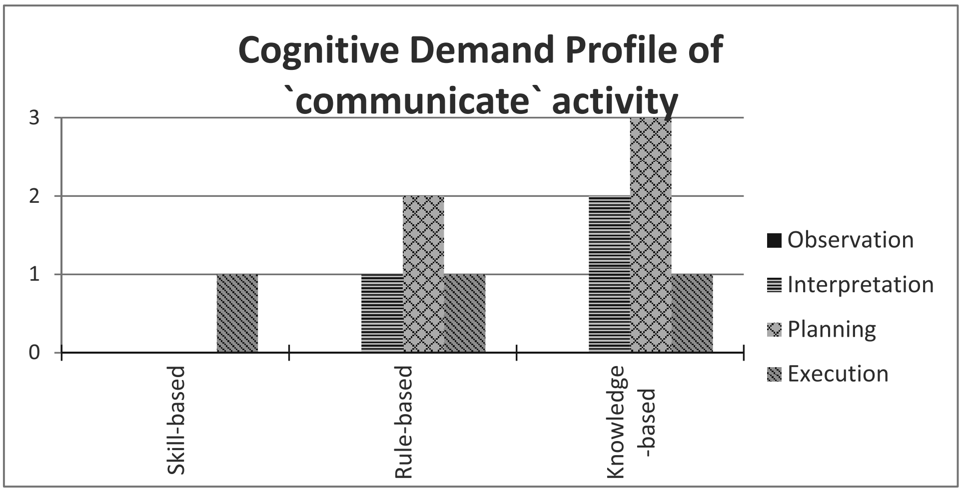


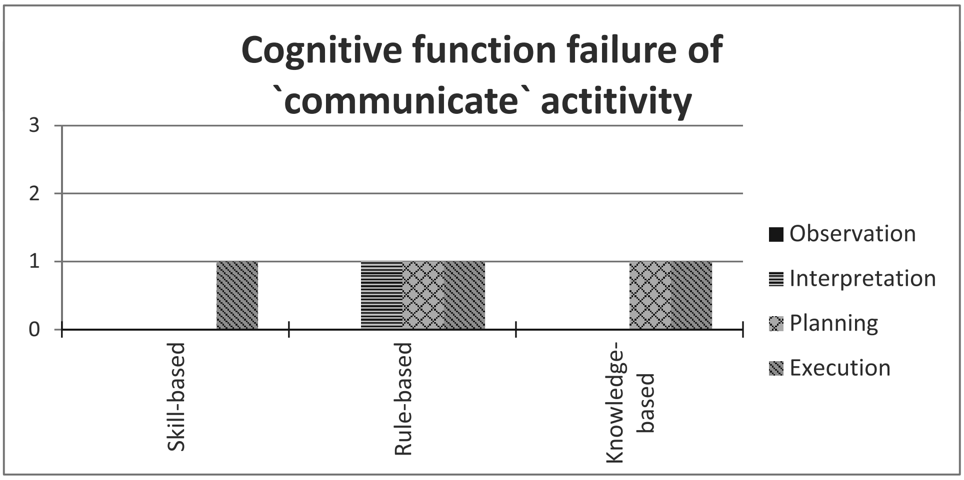
	Cognitive activities in the task: `communicate`				BCF[1]				Credible Cognitive Function Failure (CFFs)													Failure Probabilities		
	Basic Cognitive Activity	Task #	Goal	Critical Cognitive Activity (CCA)	Observation	Interpretation	Planning	Execution	Obser-vation			Inter-pretation			Plan-ning		Execution					NEP[2]	Weigh-ting factors[3]	Adjus-ted NEP
									O1	O2	O3	I1	I2	I3	P1	P2	E1	E2	E3	E4	E5			
Skill-based	Communicate	# 1 1	Communicate	Communicate				X													X	0,03	0,0256	0,0008
	Human Error Probability (HEP) of basic task execution on Skill-based level																					Fully dependent Independent		7,68E-04 7,68E-04
Rule-based level	Define activity	# 2 1	Assess task	Plan			X									X						0,01	0,025	0,0003
		# 2 2	Consider intentions	Evaluate		X	X						X											
		# 2 3	Communicate	Communicate				X													X	0,03	0,0256	0,0008
	Human Error Probability (HEP) of basic task execution on Rule-based level																					Fully dependent Independent		7,68E-04 1,02E-03
Knowledge-based level	Define activity	# 3 1	Asses task	Plan			X									X						0,01	0,025	0,0003
		# 3 2	identify goal	Evaluate		X	X						X										0,05	
	Communicate	# 3 3	Interpret discussion	Diagnose		X	X					X										0,2	0,05	0,01
		# 3 4	discussion	Communicate				X													X	0,03	0,0256	0,0008
	Human Error Probability (HEP) of basic task execution on Knowledge-based level																					Fully dependent Independent		1,00E-02 1,10E-02

[1] BCF: Basic Cognitive Functions

[2] NEP: Nominal Error Probability

[3] Depending of the context, or Common Performance Conditions (CPC)


Cognitive Demand Profile of `communicate` activity
3
2
1
0
Skill-based
Rule-based
Knowledge -based
Observation
Interpretation
Planning
Execution


Cognitive function failure of `communicate` actitivity
3
2
1
0
Skill-based
Rule-based
Knowledge-based
Observation
Interpretation
Planning
Execution

F

TASK ANALYSIS

Contents

Human Error Probabilities (HEP)			Properties task		
	Task No.	Task description	Basic task	Cognitve level	
				Expert	Novice
Geo-metry	A0.1.1	Obtain basic drawings	Obtain	SB	SB
	A0.1.2	Communicate requirements	Communicate	RB	KB
	A0.2.1	Derive floor height	Derive	SB	RB
	A0.2.2	Derive raster in x-direction	Derive	SB	RB
	A0.2.3	Derive raster in y-direction	Derive	SB	RB
Material Characteristics (Node A5)	A5.1.1	Obtain concrete requirements	Obtain	SB	SB
	A5.1.2	Communicate concrete req.	Communicate	RB	KB
	A5.1.3	Determine concrete type	Determine	RB	RB
	A5.1.4	Consult NEN-EN 1991	Consult	RB	RB
	A5.1.5	Derive specific mass concrete	Derive	SB	RB
	A5.1.6	Consult NEN-EN 1992	Consult	RB	RB
	A5.1.7	Derive concrete compressive str.	Derive	RB	RB
	A5.1.8	Derive concrete tensile strength	Derive	RB	RB
	A5.1.9	Derive concrete elasticity	Derive	RB	RB
	A5.2.1	Obtain steel requirements	Obtain	SB	SB
	A5.2.2	Communicate steel requirements	Communicate	RB	KB
	A5.2.3	Determine steel type	Determine	RB	RB
	A5.2.4	Consult material specifications	Consult	RB	RB
	A5.2.5	Derive reinforcement strength	Derive	RB	RB
	A5.2.6	Derive steel elasticity	Derive	RB	RB
Determine distributed loads (node A2)	A2.1.0	Obtain beam type	Obtain	SB	SB
	A2.1.1	Consult design rules	Consult	SB	RB
	A2.1.2	Calculate beam height	Calculate	SB	SB
	A2.1.3	Determine beam type	Determine	RB	KB
	A2.1.4	Insert beam length	Insert	SB	SB
	A2.2.1	Calculate width beams	Calculate	SB	SB
	A2.2.2	Consult design rules	Consult	SB	RB
	A2.3.0	Insert specific mass concrete	Insert	SB	SB
	A2.3.1	Calculate weight beams	Calculate	SB	SB
	A2.5.7	Communicate slab height	Communicate	RB	RB
	A2.6.2	Calculate weight slab	Calculate	RB	RB
	A3.1.1	Consult NEN-EN 1991 (table 6.1)	Consult	RB	RB
	A3.1.2	Det. functional use floor field	Determine	KB	KB
	A3.1.3	Read requirements	Obtain	RB	RB
	A3.1.4	Communicate with users/architect	Communicate	RB	RB
	A3.1.5	Consult NEN-EN 1991	Consult	RB	RB
	A3.1.6	Derive imposed load slab	Derive	RB	RB
Calculating longitudinal reinforcement beam (Node B1)	B1.1.1	Derive support length	Derive	SB	RB
	B1.1.3	Consult formula from NEN-EN 1992	Consult	SB	SB
	B1.1.4	Calculate effective beam span	Calculate	SB	SB
	B1.2.2	Update beam height	Insert	SB	SB
	B1.2.4	Update beam width	Insert	SB	SB
	B1.2.5	Calculate beam geometry	Calculate	SB	RB
	B1.2.6	Obtain beam height	Obtain	SB	SB
	B1.2.7	Obtain beam width	Obtain	SB	SB
	B1.3.1	Calculate self-weight beam	Calculate	SB	RB
	B1.3.3	Calculate self-weight on slab	Calculate	RB	RB
	B1.3.4	Calc. Imposed load on slab	Calculate	RB	RB
	B1.3.5	Det. Loading combinations ULS	Determine	KB	KB
	B1.3.6	Consult NEN-EN 1991	Consult	RB	KB

Human Error Probabilities (HEP)			Properties task		
	Task No.	Task description	Basic task	Cognitve level	
				Expert	Novice
Calculating longitudinal reinforcement beam (Node B1)	B1.3.7	Compose loading combinations	Determine	RB	RB
	B1.3.8	Calculate total load	Calculate	SB	RB
	B1.4.1	Calculate maximum field moment	Calculate	RB	RB
	B1.4.2	Calculate max. support moment	Calculate	RB	RB
	B1.4.3	obtain basic formula	Obtain	RB	RB
	B1.4.5	Calculate bottom reinforcement	Calculate	RB	RB
	B1.4.6	Calculate top reinforcement	Calculate	RB	RB
	B1.4.7	Determine Practical reinforcement	Determine	RB	RB
	B1.4.8	Insert steel strength	Insert	SB	SB
	B1.5.1	Consult basic design rules	Consult	RB	RB
	B1.5.2	Derive Cmin	Derive	RB	RB
	B1.5.3	Estimate 1/2·Φmr+Φsr	Determine	RB	RB
	B1.5.4	Calculate d	Calculate	RB	RB
	B1.6.1	Calculate As;max	Calculate	SB	SB
	B1.6.2	Consult design rules As;max	Consult	RB	RB
	B1.6.3	Determine if As<As;max	Determine	SB	SB
	B1.7.1	Insert concrete tensile strength	Insert	SB	SB
	B1.7.2	Insert steel strength	Insert	SB	SB
	B1.7.3	Consult design rules AS;min	Consult	RB	KB
	B1.7.4	Calculate As;min;1	Calculate	SB	RB
	B1.7.5	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B1.7.6	Derive width tension zone	Derive	SB	RB
	B1.7.7	Consult NEN-EN 1992-1-1	Consult	RB	KB
	B1.7.8	Calculate As;min;2	Calculate	SB	SB
	B1.7.9	Decide on As;min	Determine	SB	SB
	B1.7.10	Determine if As>As;min	Determine	SB	SB
	B1.8.5	Decide bottom reinf. layout	Determine	RB	KB
	B1.8.6	Decide top reinforcement layout	Determine	RB	KB
	B1.9.1	Consult defelection control req.	Consult	RB	KB
	B1.9.2	Calculate limiting span/depth ratio	Calculate	RB	RB
	B1.9.3	Check if deflection req. Is satisfied	Determine	RB	RB
Crack width control (node B2)	B2.1.1	Obtain concrete tensile strength	Obtain	SB	SB
	B2.1.5	Calculate x;uncracked	Calculate	RB	KB
	B2.1.6	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B2.1.7	Calculate equivalent height	Derive	RB	RB
	B2.1.8	Calculate concr. area tensile zone	Calculate	SB	RB
	B2.2.1	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B2.2.3	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B2.2.4	Calculate axial force Ned	Calculate	RB	RB
	B2.2.5	Calculate concrete mean stress	Calculate	RB	KB
	B2.2.6	Derive coefficient k1	Derive	SB	RB
	B2.2.7	Derive coefficient h*	Derive	SB	RB
	B2.2.8	Calculate Coefficient Kc	Calculate	SB	RB
	B2.3.1	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B2.3.2	Determine coefficent k	Determine	SB	RB
	B2.3.3	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B2.3.4	Decide on σs = fyk	Determine	SB	SB
	B2.3.5	Obtain steel strength	Obtain	SB	SB
	B2.3.6	Calculate As;min;3	Calculate	RB	RB
	B2.4.1	Consult NEN-EN 1992-1-1	Consult	RB	RB

Human Error Probabilities (HEP)			Properties task		
	Task No.	Task description	Basic task	Cognitve level	
				Expert	Novice
Crack width control (node B2)	B2.4.2	Consult Basic formulas	Consult	SB	RB
	B2.4.3	Determine neutral axis	Determine	KB	KB
	B2.4.4	Calculate reinforcement stress	Calculate	RB	KB
	B2.5.1	Obtain Steel elasticity	Obtain	SB	SB
	B2.5.2	Obtain concrete elasticity	Obtain	SB	SB
	B2.5.4	Consult NEN-EN 1992-1-1	Consult	SB	RB
	B2.5.5	Derive coefficient kt	Derive	SB	RB
	B2.5.3	Calculate ratio E-moduli	Calculate	SB	SB
	B2.5.6	Consult NEN-EN 1992-1-1	Consult	SB	RB
	B2.5.7	Calculate effective height	Calculate	SB	RB
	B2.5.8	Calculate effective area concrete	Calculate	SB	SB
	B2.5.9	Calculate reinforcement ratio	Calculate	SB	RB
	B2.5.10	Calculate effective strain	Calculate	RB	KB
	B2.6.1	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B2.6.2	Derive k1,k2,k3 or k4	Derive	RB	RB
	B2.6.3	Calculate max. crackspacing	Calculate	RB	RB
	B2.6.4	Calculate crack width	Calculate	RB	RB
	B2.6.5	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B2.6.6	Derive allowed crack width	Derive	RB	RB
	B2.6.7	Check allowable crack width	Determine	RB	RB
Column design (Node B3)	B3.1.1	Calculate maximum normal force	Calculate	RB	RB
	B3.1.2	Calculate maximum Moment	Calculate	RB	RB
	B3.1.0	Communicate structural dimensions	Communicate	SB	RB
	B3.1.3	Derive column width	Derive	RB	RB
	B3.1.4	Determine column depth	Determine	RB	RB
	B3.1.5	Determine concrete cover	Determine	SB	RB
	B3.1.6	Consult basic design rules	Consult	RB	RB
	B3.1.7	Calculate 1st order reinforcement	Calculate	SB	KB
	B3.1.8	Choose reinforcement layout	Determine	RB	KB
	B3.2.1	Consult NEN-EN 1992-1-1	Consult	RB	RB
	B3.2.2	Calculate α-factor	Calculate	RB	RB
	B3.2.3	Calculate reinforcement ratio	Calculate	SB	RB
	B3.2.4	Calculate fictitious elasticity modulus	Calculate	RB	RB
	B3.2.5	Calculate I	Calculate	RB	RB
	B3.2.6	Calculate EI-column	Calculate	RB	RB
	B3.3.1	Consult basic design rules	Consult	RB	RB
	B3.3.2	Calculate buckling force	Calculate	RB	RB
	B3.3.3	Calculate second order moment	Calculate	RB	KB
	B3.3.4	Calculate Concrete compression	Calculate	RB	KB
	B3.3.5	Obtain concrete compr. Strength	Obtain	SB	SB
	B3.3.6	Check allowable concrete compression	Determine	RB	RB
	B3.3.7	Calculate reinforcement stress	Calculate	RB	RB
	B3.3.8	Obtain steel strength	Obtain	SB	SB
	B3.3.9	Check reinforcement stress	Determine	SB	SB
	B3.4.1	Consult NEN-EN 1992-1-1 (9.5.2)	Consult	RB	RB
	B3.4.2	Derive minimum diameter	Derive	SB	RB
	B3.4.3	Check minimum diameter	Determine	SB	SB
	B3.4.4	Calculate minimum reinforcement	Calculate	RB	RB
	B3.4.5	Check minimum reinforcement	Determine	SB	SB

Human Error Probabilities (Inexperienced Designer)								First distribution			Second distribution		
	Task Sequence	Task description	Failure prob.	aramete	Unit	Mean value	distribution	Probability	Failure* fraction	Standard dev.	Probability	Failure* fraction	Values
Geo-metry	A0.2.1	Derive floor height	0,0008	hi	[m]	3,60	Single	Normal	1,00	0,61	▨	▨	▨
	A0.2.2	Derive raster in x-direction	0,0008	Lx;i	[m]	6,00	Single	Normal	1,00	0,61	▨	▨	▨
	A0.2.3	Derive raster in y-direction	0,0008	Ly;i	[m]	7,20	Single	Normal	1,00	0,61	▨	▨	▨
Material Characteristics	A5.1.1 to A5.1.3	Determine concrete type	0,0213	[-]	N/mm2	C25/30	Single	Discrete	1,00	▨	▨	▨	▨ e
	A5.1.4 and A5.1.5	Derive specific mass concrete	0,0132	Υc	[kN/m3]	25,00	Single	Normal	1,00	0,61	▨	▨	▨
	A5.1.6 and A5.1.7	Derive concrete compressive str.	0,0132	fck	N/mm2	30,00	Single	Normal	1,00	0,61	▨	▨	▨
	A5.1.6 and A5.1.8	Derive concrete tensile strength	0,0132	fctm	N/mm2	2,90	Single	Normal	1,00	0,61	▨	▨	▨
	A5.1.6 and A5.1.9	Derive concrete elasticity	0,0132	Ec	N/mm2	2,8E+04	Single	Normal	1,00	0,61	▨	▨	▨
	A5.2.1 to A5.2.3	Determine steel type	0,0213	[-]	N/mm2	B500B	Single	Discrete	1,00	▨	▨	▨	▨ e
	A5.2.4 and A5.2.5	Derive reinforcement strength	0,0132	fyk	N/mm2	435,00	SIngle	Normal	1,00	0,61	▨	▨	▨
	A5.2.4 and A5.2.6	Derive steel elasticity	0,0132	Es	N/mm2	2,1E+05	SIngle	Normal	1,00	0,61	▨	▨	▨
Determine distributed loads	A2.1.0 to A2.1.4	Calculate beam height	0,0425	hb	[m]	0,50	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	A2.2.2 and A2.2.1	Calculate width beams	0,0125	bb	[m]	0,275	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	A2.3.0 and A2.3.1	Calculate weight beams	0,0000	qdb	[kN/m]	3,44	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	A2.5.7	Communicate slab height	0,0010	hs	[mm]	200	Single	Normal	1,00	0,61	▨	▨	▨
	A2.6.2	Calculate weight slab	0,0008	q_{ds}	[kN/m2]	3,12	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	A3.1.1 and A3.1.6	Derive imposed load slab	0,0592	qk	[kN/m2]	3,00	Single	Normal	1,00	0,61	▨	▨	▨
Calculating longitudinal reinforcement beam (Node B1)	B1.1.1	Derive support length	0,0008	a1	[m]	0,10	Single	Normal	1,00	0,78	▨	▨	▨
	B1.1.3 and B1.1.4	Calculate effective beam span	0,0023	Leff	[m]	7,20	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.2.2	Update beam height	0,0000	hb	[m]	0,50	Single	Normal	1,00	0,61	▨	▨	▨
	B1.2.4	Update beam width	0,0000	bb	[m]	0,28	Single	Normal	1,00	0,61	▨	▨	▨
	B1.2.5 to B1.2.7	Calculate beam geometry	0,0008	Ac	[m2]	0,14	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.3.1	Calculate self-weight beam	0,0000	qdb	[kN/m]	3,44	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.3.3	Calculate self-weight on slab	0,0016	q_{ds}	[kN/m]	18,72	Comb.	Log-norm	0,70	0,67	Discrete	0,30	1,40 or 0,138 b
	B1.3.4	Calc. Imposed load on slab	0,0600	q_{ks}	[kN/m]	18,00	Comb.	Log-norm	0,50	0,67	Discrete	0,50	1,40 or 0,138 b
	B1.3.6 and B1.3.5	Det. Loading combinations ULS	0,0523	Υi,1	-	1,35	Comb.	Normal	0,50	0,61	Discrete	0,50	,74 0,88 and 1,11 c
	B1.3.6 and B1.3.5	Det. Loading combinations ULS	0,0523	Υi,2	-	1,50	Comb.	Normal	0,50	0,61	Discrete	0,50	,66 0,80 and 0,90 c
	B1.3.7 and B1.3.8	Calculate total load	0,0110	ql	[kN/m]	56,91	Comb.	Log-norm	0,50	0,67	Discrete	0,50	,94 0,38 and 0,68 d
	B1.3.7 and B1.3.8	Calculate total dead load	0,0110	qdl	[kN/m]	29,91	Comb.	Log-norm	0,50	0,67	Discrete	0,50	,94 0,38 and 0,69
	B1.3.7 and B1.3.8	Calculate total variable load	0,0110	qll	[kN/m]	27,00	Comb.	Log-norm	0,50	0,67	Discrete	0,50	,94 0,38 and 0,70
	B1.4.1	Calculate maximum field moment	0,0008	Mu,d	[kNm]	264,78	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$

Human Error Probabilities (Inexperienced Designer)								First distribution			Second distribution		
	Task Sequence	Task description	Failure prob.	aramete	Unit	Mean value	distrib ution	Probabil ity	Failure* fraction	Standard dev.	Probabil ity	Failure* fraction	Values
Calculating longitudinal reinforcement beam (Node B1)	B1.4.2	Calculate max. support moment	0,0008	Mu,s	[kNm]	318,36	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.4.3 and B1.4.5	Calculate bottom reinforcement	0,0033	As;b	[mm2]	1503	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.4.3 and B1.4.6	Calculate top reinforcement	0,0033	As;t	[mm2]	1807	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.4.7	Determine Practical reinforcemen	0,0103	As;pract	[mm2]	308	Single	Log-norm	1,00	0,67			
	B1.4.7	No. Bars pract. Reinforcement	-	No;Asp	[No.]	2							
	B1.4.7	Bar diameter pract. Reinforcemer	-	d;Asp	[mm]	14							
	B1.5.2	Derive Cmin	0,0008	Cmin	[mm]	30	Single	Normal	1,00	0,61			
	B1.5.3	Estimate 1/2·Φmr+Φsr	0,0103	Φmr+Φs	[mm]	20	Single	Normal	1,00	0,61			
	B1.5.1 and B1.5.4	Calculate d	0,0133	d	[mm]	450	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.6.1 and B1.6.2	Calculate As;max	0,0125	As;max	[mm2]	5500	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.6.3	Determine if As<As;max	0,0005	As	[mm2]	-	Single	Discrete	1,00				e
	B1.7.5 and B1.7.6	Derive width tension zone	0,0132	bt	[mm]	275	Single	Log-norm	1,00	0,67			
	B1.7.1 to B1.7.4	Calculate As;min;1	0,0232	As;min;1	[mm2]	214,50	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.7.7 and B1.7.8	Calculate As;min;2	0,0224	As;min;2	[mm2]	160,88	Comb.	Discrete	0,70	0,42	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B1.7.9	Decide on As;min	0,0005	As;min	[mm2]	248,77	Single	Discrete	1,00				e
	B1.7.1	Determine if As>As;min	0,0005	As	[mm2]	-	Single	Discrete	1,00				e
	B1.8.5	Decide bottom reinf. layout	0,0300	Asb;prov	[mm2]	1520	Single	Normal	1,00	0,43			
	B1.8.5	No. Bars bottom	-	No;Asb	[No.]	4							
	B1.8.5	Bar diameter bottom	-	d;Asb	[mm]	22							
	B1.8.6	Decide top reinforcement layout	0,0300	Ast;prov	[mm2]	1808	Single	Normal	1,00	0,43			
	B1.8.6	No. Bars top	-	No;Ast	[No.]	4							
	B1.8.6	Bar diameter top	-	d;Ast	[mm]	24							
	B1.9.1 to B1.9.3	Check if deflection req. Is satisfiec	0,0334	-	[-]	-	Single	Discrete	1,00				e
Crack width control	B2.1.1 and B2.1.5	Calculate x;uncracked	0,0202	x,uncr	[mm]	0,16	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B2.1.6 and B2.1.7	Calculate equivalent height	0,0132	h,t,ef	[mm]	0,35	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B2.1.6 to B2.1.8	Calculate concr. area tensile zone	0,0342	Act	[mm2]	94875	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B2.2.7	Derive coefficient h*	0,0008	h*	[mm]	1000	Single	Normal	1,00	0,61			
	B2.2.6	Derive coefficient k1	0,0008	k1	[-]	1,50	Single	Normal	1,00	0,61			
	B2.2.4	Calculate axial force Ned	0,0008	Ned	[N]	5000	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$
	B2.2.3 and B2.2.5	Calculate concrete mean stress	0,0326	σc	N/mm2	0,04	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ 10$^{(-)2}$ and 10$^{(-)1}$

Human Error Probabilities (Inexperienced Designer)								First distribution			Second distribution		
	Task Sequence	Task description	Failure prob.	aramete	Unit	Mean value	distribution	Probability	Failure* fraction	Standard dev.	Probability	Failure* fraction	Values
Crack width control (node B2)	B2.2.1 and B2.2.8	Calculate Coefficient Kc	0,0133	kc	[-]	0,39	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.3.1 and B2.3.2	Determine coefficent k	0,0227	k	[-]	1,00	Single	Normal	1,00	0,61	▨	▨	▨
	B2.3.3 to B2.3.5	Decide on σs = fyk	0,0130	σs	N/mm2	30,00	Single	Normal	1,00	0,61	▨	▨	▨
	B2.3.6	Calculate As;min;3	0,0008	As,min,3	[mm2]	248,77	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.2 and B2.4.3	Determine neutral axis	0,0424	x	[mm]	200	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.1 and B2.4.4	Calculate stress bottom reinforcer	0,0326	σsb	N/mm2	220,48	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.1 and B2.4.4	Calculate stress top reinforcemen	0,0326	σss	N/mm2	281,53	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.5.4 and B2.5.5	Determine coefficient kt	0,0132	kt	[-]	0,60	Single	Normal	1,00	0,61	▨	▨	▨
	B2.5.6 and B2.5.7	Calculate effective height	0,0133	hc,ef	[mm]	100	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.5.8	Calculate effective area concrete	0,0000	Ac,eff	[mm2]	27500	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.1 and B2.5.9	Calculate reinforcement ratio bot	0,0133	ρp,eff,b	[-]	0,055	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.1 and B2.5.9	Calculate reinforcement ratio top	0,0133	ρp,eff,s	[-]	0,066	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.5.1 to B2.5.3	Calculate ratio E-moduli	0,0125	αe	[-]	7,50	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.1 and B2.5.1	Calculate effective strain bottom	0,0326	εsm-εcm)	[-]	8,38E-04	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.1 and B2.5.1	Calculate effective strain btop	0,0326	εsm-εcm)	[-]	1,15E-03	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.6.1 and B2.6.2	Determine k1	0,0132	k1	[-]	0,80	Single	Normal	1,00	0,61	▨	▨	▨
	B2.6.1 and B2.6.2	Determine k2	0,0132	k2	[-]	0,50	Single	Normal	1,00	0,61	▨	▨	▨
	B2.6.1 and B2.6.2	Determine k3	0,0132	k3	[-]	3,40	Single	Normal	1,00	0,61	▨	▨	▨
	B2.6.1 and B2.6.2	Determine k4	0,0132	k4	[-]	0,43	Single	Normal	1,00	0,61	▨	▨	▨
	B2.4.1 and B2.6.3	Calculate Sr,max bottom	0,0133	Sr,max,d	[mm]	169,66	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.4.1 and B2.6.3	Calculate Sr,max top	0,0133	Sr,max,s	[mm]	141,82	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.6.4	Calculate crack width bottom	0,0008	wk,d	[mm]	0,14	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.6.4	Calculate crack width top	0,0008	wk,s	[mm]	0,16	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B2.6.5 and B2.6.6	Determine allowed crack width	0,0132	wk,all	[mm]	0,30	Comb.	Normal	1,00	0,61	Discrete		e
	B2.6.7	Check allowable crack width	0,0103		[-]	Yes	▨	▨	▨	▨	▨	▨	▨ e
Column design	B3.1.1	Calculate maximum normal force	0,0008	Nc,1	[kN]	436,60	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B3.1.2	Calculate maximum Moment	0,0008	Mc,1	[kNm]	71,47	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B3.1.3	Derive column width	0,0008	Bc	[mm]	275	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B3.1.4	Determine column depth	0,0103	Hc	[mm]	275	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{(-)3}$ $10^{(-)2}$ and $10^{(-)7}$
	B3.1.5	Determine concrete cover	0,0103	Cc	[mm]	30,00	Single	Normal	1,00	0,61	▨	▨	▨

Human Error Probabilities (Inexperienced Designer)								First distribution			Second distribution		
	Task Sequence	Task description	Failure prob.	arameter	Unit	Mean value	distribution	Probability	Failure* fraction	Standard dev.	Probability	Failure* fraction	Values
Column design	B3.1.6 and B3.1.7	Calculate 1st order reinforcement	0,0202	Asc,1	[mm2]	745	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$)^{(-)3}$ $10^{(-)2}$ and $10^{(-)1}$
	B3.1.8	Choose reinforcement layout	0,0300	Asc;prov	[mm2]	756	Single	Normal	1,00	0,61			
		No. Bars top		No;Ast	[No.]	2							
		Bar diameter top		d;Ast	[mm2]	22							
	B3.2.2	Calculate α-factor	0,0008	αn,1	[-]	0,23	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$^{-)3}$ $10^{(-)2}$ and $10^{(-)10}$
	B3.2.3	Calculate reinforcement ratio	0,0008	ρc	[-]	0,010	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{-)3}$ $10^{(-)2}$ and $10^{(-)13}$
	B3.2.4	Calculate fictitious elasticity modu	0,0008	Ef,1	N/mm2	10444,68	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$^{-)3}$ $10^{(-)2}$ and $10^{(-)14}$
	B3.2.5	Calculate I	0,0008	I	[mm4]	4,77E+08	Comb.	Log-norm	0,70	0,67	Discrete	0,30	$^{-)3}$ $10^{(-)2}$ and $10^{(-)17}$
	B3.2.6	Calculate EI-column	0,0008	EI,1	[Nmm2]	4,98E+12	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$^{-)3}$ $10^{(-)2}$ and $10^{(-)18}$
	B3.3.1 and B3.3.2	Calculate buckling force	0,0008	NB,1	[kN]	10530,21	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$^{-)3}$ $10^{(-)2}$ and $10^{(-)21}$
	B3.3.3	Calculate second order moment	0,0202	MEd,1	[kNm]	74,03	Comb.	Log-norm	0,70	1,35	Discrete	0,30	$^{-)3}$ $10^{(-)2}$ and $10^{(-)24}$
	B3.3.4	Calculate Concrete compression	0,0202	fc,1	N/mm2	29,20	Single	Discrete	1,00				[e]
	B3.3.5 and B3.3.6	Check allowable concrete compre	0,0103	fc	[-]		Single	Discrete	1,00				[e]
	B3.3.7 to B3.3.9	Check reinforcement stress	0,0013	fy	N/mm2	334,00	Single	Discrete	1,00				[e]
	B3.4.1 and B3.4.2	Derive minimum diameter	0,0132	ϕmin	[mm]	8,00	Single	Normal	1,00	0,61			
	B3.4.3	Check minimum diameter	0,0005	ϕmin	[mm]		Single	Discrete	1,00				[e]
	B3.4.4 and B3.4.5	Check minimum reinforcement	0,0013	As,min,c	[mm2]	100,37	Single	Discrete	1,00				[e]

* Fraction of the total number of failures in which the distribtion occurred

[a] Selecting beam length in X-direction (5,4) instead of Y-direction.

[b] Multiplying Load [kN/m] with wrong widths: Y-direction instead of X-direction (7,6) or unity length (1,0)

[c] Selecting wrong safety factor out of 1,0 1,2 1,35 1,5

[d] Overlooking one of the load cases

[e] Error in choice

[f] Choosen concrete strength is C25/30

[g] Equals beam width (hb)

G

STRUCTURAL ANALYSIS

Contents

INTRODUCTION

This appendix provides background information on the probabilistic analysis methodology presented in this research. The first part discusses the upper bound analysis. The second part discusses the lower bound analysis. The last part presents the results of the calculations used within the lower bound analysis.

UPPER BOUND ANALYSIS

The upper bound calculations are based on plastic equilibrium equations. In this section the equilibrium equations for the statical determined and undetermined beam will be presented.

Plastic capacity cross section

Within the equilibrium equations used in the upper bound analysis, the plastic moment capacity of a cross-section is required. Within the structure three cross-sectional types are differentiated. Two beam cross section comprising of a cross-section at the support location and a cross section at mid-span. The third cross-section is the column cross section. The plastic moment capacity of a cross section is based on the equations given in equation 11. The resulting plastic capacity of a cross section is given in equation 12. Within these formulas the positive effect of reinforcement in the compression zone is not taken into account.

$$\begin{aligned} &M = 0 \Rightarrow Asfyk - XB_bfck \\ &V = 0 \Rightarrow Mp - Asfyk(H_b - c - Z_t) - fckB_bX(Z_t - \frac{1}{2}X) \\ &Z_t = \frac{B_bEc\frac{1}{2}X^2 + AsEs(H_b - c)}{XB_bEc + AsEs} \end{aligned} \tag{11}$$

$$Mp = -\frac{\frac{1}{2}Asfyk(-2H_bfckB_b + 2cfckB_b + Asfyk}{fckB_b} \tag{12}$$

Statically determined beam

In order to form a mechanism in the statical determined beam one hinge is required. A logical location is at the maximum field moment at midspan of the beam. This is depicted in figure 52. The derivation of the equilibrium equation of this mechanism is given in equation 13.

$$\begin{aligned} &A = \frac{1}{4}ql^2 \\ &E = 2Mp \\ &Mp \leqslant \frac{1}{8}ql^2 \end{aligned} \tag{13}$$

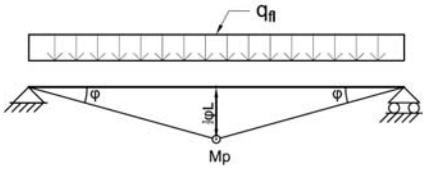
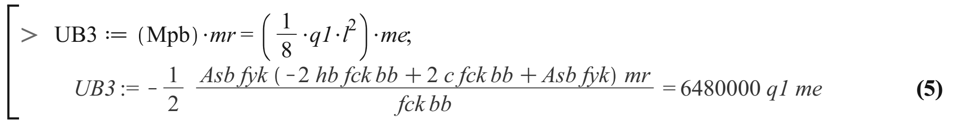


Figure 52: Mechanism statically determined beam

Combination of the formulas 12 and 13 results in a formula for the reliability function as a function of the resistance and loading parameters of the cross section. The basic form of this formula is given in figure 53.


$$> \mathrm{UB3} := (\mathrm{Mpb})\cdot mr = \left(\frac{1}{8}\cdot q1\cdot l^2\right)\cdot me;$$

$$UB3 := -\frac{1}{2}\,\frac{Asb\,fyk\,(-2\,hb\,fck\,bb + 2\,c\,fck\,bb + Asb\,fyk)\,mr}{fck\,bb} = 6480000\,q1\,me \qquad \mathbf{(5)}$$

Figure 53: Equation of the reliability function of the statically determined beam

Statically undetermined beam

The reliability function for the statically undetermined beam is not that straightforward, as 19 hinges are required to form a mechanism. This seems rather unrealistic and as a consequence failure by partial mechanisms is governing. These partial mechanisms are in line with the progressive collapse theorem: partial collapse of a beam, column or parts of the structure. This thesis focusses on partial collapse of a beam resulting in two realistic mechanisms, which are given beneath.

In order to form a mechanism in the statical undetermined beam three hinges are required. the partial mechanisms used within this research are depicted in figure 54 and 55. Mechanisms which are not considered are: buckling mechanisms and mechanisms in the roof beams. The derivation of the equilibrium equations of this mechanisms are given in the equations 14 and 15 respectively.

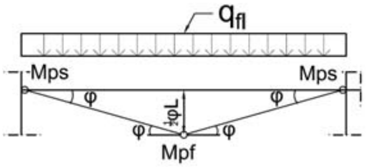


Figure 54: Partial mechanism one of the statically undetermined beam

$$\begin{aligned} A &= 2Mp_S + 2Mp_F \\ E &= \frac{1}{4}q_{FL}l_b^2 \\ Mp_S + Mp_F &\leqslant \frac{1}{8}q_{FL}l_b^2 \end{aligned} \tag{14}$$

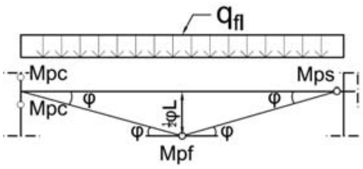
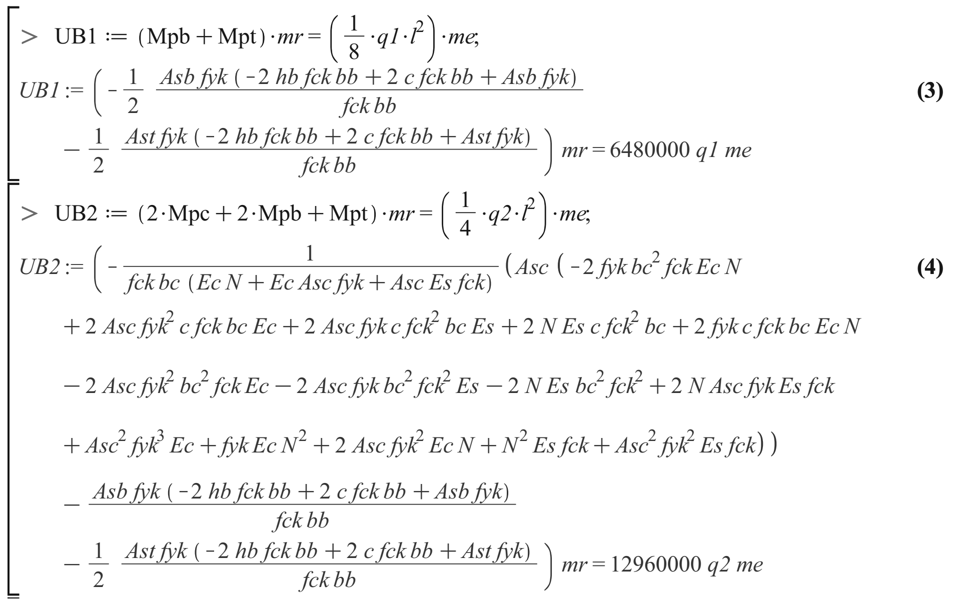


Figure 55: Partial mechanism two of the statically undetermined beam

$$\begin{aligned} A &= Mp_S + 2Mp_F + 2Mp_C \\ E &= \frac{1}{4} q_{FL} l_b^2 \\ Mp_S + 2Mp_F + 2Mp_C &\leqslant \frac{1}{4} q_{FL} l_b^2 \end{aligned} \tag{15}$$

Combination of these formulas results in a formula for the reliability function as a function of the dimensional- and material parameters from the cross section. The basic forms of this formula is presented in figure 56. It should be noted that the second formula (UB2) is differentiating from the first formula due to the inclusion of normal column force in this formula.



$$> \mathrm{UB1} := (\mathrm{Mpb} + \mathrm{Mpt}) \cdot mr = \left(\frac{1}{8} \cdot q1 \cdot l^2\right) \cdot me;$$

$$UB1 := \left(-\frac{1}{2} \frac{Asb\, fyk\, (-2\, hb\, fck\, bb + 2\, c\, fck\, bb + Asb\, fyk)}{fck\, bb} - \frac{1}{2} \frac{Ast\, fyk\, (-2\, hb\, fck\, bb + 2\, c\, fck\, bb + Ast\, fyk)}{fck\, bb}\right) mr = 6480000\, q1\, me \tag{3}$$

$$> \mathrm{UB2} := (2 \cdot \mathrm{Mpc} + 2 \cdot \mathrm{Mpb} + \mathrm{Mpt}) \cdot mr = \left(\frac{1}{4} \cdot q2 \cdot l^2\right) \cdot me;$$

$$\begin{aligned} UB2 := \Bigg(&-\frac{1}{fck\, bc\, (Ec\, N + Ec\, Asc\, fyk + Asc\, Es\, fck)} \big(Asc\, \big(-2\, fyk\, bc^2\, fck\, Ec\, N \\ &+ 2\, Asc\, fyk^2\, c\, fck\, bc\, Ec + 2\, Asc\, fyk\, c\, fck^2\, bc\, Es + 2\, N\, Es\, c\, fck^2\, bc + 2\, fyk\, c\, fck\, bc\, Ec\, N \\ &- 2\, Asc\, fyk^2\, bc^2\, fck\, Ec - 2\, Asc\, fyk\, bc^2\, fck^2\, Es - 2\, N\, Es\, bc^2\, fck^2 + 2\, N\, Asc\, fyk\, Es\, fck \\ &+ Asc^2\, fyk^3\, Ec + fyk\, Ec\, N^2 + 2\, Asc\, fyk^2\, Ec\, N + N^2\, Es\, fck + Asc^2\, fyk^2\, Es\, fck\big)\big) \\ &- \frac{Asb\, fyk\, (-2\, hb\, fck\, bb + 2\, c\, fck\, bb + Asb\, fyk)}{fck\, bb} \\ &- \frac{1}{2} \frac{Ast\, fyk\, (-2\, hb\, fck\, bb + 2\, c\, fck\, bb + Ast\, fyk)}{fck\, bb}\Bigg) mr = 12960000\, q2\, me \end{aligned} \tag{4}$$

Figure 56: Equation of the reliability function of the statically undetermined beam

In the case of the statically undetermined beam there is not a single reliability function but two reliability functions, as two failure mechanisms are governing the failure domain. Depending on the numerical values of the design parameters, one of these curves will determine the probability of failure. If the domain is restricted to three parameters (Hb, Asb, Ast) and the other parameters are kept deterministic, the failure domain consists of two curves as shown in figure 57. It can be seen from this figure that both reliability functions are governing in a part of the solution domain.

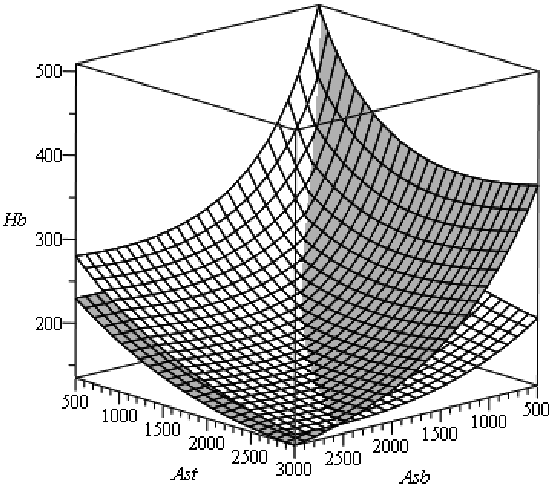


Figure 57: Governing failure curves on the failure domain Ast, Asb, Hb.

LOWER BOUND

The lower bound solution is calculated with the engineering program SCIA Engineer. The structure is modelled with 1-D elements. Table 19 list relevant properties of the calculation. The calculation is executed with geometrical and physical non-linearity. The geometrical non-linearity is modelled by geometrical deviations in the mesh points of the 1-D elements. The physical non-linearity is modelled by iterating towards equilibrium over the composite cross section. For this SCIA engineer uses the following procedure: the member is discretized in a number of sections. During the calculation process stiffness is modified for the sections where cracking takes place (SCIA, 2012). This is done by the same equations as for the upper bound analysis. As a result only σ_{xx} and ε_{xx} can be evaluated.

Table 19: Numeric properties SCIA calculation

Elements	1-D elements
Mesh length	50 mm
Solver type	Direct solver
Numeric solver	Modified Newton-Raphson
No. geometrical increments	5
cross-sectional iterations	50

In order to approximate the results of the upper bound analysis, the material properties within the lower bound calculation are kept almost similar. For this reason steel tension stiffening and concrete tensional forces are not considered. The stress/strain curves of these material properties are shown in figure 58. Another assumption is that failure occurs if the ultimate stress is reached within the cross section, and not the ultimate strain.

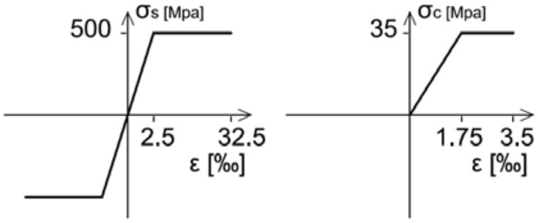


Figure 58: Stress-strain curve of reinforcement steel (left) and concrete (right) within the lower bound analysis

The failure curves found with the upper bound analysis are checked on a number of discrete point on the failure curve. These discrete points and there outcomes are given in table 20. The results for the statically determined beam are reasonable coinciding, as expected. For the statically undetermined beam this is somewhat different. In cases with a normal reinforcement layout and a design with a low amount of top reinforcement / high amount of bottom reinforcement, the values for the upper and lower bound reasonable coincide. In case of a high amount of top reinforcement / low amount of bottom reinforcement, the outcome differentiates considerable. It is not clear why this is occurring.

Table 20: Comparison of the results of the lower bound and the upper bound analysis

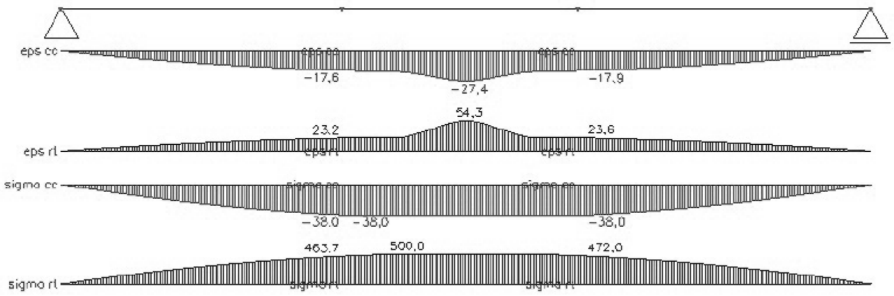
Beam parameters				Analysis results	
Structural type	Bb	Ast	Asb	h_b upper bound	h_b lower bound
Stat. determ.	400	226	1808	417	420
Statically	250	1808	1520	233	235
undetermined	250	628	2463	288	290
beam	250	2463	628	372	<350

RESULTS SCIA ENGINEER

The lower bound calculations are based on finite element analysis, conducted with the program SCIA engineer. Within the lower bound analysis, the correctness of the applicability of the upper bound equations is checked. Within this part, the results of the calculations are presented. Furthermore, there applicability is discusses as well.

Statical determined beam

For the lower bound check of the statical determined beam the correctness of formula 13 is checked. For this a single calculation is executed on a predefined point on the failure curve. According to the upper bound equation a structure with a bottom reinforcement of 1808 mm^2 will fail if the height of the beam is smaller then 417 mm. According to the lower bound analysis a plastic hinge will form if the beam height is approximately 420 mm. From this it can be concluded that the lower bound calculation coincides reasonable with the upper bound analysis. For completeness, the stress and strain properties of the beam with a height of 420 mm are presented in figure 59.



eps cc: Max. concrete compressive strain.
eps rt: Max. reinforcement tensional strain.
sigma cc: Max. concrete compressive stress.
sigma rt: Max. reinforcement tensional stress.

Figure 59: Strains and stresses of beam at ultimate capacity.

Statical undetermined beam

For the lower bound check of the statical undetermined beam the correctness of formulas 14 and 15 is checked. Within this analysis the beam width is kept equal to the design value (250 mm), while the beam height is variable in order to coincide with the upper bound results.

Within this section a single case will be considered in more detail. In this case a loading condition of 60 $\mathrm{kN/m}$ is applied resulting in a minimum beam height according to the upper bound calculation of 320 mm. Within the lower bound calculation a beam height of 325 mm is considered, as failure occurred in case of a beam height of 320 mm. In the lower bound no failure occurred. With a difference of 5 mm between the lower and upper bound calculation it can be concluded that both calculations coincide, hence the correct upper bound is determined. The resulting maximum stresses within the concrete and reinforcement of the cross-section is shown in the figures 60 and 61.

Some further attention is given to the stress-strain relation within two cross sections of the lower left beam: the cross section at beam midspan (figure 62 to 65) and at the right support (figure 66 to 69).

It can be seen from these pictures that the maximum stress in the concrete compression zone in both cross sections has some extra capacity. However the maximum concrete strain is almost reached, from this it can be concluded that the maximum capacity of the concrete is reached. The stress in the tensile reinforcement equals 500 $\mathrm{N/mm}^2$. Furthermore the reinforce-

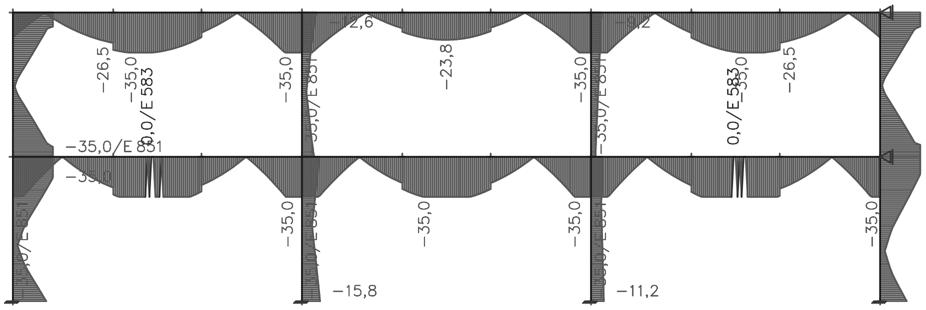


Figure 60: Maximum Concrete compression [N/mm^2] within the beam cross-section of the frame structure

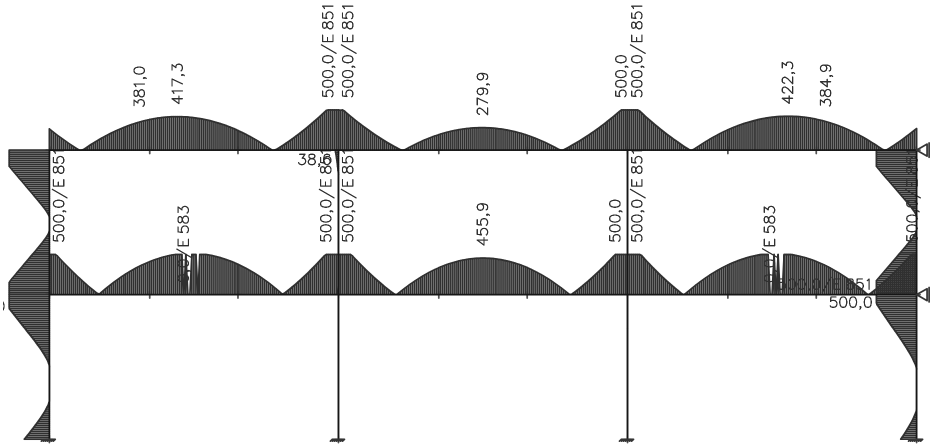


Figure 61: Maximum reinforcement tension [N/mm^2] within the beam cross-section of the frame structure

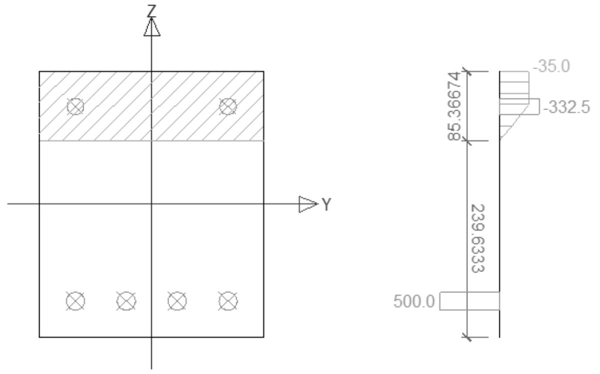


Figure 62: Stresses within the cross-section at mid-span

ment strain has not reached his limits in both cross sections. This entails that the reinforcement capacity is not reached yet. It can be concluded from this analysis that the maximum cross sectional capacity is almost reached, as concrete crushing is almost occurring. Further increase in the loading conditions will result in a mechanism, hence SCIA cannot run this analysis.

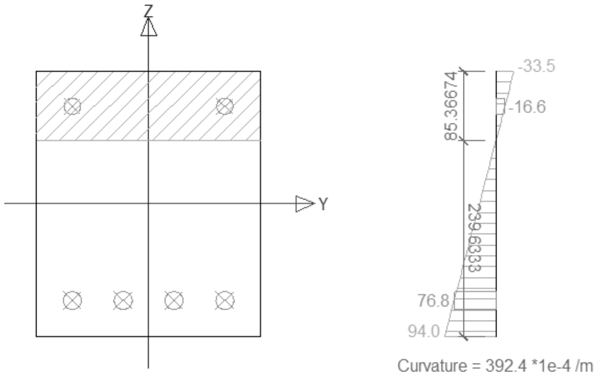


Figure 63: Strains within the cross-section at mid-span

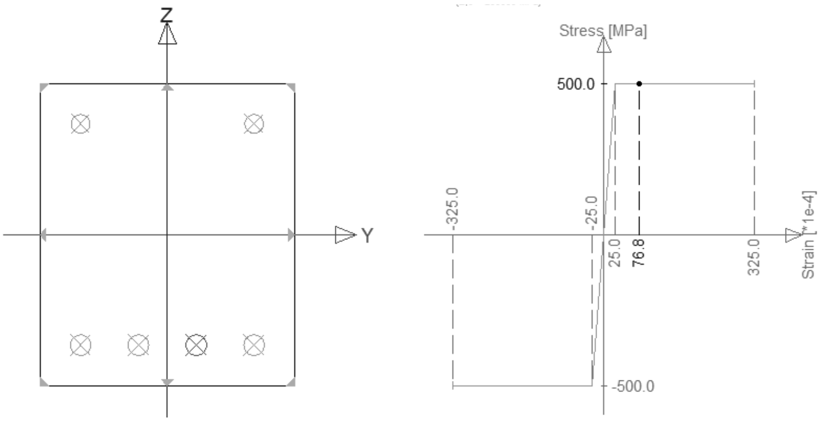


Figure 64: Reinforcement Stress - strain relation within tensile reinforcement of the cross-section at mid-span

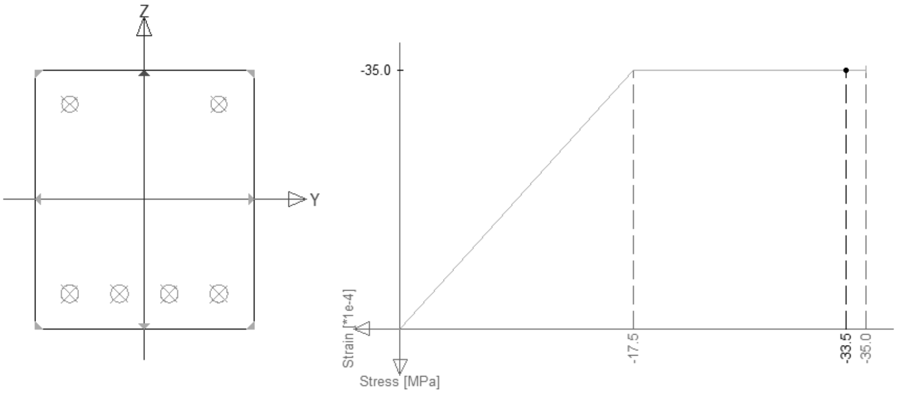


Figure 65: Concrete Stress - strain relation within concrete compressive zone of the cross-section at mid-span

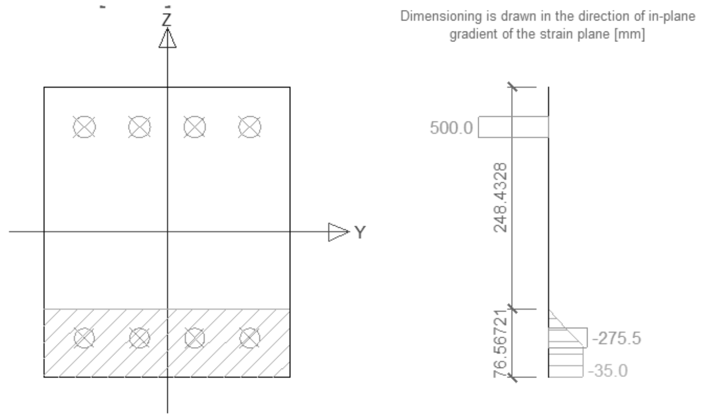


Figure 66: Stresses within the cross-section at the support

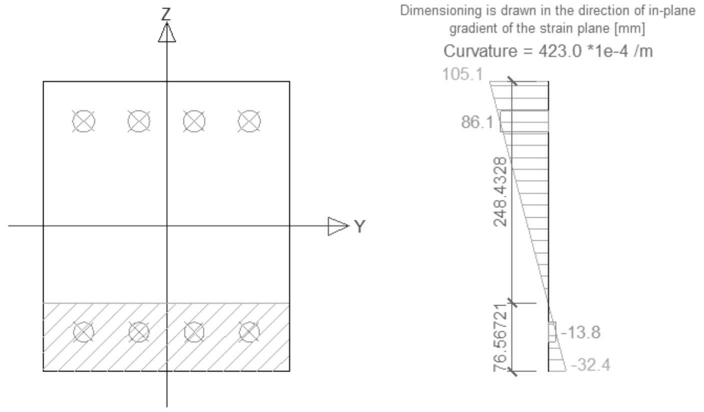


Figure 67: Strains within the cross-section at the support

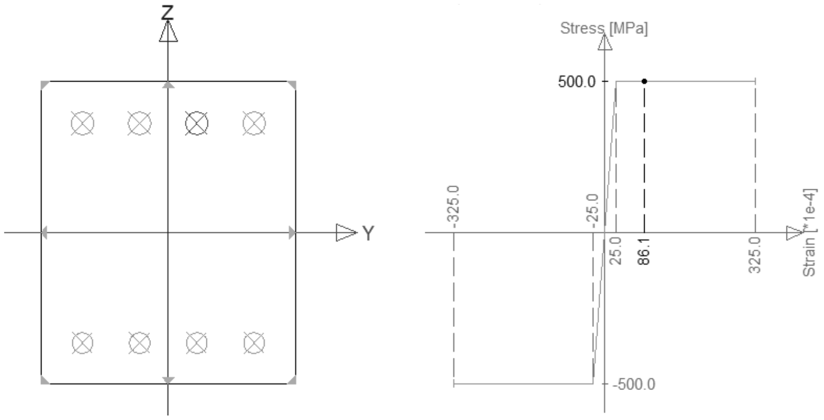


Figure 68: Reinforcement Stress - strain relation within tensile reinforcement of the cross-section at the support

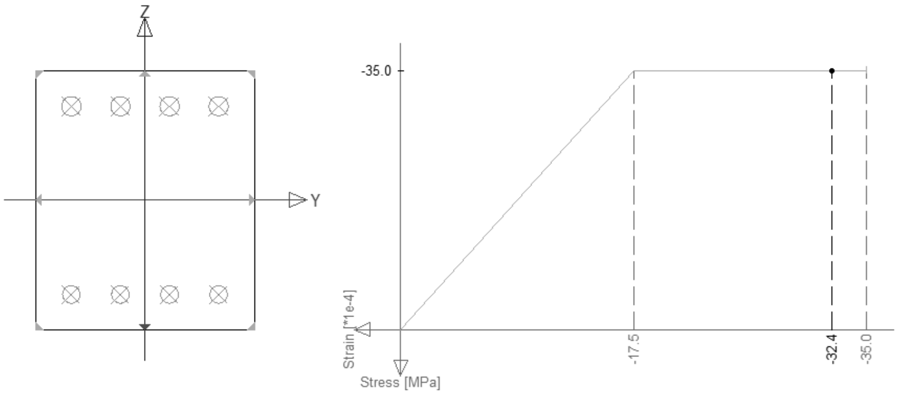


Figure 69: Concrete Stress - strain relation within concrete compressive zone of the cross-section at the support

H

SIMULATION SCRIPT

Contents

INTRODUCTION

Within this appendix the use of the Matlab program for the Monte Carlo and the FORM analysis is set-apart. This appendix contains two parts. Firstly the predefined bounds within the self-checking processes are presented. Secondly some brief elements of the used Matlab script are given.

SELF-CHECKING BOUNDARIES

Within the Monte-Carlo simulation, self-control is based on the notion that a designer uses his previous experience as a reference for assessing the correctness of the results. Within this process, the output of a series of micro-tasks is compared with the correct output of the series of micro-tasks. If the output is within predefined limits, the output is deemed correct and the design process continues. If the output is not within these predefined limits, reconsidering of the series of micro-tasks is performed. In order to perform this comparison, the correct output is multiplied with a numerical value to represent the upper- and lower bound limits. These numerical values are different for experienced and inexperienced designers. Furthermore, the values are also based on overview of the situation. For instance the beam height is quite easy to overview as anyone has some idea about a correct beam height. Opposite to this are parameters which are harder to estimate on advance. The values are presented in table 21.

Table 21: Numerical multiplication values of the self-checking limits

Parameter	Lower bound		Upper bound	
	Experienced	Inexperienced	Experienced	Inexperienced
Hb	0,6	0,5	1,6	1,7
Bb	0,55	0,45	2,18	2,36
gl	0,45	0,36	2,63	2,82
Md/Ms	0,46	0,38	3,46	3,61
Ast	0,24	0,20	4,24	4,39
Asb	0,23	0,20	4,24	4,39
Asprac	0,32	0,29	2,94	3,08
Asmax	0,5	0,5	-	-
Asmin	0,4	0,4	2	2
AsbProv	0,33	0,26	4,96	5,25
AstProv	0,28	0,22	4,17	4,24
Bc	0,55	0,45	2,18	2,36
Mc	0,46	0,38	3,46	3,61
Asc	0,24	0,20	4,24	4,39
AscProv	0,33	0,26	4,96	5,25

MATLAB SCRIPT

Within this part the used Matlab script is presented. The following elements of the script are presented: basic micro-task function file, self-checking and micro-task sequences, superior control, Monte Carlo Loading conditions, Monte Carlo Probability analysis and FORM analysis.

MICRO-TASK FUNCTION FILES

```
% B1.5.2: Estimate Cmin

function[Cminn] = Cminn(ndata)
[r] = find(ndata==2152);
FPCmin=ndata(r,3);
CMIN=ndata(r,2);
EMCmin=random('Normal',1,ndata(r,4));
RNCmin=rand(1);
if   RNCmin<FPCmin;
     Cminn=EMCmin*CMIN;
else Cminn=CMIN;
end
```

```
% B1.7.4: Calculate As;min;1

function[Output] = Asmin1n(ndata,fctm,fyk,Bt,d)
[r] = find(ndata==2174);
FP=ndata(r,3);
Parameter= 0.26*(fctm/fyk)*Bt*d;

EM=random('Lognormal',0,ndata(r,4));

FP=FP*0.70;
FP1=FP*0.105;
FP2=FP*0.015;
FP3=FP*0.03;

NP=1-FP;
DFP = randp([FP FP3 FP2 FP1 FP1 FP2 FP3 NP],1,1);

Output(DFP==1)=EM*Parameter;
Output(DFP==2)=10^-3*Parameter;
Output(DFP==3)=10^-2*Parameter;
Output(DFP==4)=10^-1*Parameter;
Output(DFP==5)=10^1*Parameter;
Output(DFP==6)=10^2*Parameter;
Output(DFP==7)=10^3*Parameter;
Output(DFP==8)=Parameter;
```

```
% B1.8.6: Decide top reinforcement layout

function[Asc_Prov,D_Asc,No_Asc] = Ascprovn(ndata,Astab,Asc)

[r] = find(ndata==2317);
FP=ndata(r,3);

FP1=FP/2;
NP=1-FP;
DFP = randp([NP FP1 FP1],1,1);

C1=(Astab(:)-Asc);
C1(C1 < 0) = [1000];
[~,ind1] = min(C1);
[m1,n1] = ind2sub(size(Astab),ind1);

Asc_Prov(DFP==1) = Astab(m1,n1);
D_Asc(DFP==1) = Astab(m1,1);
No_Asc(DFP==1) = Astab(1,n1);

C2=(Astab(:)-(Asc-(0.1*Asc)));
C2(C2 < 0) = [1000];
[~,ind2] = min(C2);
[m2,n2] = ind2sub(size(Astab),ind2);

Asc_Prov(DFP==2) = Astab(m2,n2);
D_Asc(DFP==2) = Astab(m2,1);
No_Asc(DFP==2) = Astab(1,n2);

C3=(Astab(:)-(Asc+(0.1*Asc)));
C3(C3 < 0) = [1000];
[~,ind3] = min(C3);
[m3,n3] = ind2sub(size(Astab),ind3);

Asc_Prov(DFP==3) = Astab(m3,n3);
D_Asc(DFP==3) = Astab(m3,1);
No_Asc(DFP==3) = Astab(1,n3);
```

```
NoSIM=100000;

for i=1:NoSIM

% Task 0: Determine material parameters
fykd(i)=fykn(ndata);
fckd(i)=fckn(ndata);
fctm(i)=fctmn(ndata);

% Task A: Calculate Reinforcement
% Step A1: Calculate beam height (with self-control)
count=0;
while 0.6*Hbcorrect > Hb(i) || Hb(i)>1.6*Hbcorrect;
%while 0.5*Hbcorrect > Hb(i) || Hb(i)>1.7*Hbcorrect;
a1(i)=a1n(ndata);
Ly(i)=Lyn(ndata);
Leff(i)=Leffn(ndata,Ly(i),a1(i));
Hb(i)=Hbn(ndata,Leff(i));
count=count+1;
if count>2;
    break
end
end

% Step A3: Calculate Distributed load/moment force(with self-control)

count=0;
while (5/11)*qlcorrect > ql(i) || ql(i) > (29/11)*qlcorrect ||
(6/13)*Mdcorrect > Md(i) || Md(i) > (45/13)*Mdcorrect || (6/13)*Mscorrect >
Ms(i) || Ms(i) > (45/13)*Mscorrect;
%while (4/11)*qlcorrect > ql(i) || ql(i) > (31/11)*qlcorrect ||
(5/13)*Mdcorrect > Md(i) || Md(i) > (47/13)*Mdcorrect || (5/13)*Mscorrect >
Ms(i) || Ms(i) > (47/13)*Mscorrect;
Yc(i)=Ycn(ndata);
qdb(i)=qdbn(ndata,Ac(i),Yc(i));
qds(i)=qdsn(ndata);
qks(i)=qksn(ndata);
Yi1(i)=Yi1n(ndata);
Yi2(i)=Yi2n(ndata);
qdl(i)=qdln(ndata,Yi1(i),qdb(i),qds(i));
qll(i)=qlln(ndata,Yi2(i),qks(i));
ql(i)=qdl(i)+qll(i);
Md(i)=Mdn(ndata,qdl(i),qll(i),Leff(i));
Ms(i)=Msn(ndata,qdl(i),qll(i),Leff(i));
count=count+1;
if count>2;
    break
end
end
```

```
for i=1:NoSIM
count=0;
% Task S: Checking by different person
while 0.6*Hbcorrect > HbS(i) || HbS(i)>1.6*Hbcorrect || (6/11)*Bbcorrect >
BbS(i) || BbS(i)>0.8*HbS(i) || BbS(i)>(24/11)*Bbcorrect || (6/13)*Mdcorrect >
MdS(i) || MdS(i) > (45/13)*Mdcorrect || (6/13)*Mscorrect > MsS(i) || MsS(i) >
(45/13)*Mscorrect || (500/1808)*Ast_Provcorrect > Ast_ProvS(i) || Ast_ProvS(i)
> (7541/1808)*Ast_Provcorrect || (500/1520)*Asb_Provcorrect > Asb_ProvS(i) ||
Asb_ProvS(i) > (7541/1520)*Asb_Provcorrect;
% Task 0: Determine material parameters
    fykS(i)=fykn(ndataS);
    fckS(i)=fckn(ndataS);
    fctmS(i)=fctmn(ndataS);
    YcS(i)=Ycn(ndataS);
% Step A1: Calculate beam height
    HbS(i)=Hbn(ndataS,Leff(i));
%Step A2: Calculate concrete area
    BbS(i)=Bbn(ndataS,HbS(i));
% Step A3: Calculate Distributed load / Moment force
    qdbS(i)=qdbn(ndataS,Ac(i),YcS(i));
    qdsS(i)=qdsn(ndataS);
    qksS(i)=qksn(ndataS);
    qdlS(i)=qdln(ndataS,Yi1S(i),qdbS(i),qdsS(i));
    qllS(i)=qlln(ndataS,Yi2S(i),qksS(i));
    qlS(i)=qdlS(i)+qllS(i);
    MdS(i)=Mdn(ndataS,qdlS(i),qllS(i),Leff(i));
    MsS(i)=Msn(ndataS,qdlS(i),qllS(i),Leff(i));
% step A5: Calculate Applied reinforcement
    dS(i)=dn(ndataS,HbS(i),Cmin(i),mr_sr(i));
    AstS(i)=Astn(ndataS,MsS(i),fykS(i),d(i));
    AsbS(i)=Asbn(ndataS,MdS(i),fykS(i),d(i));
    [AspracS(i),D_AspS(i),No_AspS(i)]=Aspracn(ndataS);
% Step D11: Choose Top/bottom reinforcement
    [Ast_ProvS(i),D_AstS(i),No_AstS(i)] = Astprovn(ndataS,Astab,AstS(i));
    AstS(i)=Ast_ProvS(i);
    [Asb_ProvS(i),D_AsbS(i),No_AsbS(i)] = Asbprovn(ndataS,Astab,AsbS(i));
    AsbS(i)=Asb_ProvS(i);
count=count+1;
if count>3;
    break
end

if Hb(i) < 0.7*HbS(i) || Hb(i) > 1.35*HbS(i) || Bb(i) < 0.7*BbS(i) || Bb(i) >
1.35*BbS(i) || Ast(i) < 0.7*AstS(i) || Ast(i) > 1.35*AstS(i) || Asb(i) <
0.7*AsbS(i) || Asb(i) > 1.35*AsbS(i);
Ast(i) = [0];
end

if Ast(i) > 0;
    No(i)=1;
else No(i)=0;
end
```

```
% model uncertainties
mumr=1;
sigmamr=0.05;
mr(i)=random('Normal',mumr,sigmamr);
mume=1;
sigmame=0.1;
me(i)=random('Normal',mume,sigmame);

% Permanent load beam
murhobeam=25;
sigmarhobeam=1;
murhocolumn=25;
sigmarhocolumn=1;
R = [1.000 0.7
     0.7 1.000];
s = [1;1];
V = s*s';
SIGMA = V.*R;
MU=[25,25];
R = mvnrnd(MU,SIGMA);
rhoB(i)=R(1,1);
rhoC(i)=R(1,2);
qbeam(i)=rhoB(i)*Hb(i)*Bb(i)*10^-6;

% Permanent load slab floors

murhoslab=25;
sigmarhoslab=1;
rhoslab(i)=random('Normal',murhoslab,sigmarhoslab);
muHslabMC=160;
sigmaHslab=1.12;
Hslab(i)=random('Normal',muHslabMC,sigmaHslab);
Lxreal(i)=Lxrealn(ndata);
qslab(i)=Lxreal(i)*rhoslab(i)*Hslab(i)*10^-3;

% Concrete strengths
mufck = fckd(i);
sigmafck = 0.123;
fcktr(i)=random('Lognormal',mufck,sigmafck);

mualphafck = 0.85;
sigmaalphafck = 0.085;
fck(i)=random('Normal',mualphafck,sigmaalphafck)*fcktr(i);

% Steel strengths
mufyk = 560;
sigmafyk = 30;
fyk(i)=random('Normal',mufyk,sigmafyk);
```

```
% Imposed load slab floor
for z = 1:10;
shapeqlong=.5;
scaleqlong=.637;
qlongtr(z)=random('Gamma',shapeqlong,scaleqlong);
end

for x = 1:5;
qlong(x)=qlongtr(1);
end
for x = 6:10;
qlong(x)=qlongtr(2);
end
for x = 11:15;
qlong(x)=qlongtr(3);
end
for x = 16:20;
qlong(x)=qlongtr(4);
end
for x = 21:25;
qlong(x)=qlongtr(5);
end
for x = 26:30;
qlong(x)=qlongtr(6);
end
for x = 31:35;
qlong(x)=qlongtr(7);
end
for x = 36:40;
qlong(x)=qlongtr(8);
end
for x = 41:45;
qlong(x)=qlongtr(9);
end
for x = 46:50;
qlong(x)=qlongtr(10);
end

for x=1:50;
muqshort=.2;
sigmashort=.32;
qshort(x)=random('Gamma',muqshort,sigmashort);
qimposedtr(x)=qlong(x)+qshort(x);
qimposed(i)=max(qimposedtr)*Lxreal(i);
end

% Transfer forces
qload(i)=qimposed(i)+qbeam(i)+qslab(i);
```

```
for i=1:NoSIMtr(ii)

% Failure Case 1; three hinges in beam element (UB1)

C1(i) = -6480000*(qload(i));
C2(i) = -(1/2)*((-
2*Asb(i)*Hb(i)*fck(i)*Bb(i)+2*Asb(i)*Cmin(i)*fck(i)*Bb(i)+2*Asprac(i)*Cmin(i)*
fck(i)*Bb(i)+fyk(i)*Asb(i)^2-
2*Asprac(i)*fyk(i)*Asb(i)+Asprac(i)^2*fyk(i))*fyk(i))/(fck(i)*Bb(i));
C3(i) = -(1/2)*((-
2*Ast(i)*Hb(i)*fck(i)*Bb(i)+2*Ast(i)*Cmin(i)*fck(i)*Bb(i)+2*Asb(i)*Cmin(i)*fck
(i)*Bb(i)+fyk(i)*Ast(i)^2-
2*Asb(i)*fyk(i)*Ast(i)+Asb(i)^2*fyk(i))*fyk(i))/(fck(i)*Bb(i));
FM1(i)=C1(i)*me(i)+(C2(i)+C3(i))*mr(i);

C4(i) = -12960000*qload(i);
C5(i) = (-
120*Asc(i)^2*fyk(i)*Cmin(i)*fck(i)^2*Bc(i)+60*Asc(i)^2*fyk(i)*Bc(i)^2*fck(i)^2
-
2680000*Asc(i)*fyk(i)*Cmin(i)*fck(i)*Bc(i)+1340000*Asc(i)*fyk(i)*Bc(i)^2*fck(i
)-
3366750000000*Asc(i)*fck(i)+10050000*Asc(i)*Bc(i)^2*fck(i)^2)/(fck(i)*Bc(i)*(6
70000+30*Asc(i)*fck(i)));
C6(i) = -(((-
2*Asb(i)*Hb(i)*fck(i)*Bb(i)+2*Asb(i)*Cmin(i)*fck(i)*Bb(i)+2*Asprac(i)*Cmin(i)*
fck(i)*Bb(i)+fyk(i)*Asb(i)^2-
2*Asprac(i)*fyk(i)*Asb(i)+Asprac(i)*fyk(i)*Asb(i)+Asprac(i)^2*fyk(i))*fyk(i))/
(fck(i)*Bb(i)));
C7(i) = -(1/2)*(((-
2*Ast(i)*Hb(i)*fck(i)*Bb(i)+2*Ast(i)*Cmin(i)*fck(i)*Bb(i)+2*Asb(i)*Cmin(i)*fck
(i)*Bb(i)+fyk(i)*Ast(i)^2-
2*Asb(i)*fyk(i)*Ast(i)+fyk(i)*Asb(i)^2)*fyk(i))/(fck(i)*Bb(i)));

FM2(i)=C4(i)*me(i)+(C5(i)+C6(i)+C7(i))*mr(i);

if FM1(i)<0 || FM2(i)<0;
    b(i)=1;
else b(i)=0;
end

bt(ii)=sum(b);
pfMC(ii)=sum(b)/NoSIMtr(ii)
BetaMC(ii)=sqrt(2)*erfinv((2*pfMC(ii)-1))

end
```

```
% model uncertainties
%X5: Model factor uncertainty beam/column
X5=mumr;
muX5=X5;
sigmaX5=sigmamr;

% Permanent load beam
%X7: rhobeam
X7=murhobeam;
sigmaX7=sigmarhobeam;
%X8: rhocolumn
X8=murhocolumn;
sigmaX8=sigmarhobeam;

% Lognormal Transformation concrete strength (X13)
fxX13(j)=lognpdf(X13,muX13tr,sigmaX13tr);
FxX13(j)=logncdf(X13,muX13tr,sigmaX13tr);
PhiInvX13(j)=sqrt(2)*erfinv((2*FxX13(j)-1));
fxnormalX13(j)=normpdf(PhiInvX13(j));
sigmaX13= fxnormalX13(j)/fxX13(j);
sigmaX13t(j)=sigmaX13

dX1(j)= X5*(Asb(i)*X14 + Ast(i)*X14) - (162*X2*X6*X7)/25;
dX2(j)= X5*((X14*(Asb(i)^2*X14 + Asprac(i)^2*X14 -
2*Asb(i)*Asprac(i)*X14 - 2*Asb(i)*X1*X13*X2 + 2*Asb(i)*X13*X2*X3 +
2*Asprac(i)*X13*X2*X3))/(2*X13*X2^2) + (X14*(Asb(i)^2*X14 +
Ast(i)^2*X14 - 2*Asb(i)*Ast(i)*X14 - 2*Ast(i)*X1*X13*X2;
2*Asprac(i)*X13*X3))/(2*X13*X2) - (X14*(2*Asb(i)*X13*X3 -
2*Ast(i)*X1*X13 + 2*Ast(i)*X13*X3))/(2*X13*X2)) - (162*X1*X6*X7)/25;

SX1(j)=(dX1(j)*sigmaX1);
SXk1(j)=(SX1(j))^2;

SigmaZ(j)=(SXk1(j)+SXk2(j)+SXk3(j)+SXk5(j)+SXk6(j)+SXk7(j)+SXk9(j)+SXk1
0(j)+SXk11(j)+SXk12(j)+SXk13(j)+SXk14(j))^0.5;
MX1(j)=dX1(j)*(muX1-X1);

SumMX(j)=MX1(j)+MX1(j)+MX2(j)+MX3(j)+MX5(j)+MX6(j)+MX7(j)+MX9(j)+MX10(j
)+MX11(j)+MX12(j)+MX13(j)+MX14(j);

alpha1(j)=(SX1(j)/SigmaZ(j));
alphak1(j)=(SX1(j)/SigmaZ(j))^2;

X1=muX1+alpha1(j)*BetaZtr(j)*sigmaX1;

BetaZ(i)=BetaZtr(NoFORM);
pfZ(i)=(1/2)*(1+erf(-BetaZ(i)/sqrt(2)));
pfZZ1(i)=pfZ(i)*50;

if pfZZ1(i)>1;
    pfZZ1(i)=1;
end
```