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DOCTORAL THESIS

A Probabilistic Approach to Risk Analysis

A comparison between undesirable indoor events and human sensitivity

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“Ge inte upp!
Om snöret inte håller, utan går av, är det
bara att försöka med ett annat snöre.”

Nalle Puh

PREFACE

This research project has been financially supported by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas) and the Development Fund of the Swedish Construction Industry (SBUF), through the Swedish Construction Federation (BI), and they are thankfully acknowledged.

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Now I'm looking forward to enter a new phase in life with a new home town, a new job, and foremost, the forthcoming pheasant hunts and the wealthy …☺

Luleå, November 2005

Katarina Ljungquist

ABSTRACT

Indoor environment and indoor air quality are subjected to extensive worldwide research efforts. There is much to suggest that the creation of good indoor environments is an important factor to health and well-being to humans, and progress is made in the research area of indoor air quality and health. The main objective of this thesis is to develop a probabilistic procedure similar to the one used in modern design codes for building structures. The purpose of the procedure is to estimate the risk of an unhealthy indoor environment to occur, i.e. the risk for humans to become unhealthy indoors because of the design and construction of the building.

The developed risk analysis procedure is based on the IEC standard of risk analysis combined with fault tree analysis (FTA) to evaluate the risk of an unhealthy indoor environment both qualitatively and quantitatively. Structural reliability analysis (SRA) is used in the quantitative evaluation, since several random variables can be handled using functions to express the relationship between the basic events in the fault tree. The use of SRA reveals the risk to be defined as the violation of the limit state function, i.e.:

$$M_{\text{env}} = G(X_{\text{env}}, Y_{\text{env}}) = X_{\text{env}} - Y_{\text{env}} < 0$$

The random variables X_{env} and Y_{env} are defined as:

X_{env} = the dose-response relationship, i.e. the relationship between the exposure to humans of the undesirable indoor event and the proportion of the exposed population suffering from negative health effects.

Y_{env} = the undesirable indoor event, i.e. a function of the environmental impact together with the design and construction of the building.

The objective of the risk analysis is to compare the undesirable indoor event with the consequence to humans, i.e. to estimate the risk by comparing the random variables as in SRA by using either first-order second-moment method (FOSM) or simulation to find the probability of limit state violation, exceeding a threshold value or to estimate the reliability index β.

Environmental impacts with the potential to cause an undesirable indoor event of concern to human health are identified to be microorganisms and substances from microorganisms, emissions, and ionising radiation. The proposed risk analysis process is applied to a single-family dwelling founded on a concrete slab on the ground built in an area with high levels of radon concentrations in soil. The undesirable indoor event Y_{env} "Radon concentrations in indoor air", is evaluated

and compared with the available dose-response relationship X_{env}. The probability of limit state violation living in the single-family dwelling analysed is p_f = 0,002 per year. The undesirable indoor event is also compared with the threshold value 200 Bq/m^3 stipulated in the Swedish Building Regulations to not be exceeded. The probability p_f = 0,0001 to exceed the threshold value. The estimated safety index β = 3,6 is compared with the safety indices in the Swedish Design Regulations where structures are designed according to different safety classes. The estimated safety index is in approximate accordance with safety class 1, which is valid for design of structures where risk for serious injuries or death to humans as a failure consequence is minimal.

The risk analysis process is also applied to a tenant-owned dwelling with the undesirable indoor event Y_{env} defined as "*Legionella* contaminated aerosols in indoor air". The random variables of interest in the analysis are the initiating amount of bacteria, and the time of stagnant water. The constant of specific growth rate was estimated from tests made in the dwelling shower and considered to be deterministic, though it depends on several variables, such as the amount of nutrients, biofilm and water temperature. In the risk estimation, the undesirable indoor event Y_{env} is compared with guiding values, since no dose-response relationship is available describing the sensitivity to *Legionella* bacteria in the population. The probability of exceeding, for example, the guiding value 10 000 cfu *Legionella* bacteria per 100 ml in the shower living in the tenant-owned dwelling is p_f = 0,006.

The conclusion from the work is that the undesirable indoor event Y_{env}, similar to the load effect S in SRA, and the dose-response relationship X_{env}, similar to the resistance R in SRA, can be compared as in SRA.

Key words: Probabilistic design, Indoor environment, Dose-response relationship, Radon, Legionella.

SAMMANFATTNING

Byggnaders inomhusmiljö och luftkvalitet är föremål för världsomfattande forskning. Skapandet av en bra inomhusmiljö är viktigt för människors hälsa och välbefinnande. Målet med denna avhandling är att utveckla en sannolikhetsteoretisk metod liknande den som används vid dimensionering av bärande konstruktioner. Syftet med metoden är att kunna bestämma risken för en ohälsosam inomhusmiljö, dvs. risken för att människor ska bli sjuka beroende på hur en byggnad är utformad och uppförd.

Som utgångspunkt för metoden har IEC:s standard för riskanalys kombinerat med felträdsanalys (FTA) använts för att möjliggöra en både kvalitativ och kvantitativ uppskattning av inomhusmiljön. Den säkerhetsfilosofiska metoden för analys av bärande konstruktioner (SRA) har använts för att hantera funktioner som beskriver förhållandet mellan bashändelserna i felträdet och de stokastiska variablerna. Användandet av SRA gör att risken kan definieras som att ett gränslasttillstånd inte är uppfyllt, dvs.:

$$M_{\text{env}} = G(X_{\text{env}}, Y_{\text{env}}) = X_{\text{env}} - Y_{\text{env}} < 0$$

De stokastiska variablerna X_{env} and Y_{env} definieras som:

X_{env} = dos-responssambandet, dvs. sambandet mellan exponering av den ohälsosamma inomhusmiljön och andelen exponerad befolkning som drabbas av negativa hälsoeffekter.

Y_{env} = oönskad händelse i inomhusmiljön, dvs. sambandet mellan en miljöbelastning och dimensionering och uppförande av en byggnad.

Målsättningen med metoden är att jämföra den oönskade händelsen inomhus med konsekvenserna för människor, dvs. bestämma risken för ohälsa genom att jämföra de stokastiska variablerna som vid dimensionering av bärande konstruktioner. Sannolikheten för överträdelse av ett gränslasttillstånd eller ett gränsvärden, samt säkerhetsindex β kan bestämmas med hjälp av första-ordningens nivå-2-metod (FOSM) eller genom simulering.

De miljöfaktorer som har identiferats, med potential att orsaka en ohälsosam inomhusmiljö, är mikroorganismer, eller produkter från mikroorganismer, emissioner och joniserande strålning. Den föreslagna riskanalysmetoden tillämpas på en enfamiljsvilla grundlagd med en betongplatta på mark i ett område som kännetecknas av höga nivåer av markradon. Den oönskade händelsen Y_{env} definieras som "Radonkoncentrationer i inomhusluften" och jämförs med ett befintligt dos-responssamband X_{env}. Sannolikheten är p_{f} = 0,002 per år för att

gränslasttillståndet inte är uppfyllt. Den oönskade händelsen jämförs också med gränsvärdet i de svenska byggreglerna 200 Bq/m^3 vilket ger sannolikheten p_f = 0,0001 att överskrida gränsvärdet. Detta ger säkerhetsindex β = 3,6 som kan jämföras med det säkerhetsindex som används vid dimensionering av bärande konstruktioner i säkerhetsklass 1, vilket är den lägsta säkerhetsklassen som tillämpas för konstruktioner där risken för allvarliga personskador är liten om brott inträffar.

Riskanalysmetoden tillämpas också på en bostadsrättslägenhet där den oönskade händelsen Y_{env} definieras som ”*Legionella*-kontaminerade aerosoler i inomhusluften”. De stokastiska variabler som är av intresse i analysen är bland annat kombinationen av den inkommande mängden bakterier i vattenledningen och den ackumulerade mängden i byggnadens ledningssystemet, samt tiden för stillastående vatten i ledningen. Den specifika tillväxtfaktorn har bestämts genom tester av bakteriehalten i lägenhetens duschvattnet och betraktas i studien som deterministisk trots att den beror av tillgången på näring, biofilm och vattentemperatur. Vid riskbestämningen jämförs den oönskade händelsen Y_{env} med riktvärden eftersom ett dos-responssamband som beskriver individers känslighet för *Legionella*-bakterier inte finns tillgängligt. Sannolikheten för att till exempel överskrida riktvärdet 10 000 cfu *Legionella*-bakterier per 100 ml vatten i den aktuella lägenhetsduschen är p_f = 0,006.

Slutsatsen är att det är möjligt att jämföra den oönskade händelsen Y_{env}, med dos-responssambandet X_{env} på samma sätt som lasteffekten S och bärförmågan R jämförs vid sannolikhetsteoretisk dimensionering av bärande konstruktioner.

Nyckelord: Sannoliketsteoretisk dimensionering, inomhusmiljö, dos-responssamband, radon, legionella.

NOMENCLATURE

Abbreviations

ADI	acceptable daily intake
BBR	Swedish Building Regulations
BFS	Swedish National Board of Housing, Building and Planning's Code of Statutes
BKR	Swedish Design Regulations
BMD	benchmark dose
BRI	building related illness
CCPS	Center for Chemical Process Safety
CIB	International Council for Research and Innovation in Building and Construction
CPQRA	chemical process quantitative risk analysis
EF	error factor
ETA	event tree analysis
ELIB	Elhushållning i bebyggelsen [Economising of the electricity in buildings]
EN	European Standard
EUROEXPO	European multidisciplinary review of scientific literature on dampness in buildings and health effects
EWGLI	European Working Group for Legionella Infections
FMEA	failure modes and effect analysis
FMECA	failure modes, effects and criticality analysis
FORM	first-order reliability method
FOSM	first-order second-moment theory
FTA	fault tree analysis
HAZOP	hazard and operability analysis
HEP	human error probability
HRA	human reliability analysis
IEC	International Electrotechnical Commission
IMM	Institute of Environmental Medicine at Karolinska Institutet
ISIAQ	International Society of Indoor Air Quality
ISO	International Standard
JCSS	Joint Committee on Structural Safety
LCA	life cycle assessment
MVOC	microbial volatile organic compound
NAS-NRC	US National Research Council of the US National Academy of Science
NOEL	no-observed-effect level

NORDDAMP	Nordic interdisciplinary review of scientific literature on dampness in buildings and health effects
NUREG	US National Regulatory Commission
PHA	preliminary hazard analysis
PRA	probabilistic risk analysis
Prop.	Swedish Government proposition
PSF	performance shaping factor
PVC	polyvinyl chloride
QMRA	quantitative microbial risk assessment
SBS	sick building syndrome
SFS	Swedish Code of Statutes
SLFVS	Swedish National Food Administration's Code of Statutes
SORM	second-order reliability method
SoS	Swedish National Board of Health and Welfare
SOSFS	Swedish National Board of Health and Welfare's Code of Statutes
SOU	Swedish Official Inquiries
SMI	Swedish Institute for Infectious Disease Control
SRA	structural reliability analysis
SRK	skill-, rule-, knowledge-based
SS	Swedish Standard
SSI	Swedish Radiation Protection Authority
US EPA	United States Environmental Protection Agency
VOC	volatile organic compound
WHO	World Health Organisation

Notions

B	basic event
C	thermal capacity [J/m^3 ºC]
C	consequence
C_i	radon concentration [Bq/m^3]
E	fault event
E	exhalation of radon [Bq/m^{2}h]
E_c	modulus of elasticity, concrete [N/m^2]
E_s	modulus of elasticity, reinforcement [N/m^2]
F_X	cumulative distribution function
F	surface area [m^2]
$G(\,)$	limit state function
M	minimal cut set
M	safety margin
N	number of colony forming units per volume [cfu/V]
T	top event
T	temperature [°C]
$P(\,)$	probability of occurrence
R	leakage of air through building component [m^3/s]
R	resistance
R	risk
RH	relative humidity [%]
S	load effect
V_i	volume [m^3]
X_i	random variable
$\mathbf{X}$	vector of random variables
Y_i	random variable
$\mathbf{Y}$	vector of random variables
Z	random variable
a_w	water activity
f_c	in situ compressive strength, concrete [N/m^2]
f_{cm}	mean compressive strength, concrete [N/m^2]
f_{cth}	concrete tensile strength [N/m^2]
f_{st}	reinforcement tensile strength [N/m^2]
f_X	probability density function
f_{XY}	joint probability density function
g	acceleration of gravity [m/s^2]
g	generation time [h]
h	building height [m]
i	index
l	length of cracks [m]
ℓ	number of air changes in the volume [h^{-1}]
m_X	sample mean
n	sample size
n	air changes in the volume
p	air pressure [Pa]
p	porosity, pore volume/total volume [%]
p_X	probability of occurrence
s_{rm}	distance between cracks [m]
s_X	sample standard deviation
t	depth of crack [m]
t	time [h]
v_X	coefficient of variation
vct	water-cement ratio
w	crack width [m]
x_k	individual measure of variable
y_i	individual measure of variable
z_i	individual measure of variable

$\Phi(\ )$	standard normal distribution function
Ω	sample space
α_i	sensitivity factor
β	reliability (safety) index
ε_{cd}	drying shrinkage strain, concrete [%]
ε_{sh}	shrinkage strain [%]
η	dynamic viscosity [Ns/m^2]
λ	disintegration constant for radon [h^{-1}]
λ	thermal conductivity [W/m^oC]
μ	constant of specific growth rate
μ_X	population mean
ρ	air density [kg/m^3]
$\rho_{X,Y}$	population correlation coefficient
σ_s	reinforcement tensile stress [N/m^2]
$\sigma_X{}^2$	population variance
σ_X	population standard deviation
$\sigma_{X,Y}$	population covariance
∞	infinity
$\cap$	intersection of events
$\cup$	union of events

TABLE OF CONTENTS

Preface iii
Abstract v
Sammanfattning (in Swedish) vii
Nomenclature ix

1 INTRODUCTION 1
1.1 Background 1
1.2 Research area 2
1.3 Objectives 2
1.4 Limitations 3
1.5 Disposition 3

2 LITERATURE REVIEW OF RISK ANALYSIS 5
2.1 What is ‘risk’? 5
2.2 Definition of the risk management process 7
2.2.1 Risk management of technical systems 8
2.2.2 Risk management of human health and environment 9
2.3 Risk analysis of technical systems 11
2.3.1 Definition of the risk analysis process 11
2.3.2 Scope definition 13
2.3.3 Hazard identification 14
2.3.4 Risk estimation 20
2.4 Risk assessment of human health and environment 22
2.4.1 Definition of the risk assessment process 22
2.4.2 Hazard identification 22
2.4.3 Dose-response assessment 22
2.4.4 Exposure assessment 24
2.4.5 Risk characterisation 24
2.5 System modelling/quantitative risk analysis 25
2.5.1 Uncertainty 25
2.5.2 Probability theory 27
2.5.3 Basic variables 29
2.5.4 Structural reliability analysis (SRA) 33
2.5.5 First-order second-moment theory (FOSM) 39
2.5.6 Monte Carlo simulation 42
2.6 Human error 43
2.6.1 Definition and classification 43
2.6.2 Human reliability analysis (HRA) 44
2.6.3 Human errors in structural reliability 46
2.7 Risk criteria 49
2.8 Summary of chapter 2 50

3 THE RISK ANALYSIS PROCESS ... 53
3.1 Introduction ... 53
3.2 Scope definition ... 54
3.3 Hazard identification and initial consequence evaluation ... 56
3.4 Construction of the fault tree ... 60
3.4.1 Fault tree analysis (FTA) ... 60
3.4.2 Faults and failures ... 62
3.5 Qualitative examination of the fault tree ... 63
3.6 Quantitative evaluation of the fault tree ... 64
3.7 Risk estimation ... 64
3.8 Summary of chapter 3 ... 66

4 HAZARD IDENTIFICATION AND INITIAL CONSEQUENCE EVALUATION ... 67
4.1 Introduction ... 67
4.2 Identifying undesirable indoor events, random variable Y_{env} ... 70
4.3 Identifying dose-response relationships, random variable X_{env} ... 73
4.4 Ionising radiation ... 75
4.4.1 Introduction ... 75
4.4.2 Radon concentrations in buildings ... 75
4.4.2.1 Origin ... 75
4.4.2.2 Undesirable indoor events, random variable Y_{env} ... 77
4.4.2.3 Consequences to humans, random variable X_{env} ... 82
4.5 Microorganisms ... 84
4.5.1 Introduction ... 84
4.5.2 Microbial growth in the building components ... 84
4.5.2.1 Growing conditions ... 84
4.5.2.2 Secondary metabolism ... 85
4.5.2.3 Fungal spores ... 86
4.5.2.4 Undesirable indoor events, random variable Y_{env} ... 86
4.5.2.5 Consequences to humans, random variable X_{env} ... 90
4.5.3 Microbial growth in water installations ... 91
4.5.3.1 Introduction ... 91
4.5.3.2 Environmental source of Legionella ... 92
4.5.3.3 Factors enabling amplification ... 92
4.5.3.4 Transmission of Legionella indoors ... 95
4.5.3.5 Undesirable indoor events, random variable Y_{env} ... 95
4.5.3.6 Consequences to humans, random variable X_{env} ... 97
4.6 Summary of chapter 4 ... 99

5 RISK ANALYSIS OF ENVIRONMENTAL IMPACT TO THE FOUNDATION 101
5.1 Scope definition 101
5.2 System definition 101
5.3 Hazard identification and initial consequence evaluation 103
5.3.1 Undesirable indoor events, random variable Y_{env} 103
5.3.2 Dose-response relationships, random variable X_{env} 103
5.4 Construction of the fault tree 104
5.5 Qualitative examination of the fault tree 109
5.6 Quantitative evaluation of the fault tree 112
5.6.1 Definition of the basic event B1 112
5.6.2 Definition of the fault event E3 113
5.6.3 Estimation of the pressure difference, Δp 114
5.6.4 Estimation of the radon concentration in soil air, C_{max} 117
5.6.5 Estimation of cracks and narrow openings 120
5.6.6 Estimating the undesirable indoor event Y_{env} 123
5.7 Risk estimation 126
5.7.1 Definition of random variables 126
5.7.2 Risk estimation using simulation 128
5.7.3 Risk estimation using FOSM 130
5.8 Application of the model on available data 135
5.9 Summary of chapter 5 141

6 RISK ANALYSIS OF ENVIRONMENTAL IMPACT TO THE WATER SUPPLY SYSTEM 145
6.1 Scope definition 145
6.2 System definition 145
6.3 Hazard identification and initial consequence evaluation 146
6.3.1 Undesirable indoor events, random variable Y_{env} 146
6.3.2 Dose-response relationships, random variable X_{env} 147
6.4 Construction of the fault tree 147
6.5 Qualitative examination of the fault tree 151
6.6 Quantitative evaluation of the fault tree 154
6.6.1 Definition of the fault event E1 154
6.6.2 Estimation of the constant of specific growth rate, μ 155
6.6.3 Estimation of the time of stagnant water, Δt 159
6.6.4 Estimation of the initial amount of *Legionella* bacteria, N_1 161
6.6.5 Estimating the undesirable indoor event Y_{env} 161
6.7 Risk estimation 163
6.8 Summary of chapter 6 165

7 DISCUSSION AND CONCLUSIONS **167**
7.1 Introduction 167
7.2 The proposed risk analysis procedure 167
7.3 Radon concentrations indoors 169
7.4 *Legionella* contaminated aerosols indoors 172
7.5 Comparison of risk criteria 173
7.6 Summing-up 175

8 REFERENCES **177**

APPENDIX A **A1**
APPENDIX B **B1**
APPENDIX C **C1**

1 INTRODUCTION

1.1 Background

I was writing the introduction to this thesis with the television running in the background. A reporter on the news tells me about the young family with their new turn-key built single-family dwelling. There are an absolutely awful amount of faults in their new home including for example a bathroom floor with a slope leading all the water from the shower out in the living room!

In recent years indoor environment and indoor air quality have been subjected to extensive worldwide research efforts. There is much to suggest that the creation of good indoor environments is an important factor to health and well-being to humans and progress is made in the research area of indoor air quality and health. Regardless of this knowledge, people in Sweden suffer from allergy, asthma and unspecific symptoms considered to be caused by conditions in the buildings, and though scientists have been working in the field for many years, indicators to use as a measure for good air quality are not entirely clear. The question is if progress and knowledge made in research becomes sufficiently known to the public in general and particular to the men and women working with design and construction of buildings.

The ways in which individuals perceive risk depend on a variety of factors. In general, higher risks seem to be tolerated in voluntary activities where the individual has a certain degree of control over what is happening. However, for many activities risks are not taken on voluntary nor does the individual have much control over them. In such cases, higher quality and safety requirements are demanded for risks to be regarded as acceptable. One such case is the occurrence of indoor air pollutants causing an unhealthy indoor environment to humans in buildings where people stay more than occasionally, i.e. at home or at work.

During a research project initiated and produced at the Division of Steel Structures, Luleå University of Technology, the absense of methods for determination of the risk for any defined environmental damage to occur, was noted (Sterner, 1999; Sterner 2002). A commonly accepted model for prediction of risks and consequences similar to the probabilistic methods used in modern design codes for structures and buildings could be beneficial as a tool for decision-making at different stages of the building process. The project *"Environmental decision-making in the construction process based on risk analysis"* was initiated at the Division of Steel Structure, and funded by the Swedish Council for Building Research, now Formas, in the key action *"Environment and eco-cycles in building* *and facility management"*. The project was also funded by the Development Fund of the Swedish Construction Industry, SBUF, and resulted in the licentiate thesis "Probabilistic design of indoor environment" presented in April 2003 (Ljungquist, 2003). This doctoral thesis is an extention and advancement of the licentiate thesis and also funded by Formas and SBUF, through the Swedish Construction Federation (BI).

1.2 Research area

To get an indoor environment that fulfil its intensions of being a good indoor environment to human health and well-being the quality in the building process is of outmost importance. However, the building sector is a heterogeneous group including both small and large enterprises, proprietors, consultants and suppliers, all with different economic possibilities, interest and knowledge in environmental questions. It is difficult to form an overall picture and to communicate about the consequences to indoor environment caused by decisions made in the building process about design, construction and maintenance of the future or the existing building. A probabilistic procedure that estimates the risk of an unhealthy indoor environment to occur would be beneficial as a basis for decisions about risk reducing measures. It would also be beneficial as a communication tool between participants in the building process, with insurance companies, future or existing tenants, as a marketing tool, etc.

1.3 Objectives

The main objective of the work is to develop a probabilistic procedure similar to the method used in modern design codes for building structures. The purpose of the method is to estimate the risk of an unhealthy indoor environment to occur caused by decisions made in the building process, i.e. the risk for humans to become unhealthy indoors because of the design and construction of the building. The objectives of the work are to:

- identify decisions made in the building process about the future or the existing building with the potential to cause an unhealthy indoor environment,
- find a procedure similar to the probabilistic method used in structural reliability analysis, and to
- verify the model by implementing it on hazards where sufficient data are available.

1.4 Limitations

The areas of risk management, human health and indoor environment are enormous and it is easy to drift away in different directions, since all subjects are very interesting. However, this work will focus on the risk analysis process that is one part of the risk management.

The overall system is a building built up with different sub-systems defined as building components. In the analysis, the unhealthy indoor environment is caused by an environmental impact acting on a single building component. The interaction between different environmental impacts acting on different building components are not considered. The effect of outdoor air pollutants entering the building is not considered nor is air pollutants generated in the ventilation system or by humans. The method will treat influence on the indoor environment caused by the design and construction of the buildings, while maintenance and use not are considered.

In the area of human health and indoor environment focus is put on environmental impacts affecting the building and known to cause building related illness (BRI), i.e. negative health effects known to be caused by the building. The consequence is humans becoming unhealthy and this is considered using available dose-response relationships or threshold values stated in codes. Because of its medical character any deeper analysis of consequences is a matter for others and will not be discussed here.

The occurrence of an unhealthy indoor environment depends not only on an environmental impact affecting the building but also on human intervention in some way, i.e. humans are responsible of planning, designing and constructing the building. Therefore, human reliability will be discussed, though not considered in the application of the method, since this probably comprises a thesis on its own.

1.5 Disposition

The work is in some way interdisciplinary in the attempt to develop the probabilistic method for prediction of risk for an unhealthy indoor environment to occur. The thesis includes:

- chapter 2 where both the risk analysis process of technical systems and the risk assessment process of human health and environment are reviewed,
- chapter 3 where the risk analysis procedure is developed,
- chapter 4 where the current scientific knowledge of indoor environmental problems is reviewed,

- chapter 5 where the risk analysis procedure is applied to the foundation of a single-family dwelling,
- chapter 6 where the risk analysis procedure is applied to the water supply system of a tenant-owned dwelling, and finally,
- chapter 7 where a discussion whether the objectives of the work have been achieved, together with conclusions. Further, uncertainties of the risk analysis procedure will be discussed together with the need of future research to refine the method.

2 LITERATURE REVIEW OF RISK ANALYSIS

2.1 What is ‘risk’?

Our environment has always been a risky place. Humans have always made risk-based decisions, initially considering direct experience and later using historical data passed on to succeeding generations (Gould, 1998). A group called the Asipu lived in the Tigris-Euphrates valley about 3200 B.C. One of their primary functions was to serve as consultants for risky, uncertain or difficult decisions. If a decision needed to be made concerning a forthcoming risky venture, one could consult with a member of the Asipu. The Asipu would identify the important dimensions of the problem, identify alternative actions and collect data on the likely outcomes. From their perspective, the best available data were signs from the gods. The Asipu would then create a ledger with a space for each alternative. If the signs were favourable, they would enter a plus in the space; if not, they would enter a minus. After the analysis was completed, the Asipu would recommend the most favourable alternative. However, unlike modern risk analysis, the Asipu of ancient Babylonia expressed their results with certainty, confidence and authority. Probability played no part in their analyses, since they were empowered to read the signs of the gods (from Covello and Mumpower, 1985).

Several authors in the literature of risk point out to the “problem” of terminology since the meanings of numerous concepts vary depending on what professional area the risk analyses are conducted (e.g. Covello and Merkhofer, 1993; Harms-Ringdahl, 2001). The different fields of science show different approaches and different definitions of notions easy to misunderstand. Primarily, the word ‘risk’ has to be defined. What is ‘risk’? At the 1996 Annual Meeting of the Society for Risk Analysis, Kaplan held a speech about the problems with the language in the risk analysis community and concluded that “maybe it is better not to define risk. Let each author define it in his own way, only please each should explain clearly what way it is.” (Kaplan, 1997). For many engineers, risk is simply another word for the probability of the occurrence of a defined event, while, for example, the insurance industry terms risk as money ‘at risk’.

Davidsson et al (1997) give three different definitions of risk used in different context:

1. the probability for an undesirable event to occur,
2. the negative consequence of an event or
3. a weighted evaluation of the probability and the consequence.

Kaplan and Garrick (1981) argued that when one asks, “What is the risk?”, one is really asking three questions: What can happen? How likely is it to happen? If it does happen, what are the consequences? The first question is promoting hazard-scenario thinking. The second aims to state the likelihood of a certain scenario to occur. The third question relates to the undesired consequences linked with a specific scenario. These questions are stated in the introduction to the International Electrotechnical Commission (IEC) standard on dependability management as the three fundamental questions to be answered performing a risk analysis (IEC 60300-3-9:1995). The IEC definition of risk is the “combination of the frequency (author comment: in the past), or probability (author comment: in the future), of occurrence and the consequence of a specified hazardous event.” The standard notes especially the concept of risk as always having two elements, frequency and consequence, and that risk can be individual, occupational, societal, environmental and/or give property damage and economic losses. Rowe (1977) defines risk as the potential to realise unwanted, negative consequences of an event, i.e. the combination of probability and consequence for an undesirable event to occur. The undesirable event is an unintended and unpredictable event causing damage to humans, property or the environment. The duration of the undesirable event, i.e. the time between the initiating event and the actual damage, may vary considerably. Stewart and Melchers (1997) state that risk more and more defines the probability of particular consequences, i.e. the probability of an undesirable event occurring and the possibility of damage, and can be evaluated as the ‘probability x value of consequences’, where consequences might be evaluated in terms of money or human fatalities. Kumamoto and Henley (1996) define risk as a combination of five primitives: outcome, likelihood, significance, causal scenario and population affected.

Cohrssen and Covello (1989), who refer to human health and environmental risks, define risk as “the possibility of suffering from harm from a hazard”, explaining it with “a toxic chemical that is a hazard to human health does not constitute a risk unless humans are exposed to it.” But they also describe a complete technical analysis of risk with “(1) a hazard – that is, a dangerous substance or action that can cause harm; (2) the event or events that create the possibility of harm; and (3) a statistical estimate of likelihood that the harm will occur.” Covello and Merkhofer (1993) define risk as “A characteristic of a situation or action wherein two or more outcomes are possible, the particular outcome that will occur is unknown, and at least one of the possibilities is undesired”. Ahlborg and Haag Grönlund (1995) define risk as “the probability that an adverse outcome will occur, when a person or group is exposed to particular concentrations or doses of a substance for specific periods of time. Therefore, risk is basically a function of exposure and toxicity.”

2.2 Definition of the risk management process

The primary goal of any reliability or safety analysis is to identify hazards to be able to reduce or eliminate the probability of accidents and the attending human, environmental or economic losses or combination thereof. Accidents occur when an initiating event is followed by system failure. According to, for example, Kumamoto and Henley (1996), the types of basic failure events most commonly encountered are:

- Events related to human beings, e.g. design or maintenance errors
- Events related to hardware such as leakage from valves
- Events related to the environment such as earthquakes, flood etc.

Accidents are frequently caused by a combination of failure events, i.e. human error plus hardware failure, environmental faults or both.

The term risk management is generally used to cover the complete process involving qualitative and quantitative methods to not only identify hazards and estimate risk, but also to reduce risk, i.e. reduce the total expected damage cost and lower the probability, consequence or both of an occurrence of hazards together with implementation and monitoring. Blockley (1995) talks about the three Rs, meaning the alternatives of actions taken based on the results of a risk analysis. The alternatives to consider in the risk management process are to remove, reduce or remedy the hazard.

Risk management addresses the risks in the increasing speed of technological development and the growth of public concern over safety and pollution, and provides a procedure of assessing and managing risk. Although the purpose of risk management is the same in different disciplines, i.e. to protect society from hazardous agents, events or both, there is no explicit definition of the risk management process. Debate over the definition relates mostly to establishing its appropriate scope, particularly with reference to related activities such as hazard identification, risk assessment, risk evaluation and risk analysis. Risk assessment and risk analysis are often used synonymously, though risk analysis is sometimes used more broadly to also include risk management aspects, and hazard and risk are sometimes used interchangeably (e.g. CIB, 2001; Covello and Merkhofer, 1993; Kolluru, 1996a; Kolluru, 1996b; Lees, 1996).

2.2.1 Risk management of technical systems

In the field of engineering where risks and hazards of technical systems are considered, risk management has its roots in industries with high technological complexity together with high demands in matters of safety, e.g. the nuclear, chemical, aerospace and electronic industries. The most commonly used definition of the risk management process is shown in Figure 2.1 and can be found in the standard SS-EN 1050:1996 for the safety of machinery. The International Standard IEC 60300-3-9:1995 in risk analysis has the same relationship between the activities in risk management. In this framework risk management deals with risk by using risk assessment and risk reduction in an iterative process.

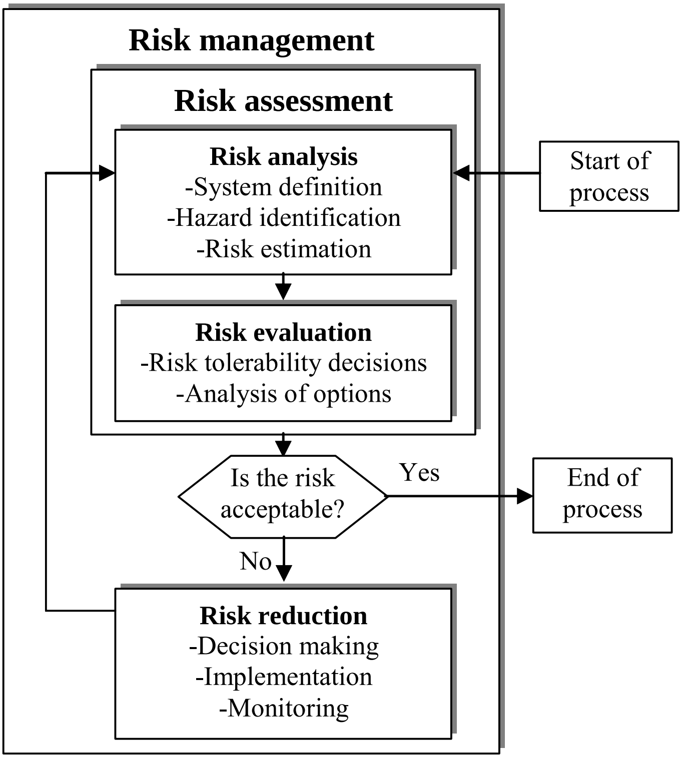


Figure 2.1 The iterative risk management process (adapted from SS-EN 1050:1996)

The purpose of risk assessment is to provide information needed to support risk management in decision-making. Risk assessment involves appreciating the risk associated with the operation of a system through an analysis (risk analysis) and comparing it with present acceptability and tolerance limits (risk evaluation). If the risk is unacceptable, risk reduction has to be considered along with analysing possibly new hazardous events. A complete description of risk is an iterative process, usually beginning with the application of qualitative methods and progressing towards quantitative if necessary and appropriate. If a quantitative analysis of risk is to be carried out, a probabilistic model of the system must be established. When the model plus the data are established, the calculations can begin to estimate the system risk and identify the critical components and events. The calculations can be carried out through analytical methods or the Monte Carlo simulation (SS-EN 1050:1996; Aven, 1992; Darbre, 2001).

The presented definition of the risk management process is used for the safety of machinery, though the framework is also applicable to, e.g. the chemical, nuclear and offshore industries with minor adaptations to the area of application (e.g. CCPS, 2000; Kemikontoret, 2001; Lees, 1996). The International Council for Research and Innovation in Building and Construction (CIB) has the same definition of the process for the building industry, which states, "the risk assessment of a system consists of the use of all available information to estimate the risk to individuals or populations, property or the environment, from identified hazards, the comparison with targets and the search for optimal solutions." (CIB report, 2001). Baker et al (1995) offer a similar risk management model for the construction industry through the following four key stages:

- hazard identification and evaluation,
- risk assessment,
- control of hazard, triggering conditions or consequences or both of the undesired event,
- monitor, review and maintain.

In addition, risk management requires some form of ongoing audit to assess the effectiveness of the various measures taken and to provide the necessary feedback.

2.2.2 Risk management of human health and environment

Risk management in the field of human health and environment follow the definition first described in 1983 by the US National Research Council of the US National Academy of Science (NAS-NRC, 1994). The NAS-NRC definition of risk management is "the process by which risk assessment results are integrated with other information to make decisions about the need for, method of, and extent of risk reduction." The process is visualised in Figure 2.2 and has been increasingly accepted and used globally (Covello and Merkhofer, 1993; Ahlborg and Haag Grönlund, 1995; Berglund et al, 2001).

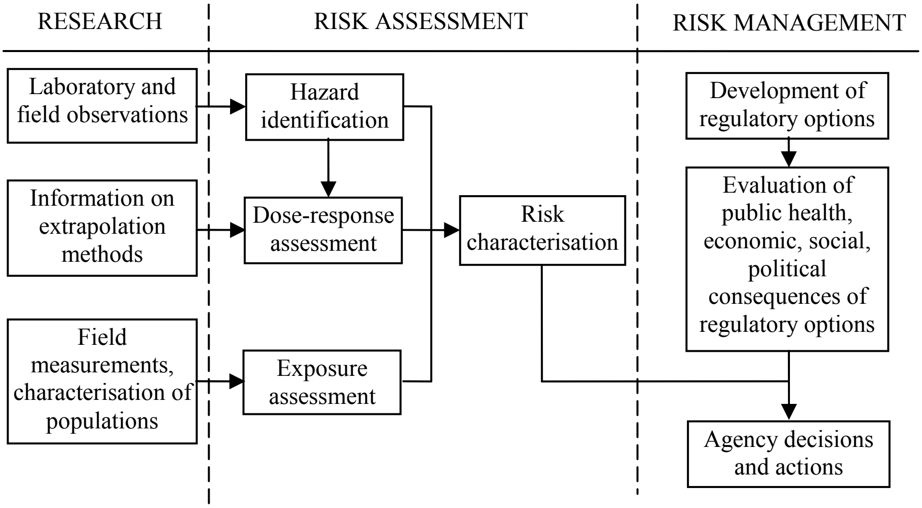


Figure 2.2 *The risk management process in the field of human health and environment (adapted from NAS-NRC, 1994, and Ahlborg and Haag Grönlund, 1995).*

Ahlborg and Haag Grönlund (1995) define risk assessment as the bridge between research and risk management, where research data are collected to be evaluated and presented to risk managers in a suitable form for decision-making and implementation. Kolluru (1996a) states, that the step risk characterisation serves to bridge risk assessment and risk management. This step includes integrating the results of exposure assessment and dose-response data to arrive at quantitative risk estimates, where key assumptions and sources of uncertainty are explicitly stated.

According to Streffer et al (2004), risk analysis consists of the whole process of risk assessment through risk evaluation to risk management, whereas Covello and Merkhofer (1993) believe that it consists of three stages:

1. Hazard identification – identifying risk agents and the conditions and events under which they potentially produce adverse consequences to people or the environment.
2. Risk assessment – describing and quantifying the risk.
3. Risk evaluation – comparing and judging the significance of the risk.

Cohrssen and Covello (1989) also include risk communication as a fourth stage. The purpose of these activities is to provide an important part of the information needed to support risk management (identifying, selecting and implementing appropriate actions to control risk).

2.3 Risk analysis of technical systems

2.3.1 Definition of the risk analysis process

The international standard IEC 60300-3-9:1995 defines risk analysis as the “Systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or the environment.” The risk analysis process according to the IEC standard is shown in Figure 2.3. The purpose of risk analysis is to define the system in mind, to identify possible hazards and to estimate the risks. The intention of the standard is to “reflect current good practices in selection and utilisation of the risk analysis techniques”; therefore, its natural generality gives guidance across many applicable areas. However, the standard is primarily intended for risk analysis of technological systems. In accordance with the IEC definition of risk analysis, the standard SS-EN 1050:1996 for the safety of machinery describes the principles of risk analysis in the same way.

The first steps of risk analysis involve the context definition related to the system and the identification of hazards, what CIB (2001) refers to as the qualitative risk analysis. Quantitative risk analysis is performed in the risk estimation, where consequences, probabilities and risks are quantified. The American Institute of Chemical Engineers (AIChE) has developed a similar methodology called quantitative risk analysis (CPQRA), whose aim is to provide the management process with a tool to evaluate overall process safety in the chemical process industry (CCPS, 2000). The principal concern of a probabilistic risk analysis (PRA) in these industries is the acute rather than chronic hazards with the emphasis on rare, but potentially catastrophic events. The methodology is based on the NUREG procedures, a PRA developed by the US Nuclear Regulatory Commission and used in the American nuclear industry. However, the methodology includes in principle the same steps as the risk analysis process illustrated in Figure 2.3, i.e. both the qualitative and the quantitative.

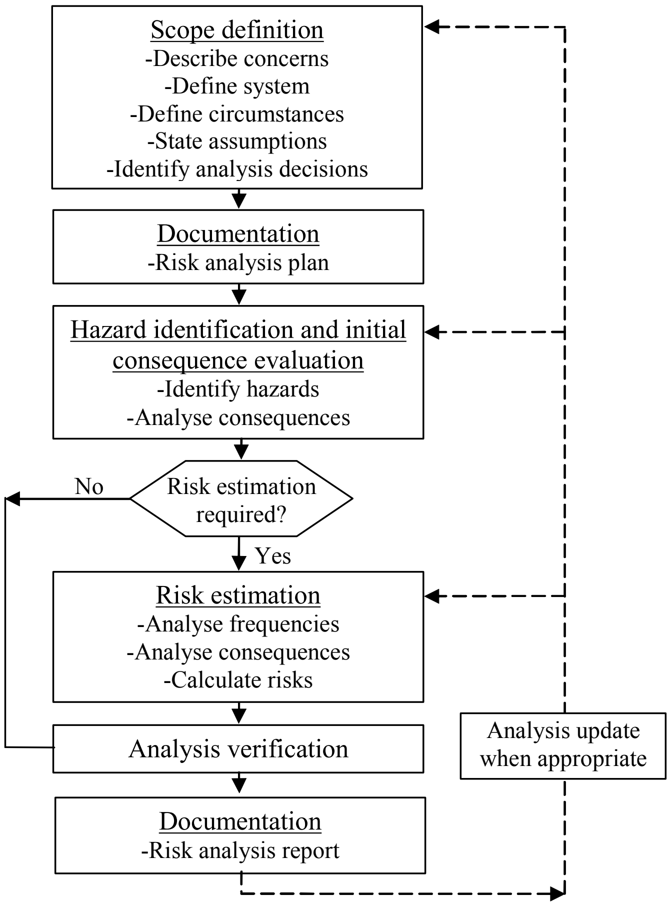


Figure 2.3 Risk analysis process (adapted from IEC 60300-3-9:1995).

A risk analysis can also be undertaken semi-quantitatively where episodic events with potentially severe consequences are identified and ranked according to a scoring system in terms of, e.g. property damage, business interruption, human injury, fatalities or a combination thereof. The ranking of risks enables managers to prioritise the relative importance of preventive measures and allocate resources to the riskiest scenarios. The methods are usually called index methods, point scheme methods, etc., and can consider both frequency and consequences (e.g. Frantzich, 1998; Stricoff, 1996).

Risk analysis can be broken down into different levels of detail, e.g. in the three levels for the nuclear industry where the analysis may be carried out according to (Bedford and Cooke, 2001; Stewart and Melchers, 1997):

- Level 1 – system analysis, i.e. analysis of the probability of certain critical states being reached;
- Level 2 – system analysis and analyses of the consequences of various critical states being reached, with associated probabilities; or
- Level 3 – where further analysis is done for the probable (adverse) effect on humans, including estimation of the loss of life and when this might occur.

The end product of a risk analysis then depends on the level of detail used, which has to be decided upon already in the scope definition before performing the analysis.

2.3.2 Scope definition

An important part of risk analysis is to formulate the objectives of the analysis together with the definition of the system to be analysed. In Figure 2.3, the scope definition includes (from IEC 60300-3-9:1995):

- Describe concerns
- Define system
- Define circumstances
- State assumptions
- Identify analysis decisions

Describing the concerns of the risk analysis should, according to the IEC standard, include a description of why the risk analysis should be conducted with a clearly specified problem formulation. The description should also include the objectives based on the main concerns identified and a definition of the criteria for success/failure of the system.

According to the IEC standard, the definition of the system should include a general description and a more thorough definition of the boundaries and interfaces. Also, the environment, materials, operating conditions, etc., have to be systematically described. Stewart and Melchers (1997) state that “A system must be able to fulfil the requirements for which it was established, it must be economical and it must perform at an acceptable level of safety.” A system can be an industrial plant including plant personnel or just one computer in the plant. The standard IEC 60300-3-9 defines a system as a “Composite entity, at any level of complexity, of personnel, procedures, materials, tools, equipment, facilities and software. The elements of this composite entity are used together in the intended operational or support environment to perform a given task or achieve a specific objective." CIB (2001) defines a system as a "bounded group of interrelated, interdependent or interacting elements forming an entity that achieves in its environment a defined objective through interaction of its parts." CIB notes that as in most systems, risk analysis of civil engineering systems usually involves several interdependent components, such as human life, injuries and economic loss.

The system is built up with parts, components and sub-systems, and both Vesley et al (1981) and Morgan and Henrion (1990) have emphasised the importance of carefully examining where to set the boundaries in the analysis process as well as looking at the implications of alternative boundaries choices. It is important to establish the external and internal (limit of resolution) boundaries of the system, i.e. how detailed will the system be when split up, since the system might have to be broken down in smaller sub-systems. The choice of external boundaries determines the comprehensiveness of the analysis; the choice of internal boundaries limits the detail of the analysis. Communicating to others what bounding assumptions have been made, how carefully they and various alternatives have been considered, and how the boundaries may limit or otherwise affect the nature of the insight and understanding of the analysis is important. It is also important to include a thorough familiarisation with the system to be analysed as a planned activity in the scope definition, since one objective is to determine where and how specialised knowledge can be integrated into the analysis (IEC 60300-3-9:1995; Morgan and Henrion, 1990).

The last three activities in the scope definition comprise the definition of circumstances (which aims to identify the sources giving details of all the technical, environmental, legal, organisational and human circumstances relevant to the activity and the problem being analysed), to state the assumptions and constraints governing the analysis, and finally, the analyst has to identify the decisions to be made, the required output from the study and to whom the results will be communicated.

2.3.3 Hazard identification

Hazard identification intends to answer the question "What can go wrong?" In the CIB report (2001) a hazard is defined as a set of conditions that may lead to undesirable events, whereas the standards (e.g. IEC 60300-3-9:1995) and most literature (e.g. Harms-Ringdahl, 2001; Bedford and Cooke, 2001) define hazard as "source of potential harm or a situation with a potential for harm". Hazards can be natural (e.g. earthquakes), technological (e.g. structures), sociological (e.g. war), or lifestyle (e.g. smoking) hazards that are apparently not mutually exclusive. Usually different hazards occur together in space and time, possibly leading to higher risks than those corresponding to the individual hazards (CIB, 2001; IEC 60300-3-9:1995).

The identification of hazards and hazard scenarios is a crucial task in risk analysis, requiring a detailed examination and understanding of the system, and has in many ways become more difficult as the depth of technology has increased. Usually, analysis is an iterative process where the initial hazard identification can be based on well-structured expert brainstorming and statistics, and is aimed at finding consequences for different events. Subsequent analysis steps can be performed using some of the developed methods that are available and widely used. A large number of methods exist for risk analysis and hazard identification depending on the purpose and the level of analysis detail. Different methods may be required at different stages of a project.

When choosing an analysis method, the purpose is to identify hazards and describe possible accident event sequences and factors that might trigger off an accident. The selected method determines how the process of hazard identification proceeds. Some methods are qualitative, while others can be used for quantitative estimation. Therefore, some aspects, like the purpose of the analysis and how much information about the system is available, should be considered before deciding on the method, since the usage of a specialised method might imply discovering certain types of hazards, while others might be overlooked. Advantages with choosing a well-known method are primarily that knowledge about the method is documented in the literature and that the analyst's own knowledge increases if focused on a basic amount of methods. Well-known methods are sometimes also possible to adjust to new applications (Lees, 1996; Harms-Ringdahl, 2001; Kemikontoret, 2001).

Two different approaches to system analysis and hazard identification exist: induction and deduction. Vesely et al (1981) define induction as constituting reasoning from the individual case to the general conclusion, whereas deduction constitutes reasoning from a general to the specific. In summary, inductive methods are applied to determine <u>what</u> system states (usually failed states) are possible, i.e. starting with an initiating event the consequences are identified; deductive methods are applied to determine <u>how</u> a given state (usually a failed state) can occur, i.e. starting with an undesirable event the causes are identified.

The following description of methods does not claim to be complete and will only briefly describe the most well known. For further reading, Lees (1996) has compiled three volumes concerning loss prevention in the process industries, including, amongst others, different hazard identification methods. More literature of interest used in this work are, e.g. Kemikontoret (2001), Harms-Ringdahl

(2001), CCPS (2000), Vesely et al (1981), Lazor (1996), Aven (1992), Darbre (2001), McCormick (1981), Ingvarson and Roos (2003), Bedford and Cooke (2001), Andrews and Moss (2002), and Stewart and Melchers (1997). Finding detailed descriptions in the literature of how to use the methods can be difficult, though for some methods standards are available.

Preliminary Hazard Analysis (PHA) is a coarse inductive and qualitative method used at an early stage of a project to identify possible hazards. The method can also be used for preliminary identification of hazards in an existing system. Guide lists of potentially hazardous elements and lists of potentially hazardous situations for specific systems often aid the conduct of a PHA. When necessary, the result from the analysis can be used for more detailed analysis using methods such as Failure Modes and Effect Analysis (FMEA), Failure Modes, Effects and Criticality Analysis (FMECA) and Hazard and Operability Analysis (HAZOP). The analysis is preferably performed by a group of people well acquainted with the system.

Each identified hazard is analysed separately to describe the possible causes, consequences and probabilities. The consequences could also be separated into, for example, environment, health and property, since they are usually evaluated differently. Thereafter, the consequences and probabilities could be ranked according to severity. The analysis yields a preliminary qualitative document of possible hazardous events according to identified risk sources that evaluate consequences and probabilities. Because of its preliminary status, a PHA would not be expected to identify failure of a specific individual component with the potential to lead to a major hazard. This is the role for FMEA, FMECA and HAZOP.

Checklists are one of the most useful tools of hazard identification, since they pass on experience gathered during an extended period of time. They are generally applicable to management systems and projects throughout all stages and should be used as a final check that nothing has been neglected.

Numerous checklists are found in the literature depending on the application area. Lees (1996) gives selected references on checklists, mostly applicable to hazards in, e.g. the chemistry industry. In the standard SS-EN 1050:1996, Annex A includes an extensive table with examples of hazard, hazardous situations and hazardous events concerning safety of machinery. Checklists applicable in the building process concern, for example, the prevention of growth of microorganisms in water installations (Stålbom and Kling, 2002) or the “green design” (Arkitekt- och Ingenjörsföretagen, 1997, 1999).

Hazard and Operability Analysis (HAZOP) is a qualitative and inductive method to systematically analyse how deviations in a system can arise, as well as an analysis of the risk potential of these deviations. The method was developed by the chemical industry in England in the 1960s and is widely used in the process industry. The International Standard IEC 61882:2001 is available for the application of HAZOP. Based on a flowchart of the system or a plant layout, and a set of guidewords or scenarios, the analysis result in identifying the hazards or operational problems. The basic concept of the HAZOP study is to take a full description of the process and question every part of it to discover what deviations from the intended design can occur and what the causes and consequences of these deviations may be. The following guidewords are commonly used: NO/NOT, MORE OF/LESS OF, AS WELL AS, PART OF, REVERSE, AND OTHER THAN. The guidewords are related to process conditions, activities, materials, time and place.

The analysis results in a qualitative documentation over system deviations with recommendations of safety measures to be taken and procedures for follow-up.

Failure Modes and Effect Analysis (FMEA) is one of the oldest and most frequently used methods developed during the 1950s and from the beginning mostly used in the aerospace industry. The International Standard IEC 60812:1985 is available for system reliability using FMEA. It is an inductive, mostly qualitative analysis method used to reveal possible failures and predict effects of these failures on the system. The method represents a systematic analysis of the system’s components to identify all significant failure modes and determine their importance for system performance. Components are considered one at a time, the other components are then assumed to function perfectly. FMEA is therefore not suitable for revealing critical combinations of component failure. The attention often focuses too much on the technical failures, whereas contributions of human error are often overlooked. The strong point of the FMEA is the fact that it gives a systematic overview of important failures of the system, while forcing the designer to evaluate the reliability of the system. In addition, it represents a good basis for more comprehensive quantitative analyses, such as fault tree analyses.

The analysis results in a systematic documentation of components, possible failure modes, consequences, risk evaluation and recommended measurements to be taken.

Failure Modes, Effects and Criticality Analysis (FMECA) is an enhancement of FMEA where a criticality analysis is performed. Criticality is a function of the severity of the effect and the frequency it is expected to occur at. The criticality analysis involves assigning a frequency to each failure mode and a severity to each failure effect.

Event tree analysis (ETA) is an inductive and qualitative method with the possibility to be used quantitatively. One starts from a real or hypothetical initiating event, identifies all the possible consequences and estimates their probability of occurrence. The events and their probabilities are visualised in a tree-like structure, shown in Figure 2.4, without the introduction of any particular symbols in the representation.

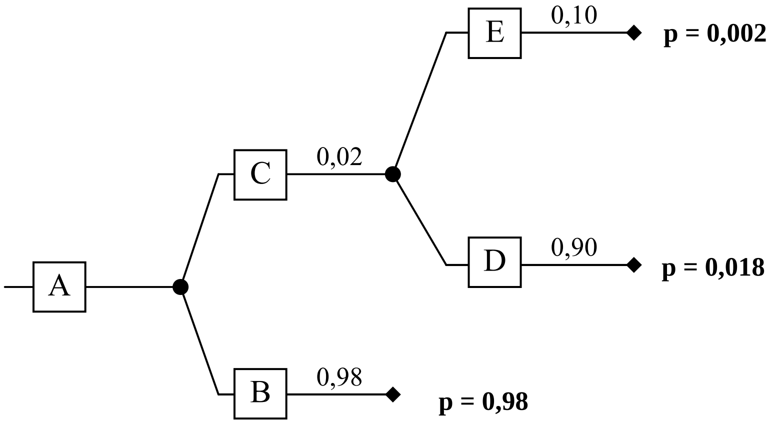


Figure 2.4 Example of event tree where the initiating event A has the probability p = 1,00.

The question to be answered in the establishment of an event tree is: What happens if...? Advantages with ETA are the possibility to include human error in the analysis and the method is well suited for analysis of safety systems and emergency routines to prevent accident event sequences in the case of, e.g. fire.

Once the potential hazards have been identified using inductive methods, like ETA, it is necessary to identify how such hazards can be realised and how they might come about. Moreover, common-cause failures and other linkages between contributing factors can be important to identify.

Fault Tree Analysis (FTA) is a deductive logical diagram that shows the relationship between system failure, i.e. a specific undesirable event in the system, and failure of the system's components. Fault tree analysis (FTA) was first developed in 1961 by H. A. Watson at Bell Telephone Laboratories in connection with a US Air Force contract to study the Minuteman Missile launch control system. The Boeing Company later modified the concept for computer utilisation. In 1965, D. F. Haasl further developed the technique of fault tree construction to be relevant to a wide variety of industrial safety and reliability problems (Lee et al, 1985; Henley and Kumamoto, 1981).

The standard SS-IEC 1025:1990 describes FTA and provides guidance on its applications. Starting from a real or hypothetical event (called top event), one identifies all the possible causes and the probability of occurrence in a tree-like structure with different symbols shown in Figure 2.5.

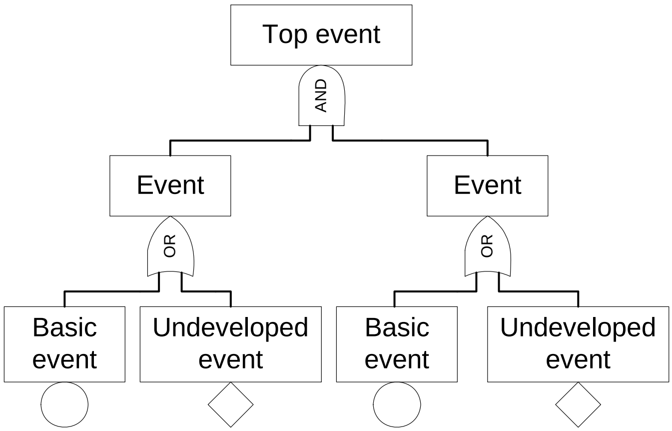


Figure 2.5 Example of the fault tree with some basic symbols.

The question to be answered in the establishment of a fault tree is: What causes the undesirable event? FTA advantages are that the qualitative analysis gives a clear picture of the accident event sequences through the logical diagram and the possibility to evaluate the tree quantitatively to find the probability of the top event, i.e. FTA is a method for both hazard identification and frequency analysis.

Summing up the different system analysis and hazard identification methods, the choice of technique depends on the actual system and the objective of the analysis. For detailed analysis the available methods comprise, e.g. fault trees (FTA), event trees (ETA) and simulations. If a quantitative analysis of risk is to be carried out, a probabilistic model of the system must be established. When the model with the data is established, the calculations can begin to estimate system risk and identify critical components and events (Aven, 1992; Kumamoto and Henley, 1996). Nevertheless, even with the best intentions, experience and data bases, it may not be possible to identify all potential failure events or hazards in an engineering system. Some failure events, referred to as 'unforeseen' events, are likely to remain (Stewart and Melchers, 1997).

2.3.4 Risk estimation

Risk estimation is the last part of risk analysis and is defined in the standard IEC 60300-3-9:1995 as a "Process used to produce a measure of the level of risks being analysed." The standard states that elements of the risk estimation process are common for all hazards. First, the possible causes of the hazard are analysed to determine the frequency of occurrence, its duration and its nature (quantity, composition, release characteristics, etc.). Secondly, the consequences of the hazard's realisation are analysed, and involves estimating the severity of the consequences associated with the hazard. Finally, the risk is calculated.

In SS-EN 1050:1996, risk estimation shall be carried out for each hazard by determining the risk associated with a particular situation or technical process as a function of the severity of the possible harm and the probability of occurrence of that harm. Boman (1999) points out the importance of avoiding confusion between the concepts 'probability of occurrence of the harm' and 'probability of occurrence of the hazardous event'. The derived risk is from a combination of the elements shown in Figure 2.6.

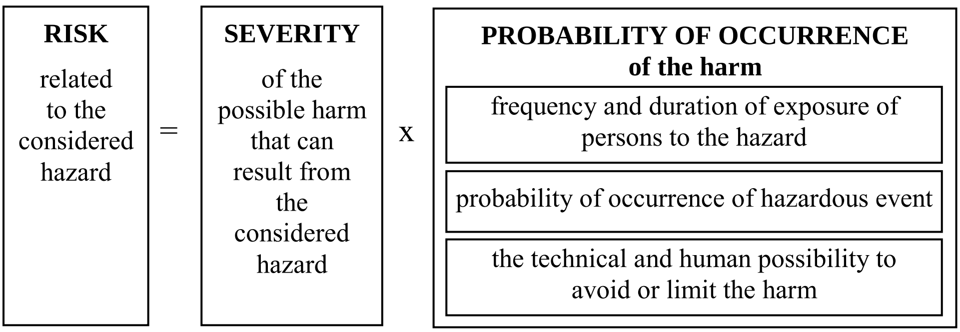


Figure 2.6 Elements of risk (adapted from SS-EN 1050:1996; Boman, 1999).

However, Andrews and Moss (2002) state that an analysis of consequences may not always be necessary to calculate the risk. For major hazard assessments, risk is generally defined as the probability of a specified undesired event, e.g. an explosion or a toxic release. This can be compared to the three different levels of detail, accounted for in section 2.3.1, for which the risk analysis can be carried out, illustrating the importance of thoroughly defining risk before conducting a risk analysis.

Methods used in estimating risks are often quantitative, though the degree of detail required in preparing the estimates will depend upon the particular application. Frequency analysis is used to estimate the likelihood of each undesired event identified at the hazard identification stage. Three approaches are commonly employed to estimate event frequency: to use relevant historical data, to derive event frequencies using analytical or simulation techniques, and to use expert judgement. All of these techniques may be used individually or jointly. When historical data is used, the data should be relevant to the type of system or activity being considered. Event frequencies can be predicted using techniques such as event tree and fault tree analysis. The use of expert judgement can be made with the help of available methods, e.g. the Delphi approach.

However, full quantitative analysis may not always be possible due to insufficient information about the system or activity being analysed, a lack of failure data, the influence of human factors, etc. Some elements of risk are not possible to quantify with, e.g. probability distributions or point estimates. The severity may then be estimated semi-quantitatively by considering the nature of what is protected (persons, property, environment), the severity of injuries or damage to health (slight, serious, death) or the extent of harm (one or several persons). It should be noted that the severity of possible harm might be defined differently depending on the situation (Bedford and Cooke, 2001; Boman, 1999; IEC 60300-3-9:1995).

Consequence analysis estimates the likely impact if the undesired event occurs, i.e. estimating the impact on people, property or environment. The consequences of different types of risk are generally expressed in terms of safety (e.g. fatalities, injuries), health (e.g. cancer), public welfare (e.g. aesthetics, nuisance conditions), ecological, financial issues, or a combination thereof. Predicting the consequences is not usually a matter for risk analysts. Input is generally required from experts in each of the areas where particular hazards and consequences have been identified (Kolluru, 1996b; IEC 60300-3-9:1995; Stewart and Melchers, 1997).

Finally, risks should be expressed in the most suitable terms. Some commonly used outputs in risk calculations are: predicted frequency of mortality to an individual, frequency versus consequence plots (F-N plots), the statistically expected loss rate in terms of casualties, economic cost or environmental damage or the distribution of risk of a specified damage level. In calculating the risk levels, both the duration of the undesired event and the probability that people will be exposed to it need to be considered.

2.4 Risk assessment of human health and environment

2.4.1 *Definition of the risk assessment process*

The risk assessment of human health and environment is a systematic way of organising and evaluating scientific information relevant to the question of whether, and with what likelihood, individuals exposed to agents in their environments will suffer harm. Berglund et al (2001) define exposure as "the contact of a chemical, physical or biological agent with the outer boundary of an organism". How the agent enters an organism is referred to as an exposure route, with the major exposure routes to humans being inhalation, ingestion and dermal contact. One must also distinguish between environmental concentration, exposure concentration and dose. The environmental concentration of an agent refers to its presence in a particular carrier medium, the exposure concentration refers to its presence in its carrier medium at the point of contact, and finally, the dose refers to the amount of a pollutant that actually enters the human body.

Illustrated in Figure 2.2, the risk assessment process included the four steps hazard identification, dose-response assessment, exposure assessment and risk characterisation. The review is based on Ahlborg and Haag Grönlund (1995), Berglund et al (2001), Kolluru (1996b), Covello and Merkhofer (1993), Felter et al (1998), and Rodricks et al (1998), if nothing else is stated.

2.4.2 *Hazard identification*

The first of the four phases, hazard identification, determines whether exposure to an agent could cause adverse health effects in humans. This classification is a qualitative decision reflecting the presence of a hazard and is based on, for example, human and animal observations (Ahlborg and Haag Grönlund, 1995).

2.4.3 *Dose-response assessment*

Dose-response assessment involves considering the toxic effects at various dose levels, i.e. quantifying the relationship between the magnitude of exposure and the occurrence of specific human health effects. There are several concepts describing the relationship between exposure and effect, e.g. exposure-effect, dose-effect, exposure-response and dose-response. The concept of dose-response relationship means the relationship between the dose and the proportion of the exposed affected population.

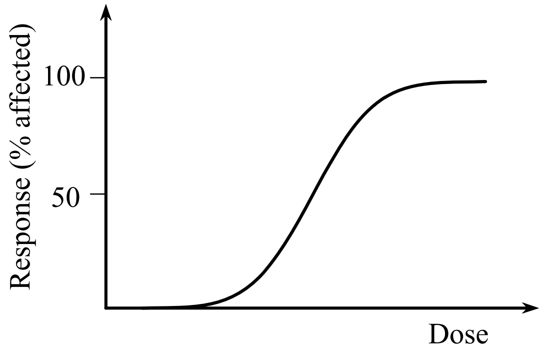


Figure 2.7 *Theoretical dose-response relationship (adapted from Nordberg and Vainio, 2003).*

When performing a risk analysis with the intention to estimate the risk, knowledge of the dose-response curves' shape is essential. A theoretical dose-response relationship is illustrated in Figure 2.7 with an S-form indicating that the effect occurs some time after the start of the exposure, the so called threshold dose. The typical S-form of the dose-relationship can also be explained by the different sensitivity for each individual, illustrated in Figure 2.8 where the variation in sensitivity is given by the probability density function normally distributed. The dose-response relationship in Figure 2.7 is then the cumulative distribution function corresponding to the probability density function in Figure 2.8.

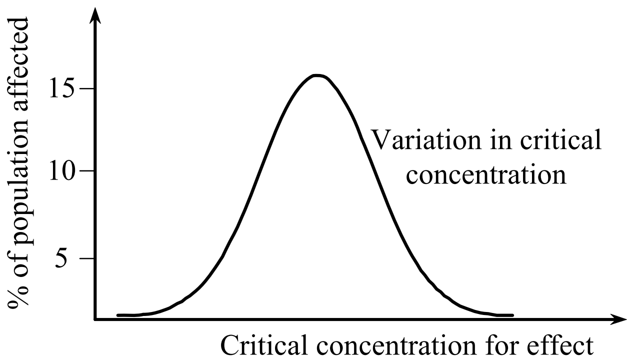


Figure 2.8 *Theoretical distribution of critical concentration when effect occurs (adapted from Nordberg and Vainio, 2003).*

The dose-response relationship of, e.g. ionising radiation causing cancer, often differs from the S-form shown in Figure 2.7. The relationship is considered to be linear with no threshold dose. Streffer et al (2004) state, that a number of arguments have been raised against the linearity of the dose-response relationship without a threshold dose since the variation in individual sensitivity is not considered.

Two approaches to dose-response assessment exist. The first approach involves the use of uncertainty factors applied to the no-observed-effect level (NOEL) in animals to derive a safe level for humans. This approach has historically been used to calculate, e.g. acceptable daily intakes (ADI), calculated by using NOEL divided by an uncertainty factor. Some limitations with the NOEL are, e.g., that experiments with few observations tend to produce larger NOEL, and the slope of the dose-response relationship plays a limited role in determining the NOEL. However, the limitations of NOEL have lead to other approaches that attempt to model probability to a toxic response as a function of dose. A benchmark dose (BMD) is predicted as a statistical lower confidence limit, e.g. the lower 5 %-percentile, for a dose that produces a predetermined change in response rate of an adverse effect. The BMD considers the dose-response relationship by fitting a mathematical model to the data. The probability, P, of a single test animal response is expressed as a function of the dose, i.e. $P = f(d)$, and the models differ only regarding the choice of the function f () (Ahlborg and Haag Grönlund, 1995; U.S. Environmental Protection Agency, 1995).

Links between exposure and observed health effects were primarily made on workers exposed to hazardous agents in their work environment. This has resulted in standards and guidelines for occupational exposure in many countries. The links between exposure and human health in the general environment are often more difficult to establish than the occupational, since the general often has much lower concentrations of hazardous agents compared to the occupational (Berglund et al, 2001).

2.4.4 Exposure assessment

Exposure is the process by which an organism comes in contact with a hazard; exposure is what bridges the gap between a hazard and a risk. Exposure assessment identifies the intensity, frequency and duration of human exposure and a description should include the type of carrier medium (air, water, food, dermal contact).

2.4.5 Risk characterisation

Finally, risk characterisation sums up all the information gathered from the entire process and presents it in a useful and understandable format. An estimation of the probability of an adverse effect in a human population based on the level of exposure and the results of the dose-response extrapolation should be included. To do this, the risk characterisation should not only contain a risk estimate for a given exposure scenario, but also a summary of the relevant biological information, the assumptions used and their limitations, and a discussion of the variability and uncertainty in the risk assessment, both qualitative and quantitative.

Within any exposed population, a substantial variability exists in exposure rates, uptake rates and sensitivity to the effect. In addition to variability, uncertainty in terms of the model and measurement errors may also be significant in risk assessment. Both the dose-response assessment and the exposure assessment are normally are associated with high uncertainty.

2.5 System modelling/quantitative risk analysis

2.5.1 Uncertainty

If a quantitative analysis of risk is to be carried out, a probabilistic model of the system must be established. According to Aven (2003), “a model is a simplified representation of a real-world system”, and “[models] only include descriptions of relationships between observable quantities.” Aven also states, “Modelling is a tool that allows us to express our uncertainty in the format found most appropriate to fulfil the objectives of performing the analysis.”

Uncertainty is a broad term and may arise because of incomplete information or a disagreement between information sources. Many factors in, e.g. the construction industry, are subjected to variability and uncertainty, some uncontrollable. For example, the required durations of various activities in a construction project will depend on the weather conditions and the availability of material and resources, including labour and equipment and their respective productivity (Ang and Tang, 1975). Human intervention is further discussed in section 2.6. Uncertainty may also arise from linguistic imprecision, variability, quantity or about the structure of a model. Even when we have essentially complete information, we may be uncertain due to introduced simplifications and approximations. Very possibly, we may be uncertain about our degree of uncertainty.

In practical scientific and engineering contexts, certainty is achieved through observation, i.e. uncertainty is removed by observations. Uncertainties are sometimes divided into two categories, aleatory uncertainty and epistemic uncertainty. Aleatory uncertainties arise through the natural variability in a system and could be quantified by measurements and statistical estimations. However, epistemic uncertainties arise through a lack of system knowledge, and can in principle be quantified by experts, though not measured. Both types of uncertainty have been given various names, e.g. stochastic, type A, irreducible and variability for aleatory, and subjective, type B, reducible and state of knowledge for epistemic (Aven, 2003; Bedford and Cooke, 2001).

In quantitative risk analysis we are interested in the probability of the occurrence of undesirable events. For this purpose a model is developed, e.g. a fault tree, with the basic event probabilities as parameters. The probabilities are subjective and express the uncertainties of the quantities. In developing and using probabilistic models, an allowance must be made for the uncertainties associated with each random variable in the model. In the literature, uncertainties are often categorised depending on what is being considered (e.g. Morgan and Henrion, 1990; Thoft-Christensen and Baker, 1982).

- Physical uncertainty are concerned with the natural variability of the probabilistic phenomenon itself such as loads, material properties and dimensions;
- Modelling uncertainty are concerned with the accuracy in mathematical models used for, e.g. calculating the load effect;
- Statistical parameter uncertainty arises due to lack of data and information, making the distribution parameters themselves to be considered as random variables.

However, some authors discuss the usefulness or relevance of including model uncertainty, since all models are simply a way of describing the world; what is really of interest is to address the goodness or appropriateness of a specific model to be used in a specific risk analysis (Aven, 2003; Bedford and Cooke, 2001). Aven (2003) argues that "a model $Y = g(\mathbf{X})$ is purely deterministic representation of factors judged essential by the analyst. It provides a framework for mapping uncertainty about the observable quantity of interest, Y, from expressions of epistemic uncertainty related to the observable quantities, $\mathbf{X}$, and does not in itself introduce additional uncertainty. /…/… the model is merely a tool judged useful for expressing knowledge about the system. The model is part of the background information on the probability distribution specified for Y."

The probability of a system failure depends on what model the analyst chooses to use. This could cause validation problems, since the outcome is not open to the test of falsification, e.g. a building is often a unique system that hopefully will not fail during its lifetime. Performing a sensitivity analysis is a way to estimate the effect of the uncertainties caused by a model, i.e. the effect of changes in input variables is estimated. This provides the so-called 'sensitivity' of the risk estimate (Melchers, 1999; Stewart and Melchers, 1997).

2.5.2 Probability theory

Probability theory can be defined as the theory for random experiments that are defined as any observation or series of observations where the possible result or results are non-deterministic (Vännman, 1979). Probability is the most widely used measure of uncertain belief, though the interpretation of the word 'probability' is often confusing. Three common interpretations of probability can be found in the literature (e.g. Andrews and Moss, 2002; Aven, 2003; Bedford and Cook, 2001; McCormick, 1981):

- the classical probability, sometimes called objective or theoretical, includes a finite set of equally possible outcomes of one experiment and where the probability of the event *A* is given by:

$$P(A) = \frac{\text{number of ways in which A occurs}}{\text{total number of possible outcomes}} \tag{2.1}$$

- the relative frequency, sometimes called empirical or experimental, includes a finite set of outcomes of an experiment that can be repeated indefinitely under 'identical conditions' and where the probability of the event *A* is given by:

$$P(A) = \lim_{n \to \infty} (X / n). \tag{2.2}$$

  For a fixed *n*, the quantity *X/n* is the relative frequency of occurrence of *A*. Since it is impossible to actually conduct an infinite number of trials so that $n \to \infty$, usually *P(A)* is just approximated by *(X/n)*. The law of large numbers and the central limit theorem provide a justification that improved estimates of *P(A)* will be obtained by increasing *n*.

- the subjective probability, sometimes called Bayesian or evidence-based, includes a set of possible states of the world (finite or infinite) and where the probability of event *A* is:

  P(A) = a degree of belief in the event A occurring

It is common to refer to the relative frequency interpretation as the classical interpretation done by, e.g. Kaplan (1997). The problem with the classical view of probability is that for most events of interest for real-world decision-making, the relevant population for trials or similar events is not clear. Aven (2003), for example, states that classical probabilities only exist as mental constructions and not in the real world, since an infinite population of similar units needs to be defined to make the classical framework operational. There is strictly no such thing as "the" probability of an event, since different people may have different information relevant to the event and may gradually acquire new information.

In the literature, the Bayesian way of thinking (Bayes equation 2.3) is considered an important tool. The basic idea behind Bayesian statistics is that the lack of knowledge is an uncertainty to be treated by probabilistic reasoning just as other types of uncertainties.

$$P(A_n|B) = \frac{P(A_n)P(B|A_n)}{\sum_{m=1}^{N} P(A_m)P(B|A_m)}, \qquad n = 1 \text{ to } N \tag{2.3}$$

According to, e.g. Aven (2003) and Faber (2001), we often see a mixture of classical and Bayesian analyses in practice and in the literature. The starting point is classical because it is assumed that an underlying true risk exists, although unknown. Subjective probability distributions are used to express uncertainty related to where the true value lies. For example McCormick (1981) states that probability is nothing more than a measure of uncertainty about the likelihood of an event or more precisely, "a probability assignment is a numerical encoding of a state of knowledge".

The outcome events of random experiments can be organised using set theory and Boolean algebra. Only the basic principles are accounted for here, since rules of Boolean algebra and probability theory can be found thoroughly explained in the literature, e.g. Andrews and Moss (2002), Ang and Tang (1975), Bedford and Cooke (2001), Melchers (1999), Thoft-Christensen and Baker (1982), and Vesely et al (1981).

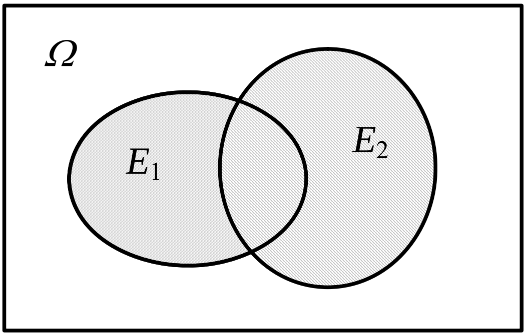


Figure 2.9 Venn diagram representation.

The set of all possible outcomes of an experiment is called a sample space (Ω), and because of the uncertainty in the number of possible outcomes, an event (E) is usually a subset of a sample space. A graphical procedure known as the Venn diagram permits the simple visualisation of the set theory. The set of all possible outcomes is usually represented by a rectangle with the events of interest shown inside, Figure 2.9. Operations with events can be defined with the help of Venn diagrams and the Boolean algebra symbols for union, intersection and complementation, e.g. the union of the events E_1 and E_2 is an event denoted ($E_1 \cup E_2$) and is a subset of sample points belonging to E_1, E_2, or both. Boolean algebra allows the expression of events in terms of other events, and the fault tree system failure, for example, can be expressed in terms of basic events by translating the fault tree into Boolean equations. Three fundamental axioms of probability theory exist:

Axiom 1: For any event E

$$0 \leq P(E) \leq 1$$

where $P(E)$ is the probability of the event E.

Axiom 2: Let the sample space be Ω. Then

$$P(\Omega) = 1$$

Axiom 3: If $E_1, E_2, ..., E_n$ are mutually exclusive events, then

$$P\left(\bigcup_{i=1}^{n} E_i\right) = \sum_{i=1}^{n} P(E_i)$$

According to, e.g. Ang and Tang (1975), the operational rules for the addition and multiplication of numbers also applies to the union and intersection of sets by assuming the following equivalences – union for addition and intersection for multiplication. In accordance with the hierarchy of algebraic operations, an intersection takes precedence over the union of events. However, conventional algebraic operations have no meaning relative to sets and events, and there are operations that apply to sets with no counterparts in conventional algebra of numbers.

2.5.3 Basic variables

Estimating system risk requires quantitative descriptions of both frequency and performance of the basic events, i.e. the performance of, e.g., components, loads, resistances and human actions must be known and it must be possible to estimate the consequences of failure. The quantitative description of the performance of each basic event will usually be either as a ‘point estimate’ (deterministic) variable or a random variable (Stewart and Melchers, 1997; Melchers, 1999). The fundamental variables that define and characterise the behaviour of a structure may be termed as basic variables that are usually employed in conventional structural analysis and design. Typical examples are dimensions, densities or unit weights, materials, loads and material strengths. The compressive strength of concrete would be considered a basic variable, though it can be related to more fundamental variables such as cement content, water-to-cement ratio, etc (Thoft-Christensen and Baker, 1982; Melchers, 1999). The probability distributions to be assigned to the basic variables depend on the knowledge available. Assuming that past observations and experience can be used, the probability distributions might be inferred directly from such observed data.

The determination of empirical properties and probability distributions are based on observing the properties of interest and are defined as random variables. From the observations, a limited amount of results or a sample compared with the total population, i.e. the possible amount of observations, is received. The sample is best presented graphically in a histogram, Figure 2.10.

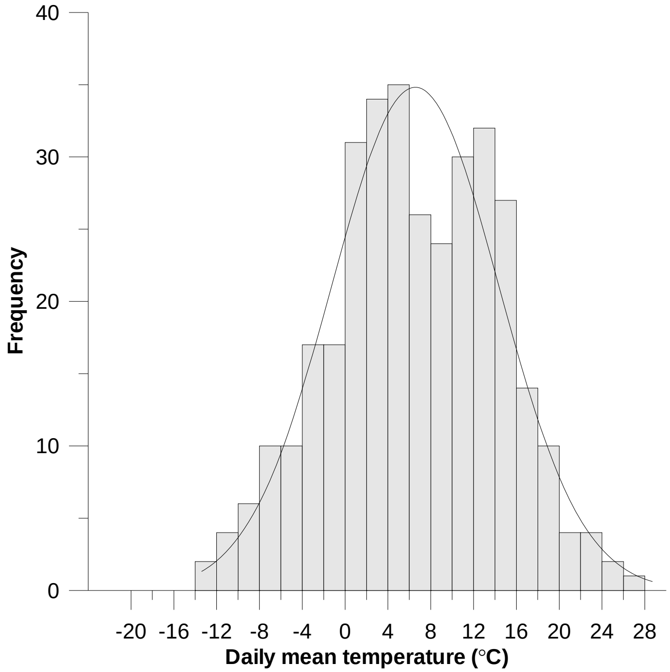


Figure 2.10 Histogram and probability density function.

The random sample can be described by so-called moments where the four main moments are mean, variance (and the standard deviation), skewness and kurtosis. Definitions of the different moments can be found in the literature, e.g. Melchers (1999). From the mean, m_x, and the standard deviation, s_x, the coefficient of variation, v_x, can be calculated by:

$$v_X = \frac{s_X}{m_X} \tag{2.4}$$

The coefficient of variation is a measure of the uncertainty in the predicted value (Cornell, 1969).

Histograms are not always a good representation of the entire population from where the random sample was taken. If the size of the random sample increases the histogram will loose its stepwise character and become more like a continuous function, defined as a distribution function. In Figure 2.10, a probability density function, $f_X(x)$, also known as pdf, is shown corresponding to the histogram. The probability density function has been integrated into the cumulative distribution function $F_X(x)$, which corresponds to the cumulative frequency of the sample in Figure 2.11.

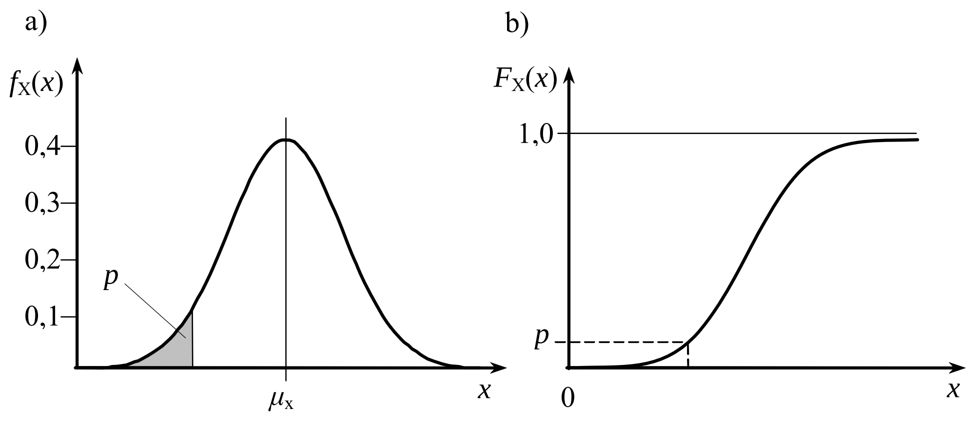


Figure 2.11 Probability density function a) and cumulative distribution function b) (adapted from Schneider, 1997).

Continuous distributions can be two-dimensional so-called joint probability density functions, $f_{X,Y}(x,y)$. The probability density functions of the random variables are called marginal density functions, since they can be represented by probability density functions on the margin, Figure 2.12.

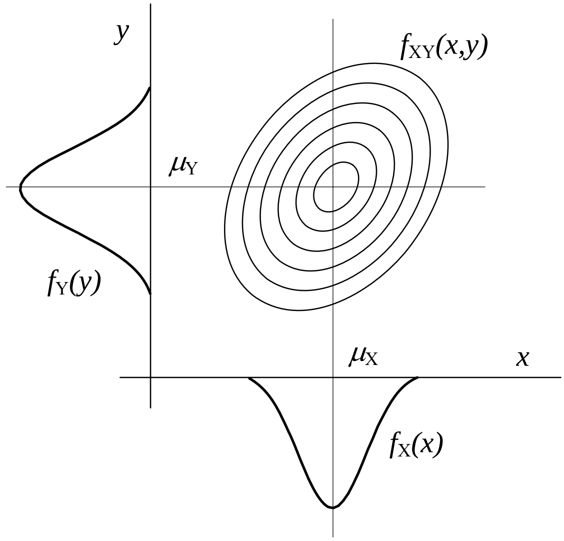


Figure 2.12 Joint probability density function and its marginal density functions.

When two or more random variables are involved, the characteristics of one variable may depend on the value of the other variable (or variables). The degree of predictability will depend on the degree of mutual dependency or the correlation between the variables, as measured (in the linear case) by the statistical correlation (Ang and Tang, 1975). Observations often include the measurements of several parameters, raising the question whether any dependency exists between the random variables. Plotting the values in a scattergram may be constituted as a first control of dependency. Further, the correlation coefficient for the sample can be calculated; however, caution is needed, since the correlation coefficient only recognises linear correlation and a higher order correlation may be present.

The covariance and correlation coefficient for continuous functions are calculated using:

$$\rho_{X,Y} = \frac{\sigma_{X,Y}}{\sigma_X \cdot \sigma_Y} \qquad -1 \leq \rho_{X,Y} \leq 1 \tag{2.5}$$

where:

$$\sigma_{X,Y} = \int_{-\infty}^{\infty}\int (x-\mu_X)\cdot(y-\mu_Y)\cdot f_{X,Y}(x,y)dxdy \tag{2.6}$$

For uncorrelated variables are:

$$f_{\mathrm{X,Y}}(x,y) = f_{\mathrm{X}}(x) \cdot f_{\mathrm{Y}}(y) \tag{2.7}$$

The theory presented can be extended to an arbitrary number of random variables. Although graphical presentation is not possible in hyperspace, analysis is. The most important computational rules for random independent variables are for the sum of two variables (Schneider, 1997):

$$Z = a + b \cdot X + c \cdot Y \tag{2.8}$$

$$\mu_{\mathrm{Z}} = a + b \cdot \mu_{\mathrm{X}} + c \cdot \mu_{\mathrm{Y}} \tag{2.9}$$

$$\sigma_{\mathrm{Z}}^2 = b^2 \cdot \sigma_{\mathrm{X}}^2 + c^2 \cdot \sigma_{\mathrm{Y}}^2 \tag{2.10}$$

and for the product of two random variables:

$$Z = a \cdot X \cdot Y \tag{2.11}$$

$$\mu_{\mathrm{Z}} = a \cdot \mu_{\mathrm{X}} \cdot \mu_{\mathrm{Y}} \tag{2.12}$$

$$\sigma_{\mathrm{Z}}^2 = a^2 \cdot (\mu_{\mathrm{X}}^2 \cdot \sigma_{\mathrm{Y}}^2 + \mu_{\mathrm{Y}}^2 \cdot \sigma_{\mathrm{X}}^2 + \sigma_{\mathrm{X}}^2 \cdot \sigma_{\mathrm{Y}}^2) \tag{2.13}$$

The central limit theorem provides useful information on the shape of the probability density functions for the sums and products of independent variables. Provided that none of the variables dominates the distribution of the sum of *n*, arbitrary random variables X_{i} approaches the normal distribution with increasing *n*, regardless of the distribution types of the variables. For the distribution of the product of *n*, arbitrary random variables X_{i} approaches the log-normal distribution with increasing *n*, regardless of the distribution types of the variables (Schneider, 1997). Another useful theorem is the law of large numbers that refers to the fact that if the sample size increases, the sample mean becomes more and more reliable as an estimate of the population mean (Johnson, 2000).

2.5.4 Structural reliability analysis (SRA)

Structures or structural components "fail" when they encounter an extreme load or when a combination of loads causes an extreme load effect of sufficient magnitude for the structure to attain "failure state", which may be an ultimate or a serviceability condition. While electronic equipment is produced in considerable numbers, thereby providing the opportunity to establish failure probabilities in terms of relative frequency, the failure probability of a structure is a function of the analyst's lack of knowledge of the structure's properties and the uncertain nature of the loading (Thoft-Christensen and Baker, 1982; Melchers, 1999).

Cornell (1969) introduced the framework for structural codes based on the probability theory to treat uncertainties by using predicted values (mean) and measures of dispersion (standard deviation or coefficients of variation). The Joint Committee on Structural Safety (JCSS) has categorised the methods for checking the safety of structures into two broad classes called level 3 and level 2, defined as:

Level 3: Methods where calculations are made to determine the exact probability of failure for a structure or structural component.

Level 2: Methods involving certain approximate iterative calculation procedures to obtain an approximation to the failure probability of a structure or structural system.

Level 1 methods are not reliability analysis methods, but rather methods for checking design and safety, e.g. the most commonly used partial coefficient method (e.g. Thoft-Christensen and Baker, 1982).

Most planning and designing of engineering systems must be accomplished without the benefit of complete information. The available and required capacity cannot be determined precisely according to uncertainties, but has to be modelled as random variables, giving reliability to the system measured in terms of probability. Therefore, safety will only be assured in terms of the probability that the available strength will be adequate to withstand the lifetime maximum load.

The random variables in structural reliability analysis (SRA) are defined as:

R = resistance, and

S = load effect,

and can be described by their probability density functions shown in Figure 2.13 (e.g. Ang and Tang, 1990; Thoft-Christensen and Baker, 1982; Melchers, 1999).

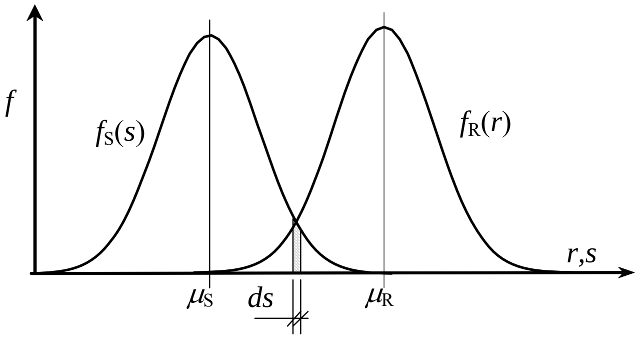


Figure 2.13 Probability density functions for random variables R and S.

The probability that *S* falls inside the infinitesimal interval *ds* is:

$$p_S = f_S(s)ds \tag{2.14}$$

and the probability that *R* falls inside or below this interval is:

$$p_R = \int_{-\infty}^{s} f_R(r)dr \tag{2.15}$$

On the conditions that *R* and *S* are statistically independent, the probability that *S* falls inside the interval *ds* when $R \leq s$ is given by:

$$f_S(s)ds \cdot \int_{-\infty}^{s} f_R(r)dr \tag{2.16}$$

The total failure probability P_f is obtained by considering all possible values of *s*, i.e. by taking the integral over all *s*:

$$P_f = \int_{-\infty}^{\infty} f_S(s)\left(\int_{-\infty}^{s} f_R(r)dr\right)ds = \int_{-\infty}^{\infty} f_S(s)F_R(s)ds \tag{2.17}$$

Melchers (1999) comments on the use of the lower limit of integration to be a negative infinity (-∞). The lower limit should be zero, since a negative resistance usually is not possible.

The probability density functions *R* and *S* in Figure 2.13 are plotted as marginal probability density functions on the *r* and *s* axes shown in Figure 2.14. The limit state equation $M=R-S=0$ separates the safe region from the failure region and divides the volume into two parts. The volume is unity and the design point (r^*, s^*) lies on the straight line where the joint probability density is greatest, i.e. if failure occurs, it is likely to be there.

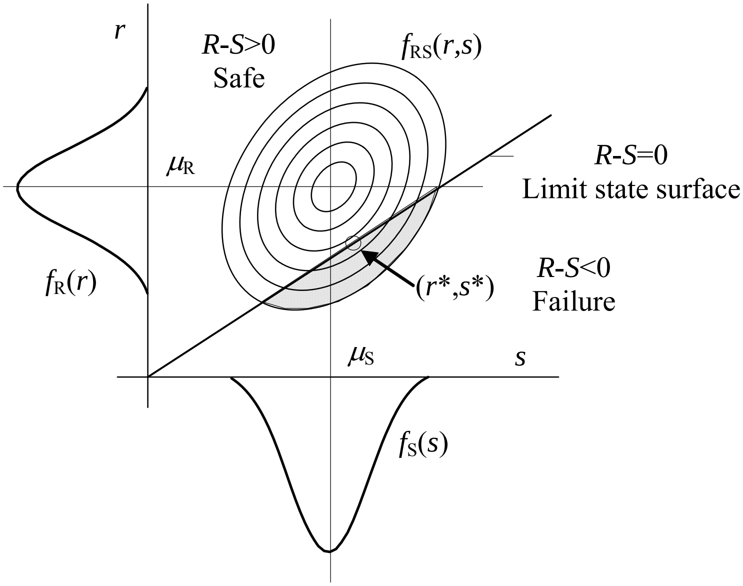


Figure 2.14 Representation of the limit state equation M = R – S separating the safe region from the failure.

The difference between the two basic variables is called the safety margin, M, and is given by

$$M = R - S \tag{2.18}$$

In general, analytical methods do not exist for the integral in equation (2.17), except if R and S are independent normally distributed variables. If so, then M, which is a linear function of R and S, is also normally distributed according to the central limit theory:

$$M \in N(\mu_{\mathrm{M}}, \sigma_{\mathrm{M}}) \tag{2.19}$$

where

$$\mu_{\mathrm{M}} = \mu_{\mathrm{R}} - \mu_{\mathrm{S}} \tag{2.20}$$

$$\sigma_{\mathrm{M}}^2 = \sigma_{\mathrm{R}}^2 + \sigma_{\mathrm{S}}^2 \tag{2.21}$$

The normal probability density function for *M* is given by:

$$f_{\mathrm{M}}(x) = \frac{1}{\sigma_{\mathrm{M}}\sqrt{2\pi}} e^{-\frac{(x-\mu_{\mathrm{M}})^2}{2\sigma_{\mathrm{M}}^2}} \tag{2.22}$$

The probability that $M < 0$ is then given by:

$$P(M < 0) = \int_{-\infty}^{0} f_{\mathrm{M}}(x)dx = \frac{1}{\sigma_{\mathrm{M}}\sqrt{2\pi}} \int_{-\infty}^{0} e^{-\frac{(x-\mu)^2}{2\sigma_{\mathrm{M}}^2}} dx \tag{2.23}$$

The normal distributed function can be standardised into $M \in N(0,1)$, given:

$$y = \frac{x-\mu_{\mathrm{M}}}{\sigma_{\mathrm{M}}} \quad \rightarrow \quad dy = \frac{1}{\sigma_{\mathrm{M}}} dx \tag{2.24}$$

$$P(M < 0) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-\frac{\mu_{\mathrm{M}}}{\sigma_{\mathrm{M}}}} e^{-\frac{y^2}{2}} dy = \Phi\left(\frac{0-\mu_{\mathrm{M}}}{\sigma_{\mathrm{M}}}\right) = \Phi\left(\frac{\mu_{\mathrm{S}}-\mu_{\mathrm{R}}}{\sqrt{\sigma_{\mathrm{S}}^2+\sigma_{\mathrm{R}}^2}}\right) \tag{2.25}$$

where Φ is the standard normal distribution function.

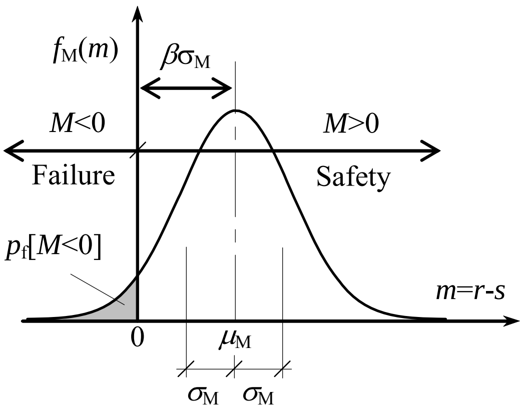


Figure 2.15 Illustration of reliability index β

The reliability (safety) index β, i.e. the number of standard deviations by which μ_M exceeds zero, illustrated in Figure 2.15, can now be defined as:

$$P_f = \Phi\left(\frac{-\mu_M}{\sigma_M}\right) = \Phi(-\beta) \tag{2.26}$$

If R and S are jointly normally distributed with correlation coefficient ρ, equation (2.26) still holds true, but σ_M is given by:

$$\sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2 + 2\rho\sigma_R\sigma_S} \tag{2.27}$$

If the safety margin M is linear in the basic variables $X_1, ..., X_n$, then:

$$M = a_0 + a_1 \cdot X_1 + ... + a_n \cdot X_n \tag{2.28}$$

It then becomes easy to calculate the reliability index β as

$$\mu_M = a_0 + a_1 \cdot \mu_1 + ... + a_n \cdot \mu_n \tag{2.29}$$

$$\sigma_M^2 = a_1^2 \cdot \sigma_1^2 + ... + a_n^2 \cdot \sigma_n^2 + \sum_{i=1}^{n} \sum_{j=1,\, j\neq i}^{n} \rho_{ij} \cdot a_i \cdot a_j \cdot \sigma_i \cdot \sigma_j \tag{2.30}$$

where the last term represents the correlation between any pair of basic variables.

For functions of several random variables, e.g. $Y = G(X_1, X_2, \ldots X_n)$, no closed-form solution can be found and the integration over the failure domain cannot be performed analytically. However, the solution can be made more tractable by simplification or numerical treatment. Two dominant approaches have emerged (Melchers, 1999):

- sidestepping the integration process completely by transformation – the so-called ‘First-order second-moment’ method and

- using simulation – the so-called ‘Monte Carlo’ method.

According to, e.g. Schneider (1997), two limitations are often assumed when calculating failure probabilities. The variables in a limit state function are independent of each other, since correlations between the variables considerably complicate the calculations, and failure probabilities are conditional on the assumption that there are no human errors in what is analysed.

2.5.5 First-order second-moment theory (FOSM)

The presentation in the previous section assumed a linear safety margin in the basic variables. If the safety margin is non-linear, approximate values can be obtained by expanding the function as a Taylor series with only the first term taken and the mixed terms neglected. For the limit state function, the mean value and variance following formulas apply (Schneider, 1997; Thoft-Christensen and Baker, 1982):

$$M \approx g(X_{\mathrm{i}}) + \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mu_{\mathrm{X_i}} - x_{\mathrm{i}}) \cdot \frac{\partial g}{\partial X_{\mathrm{i}}} \tag{2.31}$$

$$\mu_{\mathrm{M}} = g(X_{\mathrm{i}}) \tag{2.32}$$

$$\sigma_{\mathrm{M}}^2 \approx \sum_{\mathrm{i}=1}^{\mathrm{n}} \left(\frac{\partial g}{\partial X_{\mathrm{i}}}\right)^2 \cdot (\sigma_{\mathrm{X_i}})^2 \tag{2.33}$$

Approximations that linearise the limit state function at the design point **x*** are denoted 'first-order' methods. In the First-order second-moment (FOSM) method the term 'second-moment' refers to the description of all random variables only in terms of their mean (the first moment) and their variance (the second moment).

Hasofer and Lind (1974) presented a format on second-moment reliability with the emphasis to find the distance between the origin and perpendicular to the failure surface and thus calculate the reliability index β. The first step in defining Hasofer and Lind's reliability index β is to normalise the basic variables into the z-coordinate system, i.e. into their standardised form N(0,1). The variables are defined as:

$$Z_{\mathrm{i}} = \frac{X_{\mathrm{i}} - \mu_{\mathrm{X_i}}}{\sigma_{\mathrm{X_i}}} \qquad \text{where } \mathrm{i} = 1,\ 2, ..., \mathrm{n} \tag{2.34}$$

where μ_X and σ_X are the mean and the standard deviation of the random variable X. Note that $\mu_Z = 0$ and $\sigma_Z = 1$. The limit state function must also be transformed, given by g(**Z**) = 0. The transformation can only be performed if the random variables are uncorrelated. If not, uncorrelated random variables will have to be found using eigenvalues and eigenvectors. This will not be shown here, but can be found in, e.g. Melchers (1999). Weak correlation, e.g. $\rho < 0{,}2$, can usually be ignored and the variables can then be treated as independent of each other (Melchers, 1999; Schneider, 1997). The limit state function after normalisation is defined as:

$$M = g(Z_1, Z_2 ..., Z_n) \tag{2.35}$$

Hasofer and Lind's reliability index β is defined as the shortest distance from the origin perpendicular to the failure surface in the normalised z-coordinate system. For the two-dimensional case in Figure 2.16 the reliability index β is equal to the distance OA. Further, point A on the failure surface is called the design point.

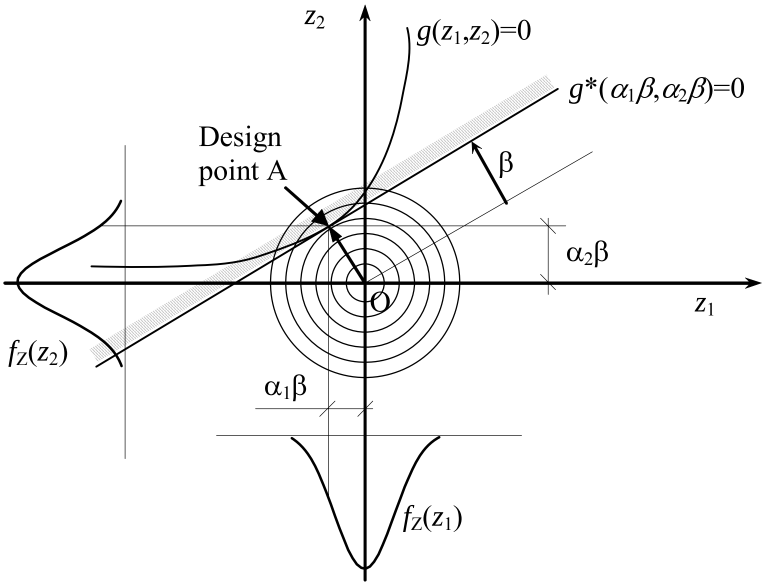


Figure 2.16 Definition of Hasofer and Lind's reliability index β.

In the design point the limit state function is given by:

$$M = g(Z_{X_1}, Z_{X_2}, ..., Z_{X_n}) = g^*(\alpha_{X_1} \cdot \beta, \alpha_{X_2} \cdot \beta ..., \alpha_{X_n} \cdot \beta) \tag{2.36}$$

The vector perpendicular from origin to the limit state function and the design point is then given by:

$$\left(-\frac{\partial g^*(\alpha_{X_1} \cdot \beta, \alpha_{X_2} \cdot \beta ..., \alpha_{X_n} \cdot \beta)}{\partial z_1}, \dots, -\frac{\partial g^*(\alpha_{X_1} \cdot \beta, \alpha_{X_2} \cdot \beta ..., \alpha_{X_n} \cdot \beta)}{\partial z_n} \right) \tag{2.37}$$

Further, the length of the vector is (2.38):

$$\sqrt{\left(\frac{\partial g^*(\alpha_{X_1}\cdot\beta, \alpha_{X_2}\cdot\beta \ldots, \alpha_{X_n}\cdot\beta)}{\partial z_1}\right)^2 + \ldots + \left(\frac{\partial g^*(\alpha_{X_1}\cdot\beta, \alpha_{X_2}\cdot\beta \ldots, \alpha_{X_n}\cdot\beta)}{\partial z_n}\right)^2}$$

The vector coincides the unity vector (α_1, α_2, ..., α_n), giving a sensitivity factor α defined as:

$$\alpha_i = \frac{-\dfrac{\partial g}{\partial z_i}}{\sqrt{\sum_{k=1}^{n}\left(\dfrac{\partial g}{\partial z_k}\right)}} \qquad \text{where } i = 1,\ 2, \ldots, n \tag{2.39}$$

The sensitivity factor has an important practical implication, since a very low value for α_i signals that the random variable z_i might well be treated as a deterministic variable. The sensitivity factors α and the reliability index β can now be estimated iteratively.

The FOSM method can be extended to also include non-normal random variables provided that each variable is first transformed to an equivalent normal random variable. The procedure for doing this, according to Melchers (1999), is called the First Order Reliability Method (FORM). However, the literature is somewhat confused in its definition of FOSM and FORM, i.e. Schneider (1997), for example, calls the above method when only the first term of the Taylor series is considered FORM. For non-normally distributed variables, Schneider (1997) discusses two approaches namely tail approximation and transformation into standard normal space. Approximating the limit state surface with a linear surface through a Taylor series expansion may not be satisfactory if the limit state surface has a significant curvature. However, if the second order term of the Taylor expansion is also included in the analysis, then the limit state function is approximated by a tangent hyper-surface to fit the curvature of the limit state function in the design point. This method is called the Second Order Reliability Method (SORM) (Melchers, 1999; Schneider, 1997).

One attempt to use FORM in the area of public health risk assessment have been found in the literature review. Hamed (1996) used FORM in what was called a new methodology for probabilistic public health assessment providing the opportunity to compare the lifetime cancer risk from exposure with a threshold level.

The tail sensitivity problem is vital if the aim of the structural reliability analysis is to estimate realistic probabilities. In this case, considerable attention must be paid to use the best available probabilistic model; in particular that best models the relevant extremes (tails) of the probability density functions. Generally, this means that the tails of the models must be good fits for the higher values of the loads and for the lower values of the resistance (Melchers, 1999).

2.5.6 Monte Carlo simulation

As the name implies, Monte Carlo simulation involve sampling at random to artificially simulate a large number of experiments and to observe the results. In its simplest approach this means randomly sampling each random variable X_i to give a sample value x_{ik}, where the index k stands for the kth simulation of a set of x_i. Each set of the k realisations gives a value:

$$g_k = G(a_0, x_{1k}, x_{2k}, ..., x_{nk}) \tag{2.40}$$

By repeating this process many times it is possible to simulate the probability distribution for G by progressively building up a large sample that may be treated as any other statistical sample. The exact probability distribution for G will not be of any standard form, though the form of the probability distribution of the most dominant basic variable may govern it.

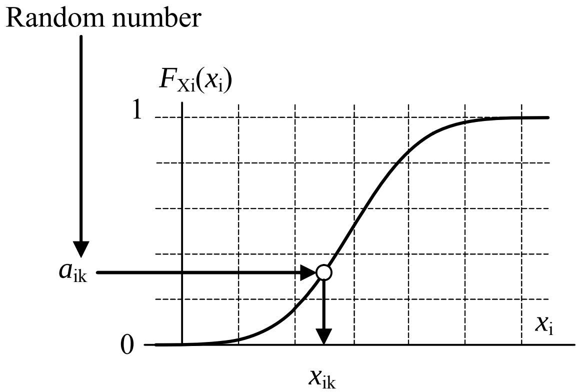


Figure 2.17 Principles for Monte Carlo simulation (from Schneider, 1997).

The simulation is made with a random number generator that produces random numbers a_{ik} between 0 and 1, Figure 2.17. Such a number is interpreted as a value of the cumulative distribution function $F_{Xi}(x_i)$ and delivers the associated realisation x_{ik} of the variable X_i. Since $G \leq 0$ corresponds to failure, P_f may be expressed as:

$$P_{\mathrm{f}} = P(G \leq 0) = \lim_{z \to \infty} \frac{z_0}{z} \tag{2.41}$$

where z is the total number of trials and z_0 is the number of failures, i.e. where $G(x_1, x_2, ..., x_n) \leq 0$ (Thoft-Christensen and Baker, 1982). The greater the number of z_0, the more reliable is the value of P_{f}. The necessary number of trials depends on the required coefficient of variation for the probability of failure. According to Schneider (1997), the coefficient for small P_{f} can be written as:

$$v_{\mathrm{P_f}} \approx \frac{1}{\sqrt{z \cdot P_{\mathrm{f}}}} \tag{2.42}$$

For a 10 % coefficient of variation and the probability for failure of 10^{-4}, as many as 10^6 simulations have to be produced. Simplifying the problem as much as possible is advisable, though attention needs to be given to whether or not the output is likely to be meaningful with the available data. A second-moment analysis may be useful and accurate to check the outcome (Stewart and Melchers, 1997).

2.6 Human error

Limitations often assumed concerning the calculation of failure probabilities has been mentioned in section 2.5.4, including that failure probabilities are conditional assuming that no human errors exist in what is analysed. However, human influence is very much involved in the planning, designing, constructing and maintaining of buildings, considered vital throughout the risk management process.

2.6.1 Definition and classification

When discussing human error, the point of view is often quite different. An engineer may prefer to view humans as a system component where success and failure can be described similarly to equipment, while psychologists or sociologists put the emphasis on, e.g. human behaviour and organisational structures (Hollnagel, 1998). Engineers are basically interested in predicting events, whereas cognitive psychologists, for example, are mostly interested in explaining events.

The term “human error” is somewhat disputed. Technical literature (e.g. Melchers, 1999), commonly refer to human actions causing structural failures as “human errors” or “gross errors”, while Hollnagel (1998), for example, states that the preferred term is human erroneous actions or performance failure. From the standpoint of cognitive psychology, human intentions are the basis and referred to as slips and mistakes.

There are two forms of human failure, errors and violations. Violation is a deliberate performed act that is either prohibited or different from described. Errors could be identified and described by grouping similar error types together and developing classification schemes. The categories of errors have different approaches depending on the fields of interest. The traditional human reliability analysis (HRA) is based entirely on observational behaviours and distinguishes between, e.g.:

- errors of omission – the failure to perform a required action,
- errors of commission – an action performed incorrectly,

The information processing approach, with an emphasis on the man-machine interface, distinguishes between:

- skill-based – actions performed without conscious thoughts,
- rule-based – actions performed following rules from, e.g. training,
- knowledge-based – actions performed in a completely conscious manner.

An extension of the approach has adopted the cognitive perspective using slips and mistakes, resulting in skill-based slips, rule-based mistakes and knowledge-based mistakes (Hollnagel, 1998, CCPS, 1994).

2.6.2 Human reliability analysis (HRA)

Human reliability analysis (HRA) is concerned with predicting the likelihood that a human action may fail. The emphasis has been on techniques for the derivation of numerical error probabilities to be used in fault trees where human error probabilities are combined with hardware analysis to permit an overall measure of risk to be calculated. However, the major benefits of applying a risk assessment are the qualitative insights that emerge regarding the source of risk (CCPS, 1994, Hollnagel, 1998).

To perform an HRA, a reliability model that represents the system, together with Performance shaping factors (PSF), is needed. In the case of HRA, the system is the human operator, and the PSFs are the conditions under which the tasks or activities are carried out. PSFs can be divided into external and internal PSFs. External PSFs are related to the physical work environment or task situation, e.g.

inadequate work layout and time pressure, and are generally outside the control of the individual. Internal PSFs include personal attributes like experience, skill and motivation (Stewart and Melchers, 1997; CCPS, 1994; Hollnagel, 1998).

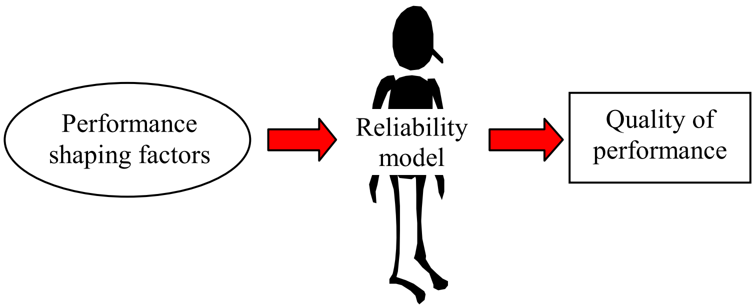


Figure 2.18 The role of the reliability model (Hollnagel, 1998).

Qualitative human error analysis is performed by describing the task, and includes performance shaping factors that analyse how to predict errors and the consequences. Finally, the possibility to reduce errors is analysed. If the results from the qualitative analysis are to be used for quantification, they need to be appropriately represented in, e.g. a fault tree or event tree (CCPS, 1994). To consider an action erroneous (Hollnagel, 1998),

1. a clearly specified performance standard or criterion has to be defined,
2. there must be an event or an action that results in a measurable performance shortfall, and
3. the person has the opportunity to act in a way that would not be considered erroneous.

The probability may be derived from expert judgement or empirical data. It usually represents the error likelihood under “average” conditions and may be modified using performance shaping factors to account for abnormal conditions, e.g. stress. The probability called error rate or Human Error Probability (HEP) is given by:

$$\text{HEP} = \frac{\text{number of errors}}{\text{total number of opportunities for error}} \tag{2.43}$$

The main problem of predicting HEP is the lack of workplace related data and, above all, estimating the total number of opportunities for errors to occur in reality (the denominator problem) (CCPS, 1994; Stewart and Melchers, 1997). Error rates are not necessarily constant and are likely to vary both from individual to individual and eventually with the performances of skilled persons tending to have lower levels of error rates. When considered in terms of a probabilistic distribution of error rates, this suggests that lognormal distribution is appropriate for modelling human performance data (Swain and Guttman, 1983, from Stewart and Melchers, 1997). The measure of dispersion used is the “error factor” (EF), expressed as:

$$EF = \sqrt{\frac{\Pr(F_{95th})}{\Pr(F_{5th})}} \tag{2.44}$$

where $\Pr(F_{5th})$ and $\Pr(F_{95th})$ are the error rates corresponding to the 5^{th} and 95^{th} percentiles of the error rates distribution. Numerical values of error rates, EFs and PSFs can be found in databases, though they are mainly developed for nuclear power plant operators.

Although risk assessment usually concentrates on the negative human effects in the system, humans also have the capability to reduce risk by recovering from hardware failures or earlier errors. An erroneous action may even strengthen the system being considered.

2.6.3 Human errors in structural reliability

Humans are very much involved in the planning, designing and constructing of a future building. Several studies show the influences of human intervention in structural reliability, e.g. the survey by Matousek and Schneider (1976), where 800 cases of damages to structures were analysed. The actual causes of failures could be traced back to ignorance, carelessness and negligence (37 %), insufficient knowledge (27 %), underestimating influences (14 %) and to forgetfulness, unjustifiable trust in others and objectively unknown influences (22 %).

The objectives of a Swedish study initiated in 1995 were to reveal the size and causes of quality fault costs in building projects (Josephson and Hammarlund, 1996a, 1996b). The design and construction phases were responsible for about three-quarters of the total amount of faults, while the remaining quarter was due to proprietor, material delivery, machines and public. Almost 60 % of the faults could be related to insufficient commitment and less than 20 % each to insufficient information and insufficient knowledge respectively, Figure 2.19. The direct cause could primarily be attributed to individuals. However, every action by an individual is influenced by a multitude of conditions, e.g. satisfaction concerning work environment and individual well-being.

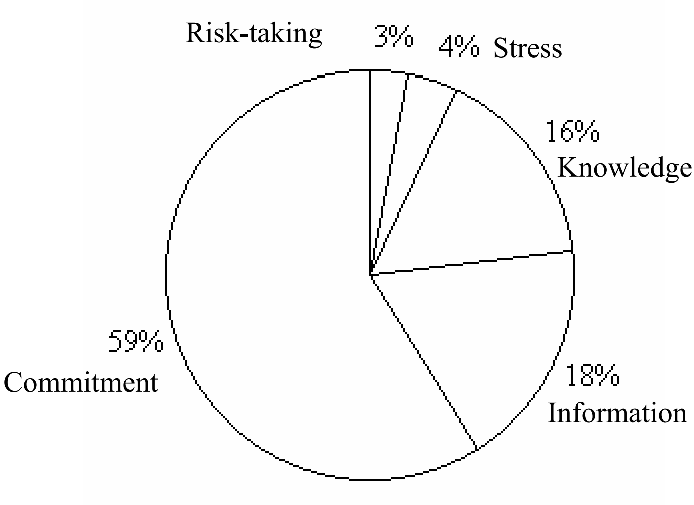


Figure 2.19 The primary causes of faults (Josephson and Hammarlund, 1996a).

Human reliability analysis models have also been studied in structural reliability. Stewart and Melchers (1988) and Stewart (1991) have used the probabilistic risk assessment approach to examine the effects of human error through event-tree methodology and the Monte Carlo simulation. Stewart categorises human errors in slips and mistakes, where a slip could be, e.g., forgetting to apply a correction factor, and a mistake could be, e.g., selecting an unsuitable design loading combination. The SRK-framework is also explained as skill-based behaviour being a simple arithmetic task and rule-based behaviour consisting of a more complex arithmetic task. Knowledge-based behaviour involves, e.g., the analysis of a novel structure. However, Stewart defines both skill-based and rule-based behaviours as slips that are not in line with, e.g. Hollnagel (1998) and CCPS (1994).

Stewart (1993) has proposed a model incorporating the effect of designer checking, independent design checking, engineering inspection of construction works, and interaction between the designer and the contractor. The design and construction tasks are split up into micro tasks for which average error rates are represented by the lognormal distribution and EFs are established using expert judgement, appropriate literature or both (Stewart, 1992). For example, human error rates in structural design tasks were obtained from practising professional engineers performing cognitive tasks such as calculation, table look-up and ranking (Stewart, 1992). Examples of parameters are:

- “table look-up” in design has an average error rate of 0,013 and an EF of 3,
- “inadequate concrete mix” in construction has an average error rate of 0,0049 and an EF of 3.

Most of the existing databases contain human error probabilities associated with operation and maintenance of nuclear, chemical or process plants. However, the relative lack of databases for other systems does not necessarily imply the absence of human reliability data. Several studies have been performed to investigate human influence on structural reliability. Stewart (1991, 1992 and 1993) and Stewart and Melchers (1988, 1997) have modelled human errors in structural design and construction using event tree logic and the Monte Carlo simulation to estimate human error rates. Human error rates, lognormal distributed, and EFs can be found for different micro tasks in design and construction.

The Swedish study referred to earlier was initiated to reveal the causes of quality fault costs in building projects (Josephson and Hammarlund, 1996a, 1996b). Seven different building projects were observed and a total of 2879 faults were registered. Each fault was registered together with essential data like:

- Description of fault
- Part of building component involved
- Origin of fault, i.e. which part of the building process was responsible.
- Primary cause
- Type of fault

The faults were distributed according to type of work performed, with approximately 120 faults originating from assembling of formwork, 70 faults from reinforcement work and 180 faults from concrete casting.

Examples of faults originating from assembling of formwork were:

- Incorrect placement of construction joint (cause: knowledge)
- Recess in construction joint not carried out (cause: commitment)

Examples of faults originating from reinforcement work were:

- Wrong reinforcement prescribed (cause: commitment)
- Recess strip misplaced (cause: information)

Examples of faults originating from concrete casting were:

- Wrong quality of concrete delivered (cause: commitment, information)
- Casting damages (cause: commitment, unavoidable due to existing knowledge, method and equipment)
- Unfulfilled curing of concrete wall (cause: time pressure)

With more detailed information about the different faults, finding out the nominator “number of errors” would probably be possible. The problem is to find the denominator. However, it might be possible to find even the denominator for at least some of the faults. For example, delivery of the wrong quality of concrete can be compared with the total amount of deliveries. Misplacement of reinforcement or recess strips would be possible to compare with the total amount used.

2.7 Risk criteria

Results from the risk estimation of a risk analysis can be used by decision-makers to help judge the tolerability of risk and aid in choosing between potential risk-reduction and risk avoidance measures (IEC 60300-3-9:1995), as is done in the risk evaluation, i.e. the second part of the risk assessment, cf. Figure 2.1. The estimated risk is to be compared with risk criteria that are generally based on regulations, standards, experience, theoretical knowledge, or a combination thereof used as a basis for deciding about acceptable risk (CIB, 2001). Criteria for accepting or rejecting the assessed risks include two related entities: the frequency of an undesired event and the consequences (casualties, monetary values, environmental values). However, it is not necessarily the hazard to humans that governs the analysis. The objective of the analysis can be, for example, to minimise the maximum allowed release of gas or to optimise safety measures restricted by constraints such as authority regulations (CIB, 2001; Frantzich, 1998).

Often, it is generally stated in the literature that people are prepared to tolerate higher levels of risk to hazards to which they expose themselves voluntarily (e.g. Lees, 1996). But, what is ‘acceptable’ risk? How do individuals or society perceive risk? One aspect of the risk debate concerns the relationship between objective risk, i.e. statistical, and subjective risk, i.e. perceived. Another aspect is acceptable risk versus tolerable risk. CIB (2001) states, “fundamental levels of safety have to be acceptable to society as a whole, for it is on their behalf that engineers make such decisions.” Rowe (1977) states, “as one looks toward decision making in society the subjective risk is perceived to be reality. People base their decisions on subjective risk estimates, not on what is objective. In other words, the emotional aspects, rather than objective scientific knowledge are what drive people.”

Davidsson et al (1997) state, that "acceptable" risk does not exist since every risk to human life and well-being are unacceptable. However, everyday life includes risks and the economic ability to totally reduce risk is limited. Since we have to accept some risks today, the vision for tomorrow has to be a "non-risk society".

Tolerability does not mean acceptability. It refers to the willingness to live with a risk to secure certain benefits and with the confidence that it is being properly controlled. To tolerate a risk means that we do not regard it as negligible or something we might ignore, but rather as something we need to keep under surveillance and reduce still further if and when we can. The setting of risk criteria involves issues such as who decides what the critical risks and consequences are, what will be the acceptance standards, and how much will be disclosed and to whom. Evidently, answers to these matters are not straightforward. Much will depend on the context where the risk analysis is to be performed, whether in the private or public domains, what the nature of the hazard is, as well as what the possible consequences of system failure might be (Lees, 1996; Stewart and Melchers, 1997).

2.8 Summary of chapter 2

The objective of this work is to develop a method to predict the risk for an unhealthy indoor environment to occur. This includes both the risk management of technical systems and the risk management of human health and environment, and more explicitly, parts of the risk management processes including risk estimation. In the risk management of technical systems, risk estimation is performed in the risk analysis process. In the risk management of human health and environment, risk estimation is performed in the risk assessment process.

Regarding the risk management process, the most important difference between the disciplines of engineering, and human health and environment is the definitions of risk analysis and risk assessment. Roughly speaking, what is defined as risk analysis in engineering is defined as risk assessment in the field of human health and environment. To develop a procedure for how to conduct a risk analysis, with the purpose to estimate the risk of indoor air pollutants occurring and causing an unhealthy indoor environment to humans, both disciplines are involved and have to be used. Primarily, the procedure to find the hazards and the undesirable indoor event will be based on the risk analysis processes used in the field of engineering, because the undesirable indoor event occurs as a combination of an environmental impact and the technical system, i.e. how the building is designed and constructed. The procedure is developed in chapter 3. The undesirable indoor event is compared with the consequences to humans, by using research results from the field of human health and environment. This corresponds to the fact that the consequences are usually not a matter for risk analysts and input is generally required from experts in each area. The estimated risk is to be compared with risk criteria based on findings in the risk assessment of human health, regulations or standards.

Note that the identification of hazards and the valuation of risks is a matter of subjective judgement and evaluation. The definition of ‘risk’ principally depends on whom you ask, with the recommendation for it to be clearly defined. The definition of risk used in this work is outlined in chapter 3.

The risk analysis process applied to an indoor environment has to include both a qualitative and a quantitative analysis to be able to estimate the undesirable indoor event and compare it with the negative health effects to humans. In some system analyses, the undesirable event is unknown and has to be established by using inductive reasoning before the cause of the hazard can be developed. When the undesirable event is established the question is: How does the unhealthy indoor environment occur? It constitutes a deductive reasoning to find out what basic faults contribute to system failure. Fault tree analysis will be used, since it is a commonly used deductive method that allows for both qualitative and quantitative evaluation and for which rules and guidelines exist. Ljungquist (2003) proved fault tree analysis to be an efficient tool also in the building process.

Fault tree analysis was mainly developed to use on systems built with electronic equipment, where basic event probabilities often are tabulated in different kinds of databases, e.g. the nuclear industry. In the building industry, failure probabilities are more difficult to establish in terms of relative frequency. This uncertainty can be handled using structural reliability analysis (SRA) in the quantitative analysis, since a special feature of SRA is that several random variables can be considered in a single analysis (Rettedal et al, 2000), making it possible to analyse a whole branch of a fault tree in a single analysis based on SRA. The use of continuous variables is common in SRA and the ability to treat continuous variables is considered to be one of this technique’s main attractions. SRA will, therefore, be used, comprising probability theory to handle the uncertainties, and first-order second-moment analysis (FOSM) and the Monte Carlo simulation to evaluate the risk for the occurrence of an unhealthy indoor environment depending on how the building is designed and constructed.

It was mentioned earlier that humans are very much involved in the design and construction of a future building. However, failure probabilities in SRA are often conditional on the assumption that no human errors exist in what is analysed. Human reliability analysis (HRA) is concerned with predicting the likelihood that a human action may fail. The emphasis has been on techniques to derive numerical error probabilities for use in fault trees, where the human error probabilities are combined with hardware analysis to allow an overall measure of risk to be calculated. Some focus will be placed on human influence.

3 THE RISK ANALYSIS PROCESS

3.1 Introduction

The literature review conducted and compiled in chapter 2 showed that no explicit definition of the risk management process exists within and between different fields of science. To achieve transparency from the results of the risk analysis conducted to support the risk assessment and the risk management process, it is important to establish clear steps within a procedure and to clearly define the notions used. The objective of this chapter is to develop a procedure for how to conduct a risk analysis with the purpose to quantitatively estimate the risk of indoor air pollutants to occur causing an unhealthy indoor environment to humans.

The risk analysis will follow the main parts of the IEC 60300-3-9:1995 standard for risk analysis of technological systems, shown in Figure 2.1, chapter 2. This procedure has been proven, in the literature review in chapter 2, to be a common approach to risk analysis of technical systems, whether the system is a machine or a building structure. The risk analysis process proposed in the IEC 60300-3-9:1995 standard will be combined with fault tree analysis to find the causes of undesirable indoor events and evaluate the risk quantitatively (SS-IEC 1025:1990; SS-EN 1050:1996; IEC 60300-3-9:1995; CCPS, 2000; Andrews and Moss, 2002; Kemikontoret, 2001). In Ljungquist (2003), fault tree analysis was found to be a well working tool also in the building process, since small steps are taken in the deductive reasoning to find the closest cause to an undesirable event. The extended risk analysis process is shown in Figure 3.1.

The purpose of this work is to compare the consequences of a failing technical system affected by an environmental load, i.e. the occurrence of an unhealthy indoor environment, with consequences to human health, i.e. humans suffering from negative health effects caused by the unhealthy indoor environment. The objective is to use structural reliability analysis (SRA) as a basis for the risk analysis. SRA uses the safety margin where the limit state equation separates the acceptable, or safe, region from the region characterised as failure.

$$M = G(R,S) = R - S = 0 \tag{3.1}$$

Risk is then defined as the probability of limit state violation or the probability of failure, i.e. that $R - S < 0$. Risk analysis is performed with the intention to produce quantitative estimates, primarily in the form of probability density functions, or as point estimates. However, note that when performing a risk analysis, the intention may not be possible to fulfil due to lack of information about the system.

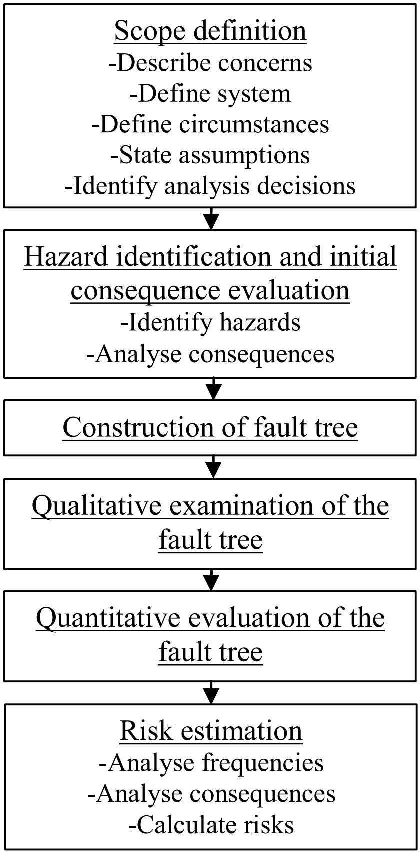


Figure 3.1 Risk analysis process.

Before the risk analysis can be performed, its intention and why conduct it have to be established.

3.2 Scope definition

Since a specialist mainly conducts the risk analysis before handing it over to others for evaluation, it is important to thoroughly specify its aim and scope. A thorough scope definition ensures a carefully planned analysis where the choice of methods to use and the depth of study have been considered, ensuring that the analysis will be carried out effectively.

Why evaluate the risk of an unhealthy indoor environment to humans? What do we want to achieve? The Swedish Act on Technical Requirements for Construction

Works etc. (SFS 1994:847), i.e. the national harmonisation of the Construction Products Directive (Council Directive 89/106/EEC), states “construction works shall, under the conditions of normal maintenance, fulfil requirements during a reasonable economic life-cycle, regarding protection concerning hygiene, health and environment.” This is formulated in more detail in section 5 in the Decree on Technical Requirements for Construction Works, etc. (SFS 1994:1215), stating “construction works shall be designed and constructed such that hygiene or health risks are limited regarding:

1. release of poisonous gas,
2. occurrence of airborne particles or gases,
3. hazardous radiation,
4. pollution or poisoning of water or ground,
5. insufficient caretaking of waste water, smoke and solid or liquid waste,
6. occurrence of moisture in components or on surfaces of construction work.”

The objective of the study and the choice of methods depend on what phase of the building’s life-cycle is of interest. For a new building the analysis may intend to compare different alternatives of the design of building components. In an existing building, the causes of negative health effects to humans may need to be identified to select the proper risk reduction measures. Two broad categories emerge that will influence the selection of method to use.

1. Hazards to the indoor environment are **unknown**, e.g. a new building project is planned and the possibility of undesirable indoor events needs to be investigated, or humans feel unhealthy in an existing building with unknown causes.
2. Hazards to the indoor environment are **known**, e.g. causes to the undesirable indoor events in an existing building need to be investigated, or specific environmental conditions are known when planning a new building.

If the hazards to the indoor environment are unknown an inductive reasoning has to be initially applied to identify the potential hazards and undesirable indoor events, and to analyse the consequences. From the inductive methods reviewed in chapter 2, one way of finding the hazards and the undesirable indoor events is to use checklists based on the requirements of the codes, together with “brainstorming” in a group with people involved in the different disciplines of the building process.

After finding the possible hazards and undesirable indoor events, a deductive reasoning, such as fault tree analysis, can be applied to establish the causes, which is also the approach to be used in the second category.

The definition of the system shall include a general description of the system to be analysed including the type of system and the main purpose followed by establishing the boundaries of the system. External boundary may be the climate shield and the internal boundaries depend on the level of analysis detail. Detailed knowledge of the system is important and information may be collected from drawings and technical descriptions. If the analyst responsible for the risk analysis does not have the necessary competence to perform the analysis alone, experts have to be connected to the work.

The circumstances/conditions relevant to the activity and the problem have to be defined, e.g. technical, environmental, organisational and human conditions, like the potential severity, number of fatalities, environmental damage or economic loss. Assumptions governing the analysis may be the level of resources available for the analysis concerning, e.g. time limitations or expertise. Constraints may be regulatory or contractual obligations. Finally, analysis decisions have to be identified and to who the results are intended to be communicated. It is important at this stage of the analysis to clarify the criteria for failure/success of the system, i.e. when is the outcome or condition undesirable. The failure/success criteria could be a threshold limit stated in the codes, or by the developer, to not be exceeded.

3.3 Hazard identification and initial consequence evaluation

In chapter 2, a hazard was defined as a source of potential harm that may lead to undesirable events. In this context, a hazard is the combination of an environmental impact and the design and construction of the system that together may cause an undesirable indoor event, Figure 3.2. In turn, the undesirable indoor event has the potential to lead to consequences to humans in the form of an unhealthy indoor environment. The term ‘event’ is used throughout the work as a definition of the indoor environmental state, whether the state is temporary or permanent. Figure 3.2 shows an environmental impact affecting the building component from the outside. However, the impact may as well affect the building from the inside, e.g. moisture from showering, cooking, etc., and together with the system create an undesirable indoor event.

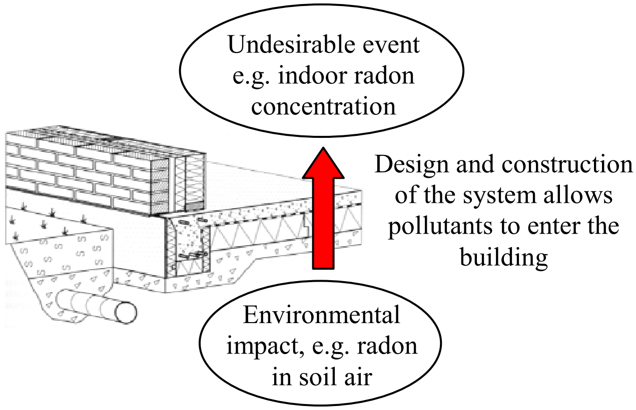


Figure 3.2 The environmental impact together with the design and construction of the system may cause an unhealthy indoor environment to humans.

This reasoning agrees with the proposed definitions in Ljungquist (2003), where the random variables "resistance" and "load effect" were established as for the resistance *R* and the load effect *S* in structural reliability analysis (SRA). In SRA, resistance and load effect can be defined and illustrated by looking at the simply supported beam in Figure 3.3, with the uniform load *q* and the length *L*.

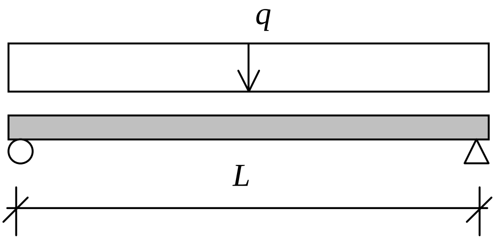


Figure 3.3 Simply supported beam with a uniform load.

The load effect of the bending moment M_S depends on the load *q* and how the structure is designed without any respect to the appearance or material of the beam:

$$M_S = \frac{qL^2}{8} \tag{3.2}$$

The bending resistance M_R depends on the material strength f_y and the appearance of the beam *Z*:

$$M_R = f_y \cdot Z \tag{3.3}$$

The failure state occurs when the beam cannot withstand the load effect, and to avoid failure the safety conditions can be written $M_R - M_S > 0$. An environmental impact, e.g. radon, can be illustrated as in Figure 3.4, with the building component concrete slab on the ground exposed to the uniform environmental impact (load) q_{env}.

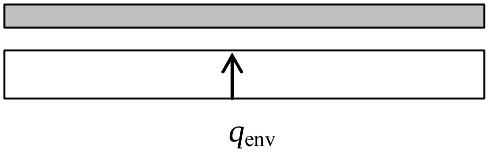


Figure 3.4 Concrete slab on the ground with a uniform environmental load.

The "load effect", denoted Y_{env}, is a function of the environmental load q_{env} and the design and construction of the building component, denoted D_{env}.

$$Y_{env} = f\left(q_{env}, D_{env}\right) \tag{3.4}$$

Unlike the load effect S of the beam in Figure 3.3, the undesirable indoor event Y_{env}, depends not only on the environmental impact, but also on the appearance of the building component and the included building materials, since the main purpose of this barrier is to resist all kinds of environmental impact, like radon, in a passive manner.

The "resistance", denoted X_{env}, is the ability of humans to withstand the different indoor air pollutants without becoming unhealthy. In risk assessment in the field of human health and environment, the dose-response relationship is used to describe the relationship between the exposure to toxic substances and the proportion of the exposed population suffering from negative health effects. The dose-response relationship may then be compared with the resistance of the beam in Figure 3.3. When developing a frequency distribution of material resistance, several components are tested and a histogram is created showing how much load each component could resist, i.e. the 'sensitivity' of the population of components, Figure 3.5. The frequency distribution of the dose-response relationship shows how much "load", or dose, of a substance each individual can resist before becoming unhealthy, i.e. the sensitivity in the population of individuals.

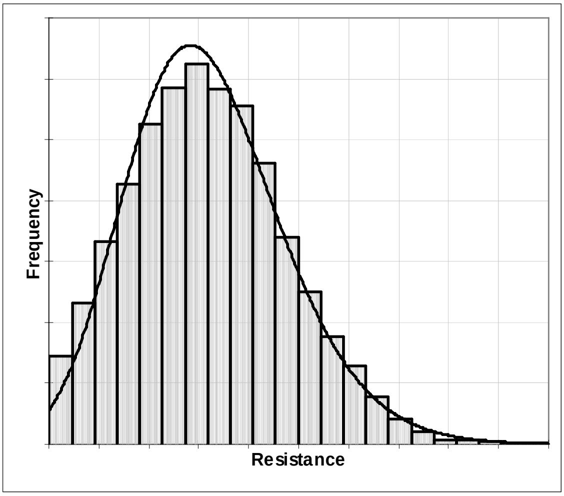


Figure 3.5 *Example of histogram for component resistance or “human resistance”.*

The definitions of the random variables X_{env} and Y_{env} in this work are then given by:

X_{env} = the dose-response relationship, i.e. the relationship between the exposure to humans of the undesirable indoor event and the proportion of the exposed population suffering from negative health effects.

Y_{env} = the undesirable indoor event, i.e. a function of the environmental impact together with the design and construction of the building.

Analogous to SRA, the random variables X_{env} and Y_{env} may be defined with probability density functions according to Figure 3.6.

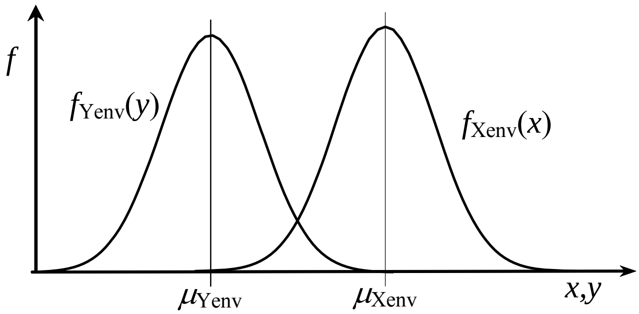


Figure 3.6 *Probability density functions for the random variables X_{env} and Y_{env}.*

In section 3.1, risk in SRA is defined as the probability of limit state violation or the probability of failure. In accordance with SRA, the risk of an unhealthy indoor environment to humans is defined as the violation of a limit state function:

$$M_{\text{env}} = G(X_{\text{env}}, Y_{\text{env}}) = X_{\text{env}} - Y_{\text{env}} < 0 \tag{3.5}$$

In conclusion, the objective of hazard identification in the risk analysis process is to define the random variable Y_{env}, i.e. to find the possible undesirable indoor events regarding the actual system. The objective of the initial consequence evaluation is to define the random variable X_{env}, i.e. to find the dose-response relationship related to the undesirable indoor event. The dose-response assessment is performed in the risk assessment in the field of human health and environment, and the definition of the random variable X_{env} is therefore collected from research performed in this specific area or from the threshold or guiding values stated in the codes.

3.4 Construction of the fault tree

3.4.1 Fault tree analysis (FTA)

There are several reasons to perform an FTA, e.g. to identify the causes or combinations of causes leading to the undesirable top event and hence, the common events or common cause failures (SS-IEC 1025:1990). The principles of fault tree construction were described in Ljungquist (2003) and will therefore be briefly described here. Literature with more detailed explanations on fault tree analysis and fault tree construction is sparse. Except for the standard SS-IEC 1025:1990 on fault tree analysis, the most comprehensive work is the Fault Tree Handbook compiled by Vesely et al (1981), with the purpose to help codify and systematise the fault tree approach in system analysis, mainly for the nuclear industry.

The objectives of fault tree analysis are to identify the various possible event combinations leading to a single undesirable event, the top event, and to represent these combinations graphically by means of a tree-like structure. The method enables the analyst to identify the various causes of a single, clearly predefined event by applying deductive reasoning based on a number of principles and rules. The faults can be events that are associated with component failure, human error or any other event that may lead to the undesired event. This deductive process is continued until so-called basic events are identified for which probabilities will have to be provided if the fault tree is to be used for quantitative analysis in which the probability of the undesirable top event to occur is calculated. Fault tree structures are not unique; no two analysts construct identical fault trees (Kumamoto and Henley, 1996; Villemeur, 1991; Vesely et al, 1981).

According to Vesely et al (1981) the undesirable event of the system analysed constitutes the top event of the fault tree and the top event must be chosen carefully to provide a successful analysis of the system. A too general top event gives an oversized fault tree that is almost impossible to evaluate, and a too specific description of the top event does not provide a sufficiently broad view of the system. The top event shall be defined in measurable units, whenever possible (SS-IEC 1025:1990).

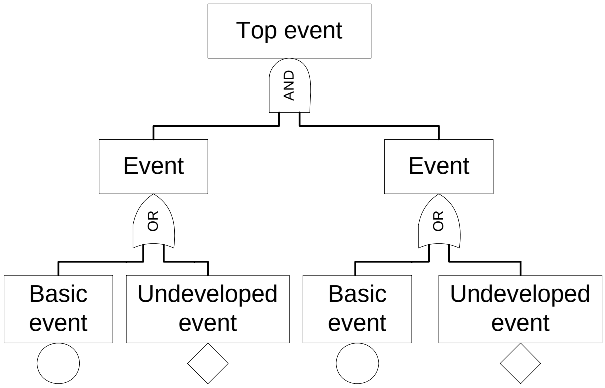


Figure 3.7 *Example of logic diagram in fault tree analysis with the most common standardised gate and event symbols.*

The fault tree is a graphical presentation built up with a set of standardised symbols denoted as events and gates. The gate symbols represent the causal relationship between the events. The gate symbols AND-gate and OR-gate are most commonly used and shown in Figure 3.7. Special gates also exist, primarily used for convenience and can often be replaced by an AND-gate or an OR-gate. The causal relation expressed by a gate is deterministic since the occurrence of the output event is completely controlled by the input events. The event symbols commonly used are rectangles for fault events and circles for basic events along with diamonds for not fully developed events and ovals for conditional events. Triangular symbols provide a tool to avoid repeating sections of a fault tree or to transfer the tree construction from one sheet to another.

Fault trees are drawn in accordance with some basic rules to ensure a successful analysis. Certain ground rules exist for the proper procedure, i.a. to write the statements that are entered in the event boxes as faults, state precisely what the fault is and when it occurs, and expect no miracles. If the normal functioning of a component propagates a fault sequence, then it is assumed that the component functions normally. Further, all inputs to a particular gate should be completely defined before further analysis of any is undertaken. Gate inputs should be properly defined fault events, and gates should not be directly connected to other gates. The last rule is a no-gate-to-gate rule from Vesely et al (1981), since shortcuts may lead to confusion. However, Kumamoto and Henley (1996) use combinations of AND-gates and OR-gates to substitute more specified gates.

3.4.2 Faults and failures

Vesley et al (1981) discuss the question of why using failure events instead of success events and establish it to be easier to define system failure than system success. Failure is defined as the termination of the ability of an entity to perform a required function, i.e. an entity will have failed when it is no longer able to fulfil its function. When the entity works properly but at the wrong time it becomes a fault. They also state that all failures are faults but all faults are not failures, stating that the definition is sometimes disputable. Kumamoto and Henley (1996), on the contrary, define everything as failures and do not separate fault and failure depending on background.

Faults can be classified in three categories: primary, secondary or command fault, depending on their causes. A primary fault is a fault of a component occurring in an environment where the component is qualified and not caused by the failure of another entity. A secondary fault is any fault occurring in an environment where the component is not qualified and directly or indirectly caused by the failure of another entity. However, a command fault involves the proper operation of a component, but at the wrong time or at the wrong place (Henley and Kumamoto, 1981; Kumamoto and Henley, 1996; Vesely et al, 1981; Villemeur, 1991).

In practice, all basic events are assumed to be statistically independent unless they are “common cause failures”. Failure of multiple components or systems due to a single event is classified as a common cause failure, e.g. fire, power failure and human acts. The phrase “common mode failure” describes a common cause failure that acts on a set of identical components of a system, e.g. a manufacturing defect in a group of relays. The terms common cause and common mode are frequently used interchangeably, since they are closely related and because their identification is so similar when performing a fault tree analysis (McCormick, 1981).

3.5 Qualitative examination of the fault tree

When the tree structure has been established, a qualitative examination of the fault tree can be performed to reduce the tree to a logically equivalent form in terms of specific combinations of basic events sufficient to cause the undesired top event to occur. This will provide valuable information for design purposes, because the critical events will be identified and the design can be revised. The basic mathematical technique involved in assessing fault trees is probability theory, since it provides an analytical treatment of events that are fundamental components in fault trees.

A fault tree can be seen as a reliability block diagram of series or parallel type, where a series of linked boxes corresponds to an OR-gate and boxes in parallel correspond to an AND-gate, shown in Figure 3.8 (Rettedal et al, 2000; Schneider, 1997).

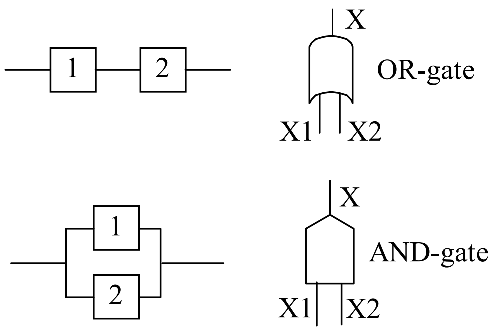


Figure 3.8 Reliability block diagram and equivalent fault tree symbols for series and parallel systems.

Evaluating the fault tree with Boolean algebra rearranges the fault tree into a new fault tree that is logically equivalent to the original, consisting of an OR-gate beneath the top event whose inputs are the minimal cut sets. The minimal cut set expression for the top event can be written in the general form:

$$T = M_1 \cup M_2 \cup \dots \cup M_k \tag{3.6}$$

where T is the top event and M are the minimal cut sets. Each minimal cut set is an AND-gate containing a set of basic events necessary and sufficient to cause the top event. The general n-component minimal cut set can be expressed as:

$$M_1 = X_1 \cap X_2 \cap ..... \cap X_n \tag{3.7}$$

where X_1, X_2, etc., are basic component failures in the tree. The minimal cut sets offer a qualitative examination of the fault tree by identifying critical events in the design phase to be eliminated or reduced (Ang and Tang, 1990). Vesely et al (1981) point out another advantage of the minimal cut sets, i.e. the possibility to look for common-cause failures. By definition, the top event occurs only if all basic events in a minimal cut set occur and common-causes of interest are those events triggering all the basic events in a minimal cut set to therefore occur.

3.6 Quantitative evaluation of the fault tree

The purpose of the quantitative evaluation of the fault tree is to establish the undesirable indoor top event, i.e. to establish the random variable Y_{env} defined, if possible, by the probability density function $f_{Y_{env}}(y_{env})$.

When using minimal cut set analysis the quantitative evaluation is usually performed by first determining the component failure probabilities, i.e. the basic event probabilities, then the minimal cut set probabilities and finally the top event probability. When using SRA the basic events in the fault tree being considered must be dependent on the outcome of a set of random variables, the basic variables $\mathbf{Y} = (Y_1, Y_2, \ldots, Y_n)$ where the continuous random variables are expressed by their probability density functions $f_{Y_i}(y_i)$. Further, it must be possible to describe the conditions under which the event will occur, the event space, by using functions logically connected by unions and intersections according to the minimal cut sets from the qualitative examination of the fault tree. $\mathbf{Y_{env}}$ is then the vector of all relevant basic variables and $G(\ )$ is some function expressing the relationship between the basic variables giving the undesirable indoor top event.

3.7 Risk estimation

The objective of the risk estimation is to compare the occurrence of an undesirable indoor event with the consequence of the occurrence, i.e. the occurrence of specific human health effects. The random variables in SRA, the resistance R and the load effect S, are defined with probability density functions and compared as marginal density functions giving the safety margin M, cf. section 2.5.4. Similarly, the dose-response relationship X_{env} and the undesirable indoor event Y_{env} are to be compared. In section 3.3, risk in this work is defined as the violation of the limit state function given by:

$$M_{env} = G(X_{env}, Y_{env}) = X_{env} - Y_{env} < 0 \tag{3.8}$$

The total failure probability p_f is defined as in section 2.5.4 for the resistance R and the load effect S in SRA. When X_{env} and Y_{env} are statistically independent the total failure probability p_f is obtained by integration over all possible x:

$$p_f = P(X_{env} - Y_{env} < 0) = \int_{-\infty}^{\infty} F_{X_{env}}(x)\, f_{Y_{env}}(x)\, dx \tag{3.9}$$

This is explained in Figure 3.9 where the probability that the undesirable indoor event Y_{env} affects the indoor environment has a value between x and $x+\Delta x$ when $\Delta x \to 0$ (Δx is denoted dx in Figure 3.9). $F_{Xenv}(x)$ is the probability that the ability of humans to withstand the indoor pollutants is less than some value x, i.e. this represents failure to withstand the actual dose x.

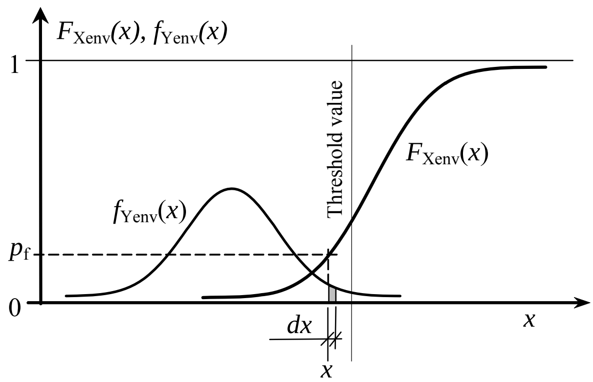


Figure 3.9 Comparison between the undesirable indoor event Y_{env}, and the dose-response relationship X_{env}.

Generally some characteristic upper or lower values describe the design value of the load or strength. This is achieved by using, e.g. the 5 %-percentile for the strength and the 95 %-percentile for the load. No such characteristic value exists for the undesirable indoor event Y_{env}. For the dose-response relationship a benchmark dose may be used as a characteristic value. However, the risk can be estimated by calculating the total failure probability integrating over the entire failure domain. A comparison can then be made by integrating between the lower limit and a threshold value if such is available.

For functions with several random variables integration over the failure domain cannot be performed analytically and the comparison must be made using either FOSM or simulation. The risk can then be expressed by the total failure probability, the probability of exceeding a threshold value or by the reliability index β.

3.8 Summary of chapter 3

The procedure for the risk analysis process is developed using the risk analysis process from the IEC 60300-3-9:1995 standard as a basis combined with fault tree analysis to evaluate the risk both qualitatively and quantitatively. Structural reliability analysis is used for quantitative evaluation since several random variables can be handled using limit state functions to express the relationship between the basic events in the fault tree.

The objective of the analysis is to compare the undesirable indoor event with the consequence to humans. The undesirable indoor event Y_{env} has been defined as a function of the environmental impact together with the design and construction of the building. The undesirable indoor event is either known or unknown, which influence the selection of methods used. However, when the possible undesirable indoor events are identified, deductive reasoning can be used to find the primary causes of the events. Together with identifying the undesirable indoor events, the consequences to humans X_{env} have to be found in the form of dose-response relationships between the exposure to the unhealthy indoor environment and the occurrence of specific human health effects, or in the form of the threshold or guiding values stated in, e.g. the codes. The risk is estimated by comparing the random variables as in SRA by using FOSM or the simulation to find the probability of exceeding a threshold value or to estimate the reliability index β.

The objective of the following chapter is to identify the possible undesirable indoor events caused by some environmental impact, and the design and production of the system. The aim is also to identify dose-response relationships and threshold values connected to the undesirable indoor events.

4 HAZARD IDENTIFICATION AND INITIAL CONSEQUENCE EVALUATION

4.1 Introduction

In chapter 3, hazard was defined as the combination of environmental impact and the design and construction of the system, which together may cause an undesirable indoor event and hence an unhealthy environment to humans. The objective of this chapter is to identify the undesirable indoor events that are combinations of environmental impacts and the design or construction of the building or combination thereof, i.e. the random variable Y_{env}. Further, the objective is to find the dose-response relationship between the exposure of the undesirable indoor events and the occurrence of specific human health effects, i.e. the random variable X_{env}. An introduction on some actions taken, primarily in Sweden, and methods developed to improve the indoor environment are first presented.

An early public health goal in Sweden was to eliminate overcrowding and the creation of dry, light and spacious dwellings for all social layers of the population. With social policies and building regulations these goals became to a large extent accomplished after the Second World War (Thörn, 1999). But the situation changed and in the beginning of the 1970s attention again focused on the emergence of health problems connected with the buildings. This resulted in the ELIB-study in 1991/1992, one of the first nationwide surveys in Sweden concerning the indoor climate of dwellings. The survey yielded strong evidence that Sweden was confronted with health problems related to the indoor climate (Norlén and Andersson, 1993).

In 1996, a plan of action was presented by the Commission on Environmental Health, appointed by the Swedish Government, whose primary aim was to obtain an overall picture of environmental and public health. One area of concern was indoor air, with a focus on radon and “sick buildings” (SOU 1996:124). The plan resulted, amongst others, in an information campaign called “Inne 99” conducted by the Swedish National Institute of Health, with several authorities and organisations (Folkhälsoinstitutet, 1998). In 1999, the Swedish Environmental Code (SFS 1998:808) was adopted, with the Swedish Parliament also adopting 15 environmental quality objectives. The Swedish National Board of Housing, Building and Planning is responsible for the interim targets and action strategies concerning the environmental quality objective “A Good Built Environment”. One target considers an improved indoor environment where humans are protected from the negative exposure of a poor indoor environment caused by, e.g. temperature, emissions, ventilation, moisture, noise, radon or electromagnetic fields. The goal by 2020 is to eliminate building related health problems and to improve the knowledge of problems, thresholds and preventative measurements in medical research (Boverket, 1999).

Several commissions regarding the indoor environment have been appointed by the Swedish Government, e.g. the Radon Commission (SOU 2001:7) resulting in the following Swedish Government proposition covering certain indoor environment issues (Prop. 2001/02:128), and the not yet completed Commission on Building Environment that has delivered a memorandum concerning, i.a. dampness in buildings proposing a first step including mapping of damages caused by moisture (M 2004:1). On behalf of the Swedish National Board of Health and Welfare, the Institute of Environmental Medicine at Karolinska Institutet (IMM) and the Department of Environmental Medicine at Stockholm County Council (MME) jointly produced the Environmental Health Report 2001 that was revised in 2005, including i.a. health issues caused by the indoor environment. An important objective of the report is to constitute a basis for application of the Environmental Code and for revision, implementation and follow-up of the environmental quality objectives (IMM, 2001; IMM, 2005).

Environmental work performed in the building sector is rapidly developing and the sector has, through the Ecocycle Council, undertaken a voluntary environmental responsibility (Kretsloppsrådet). In the "Environmental Program 2003", a significant environmental aspect identified is the impact on indoor air quality in buildings and some actions to be taken are the development of templates for the indoor environment and moisture protection. The Environmental Advisory Council, appointed by the Swedish Government, started a dialogue with companies and municipalities to focus on the building and real estate sector, named Building and Living (SOU 2001:20). The group formulated objectives, i.a. to ensure that all new buildings and at least 30 per cent of the existing building stock were classified regarding building-related health and environmental impacts by the year 2010, which has constituted a base for the Commission on Declarations of Buildings (SOU 2004:78).

In 1997, the Swedish Council for Building Research, later included in Formas, instituted together with a number of other research funding organisations the interdisciplinary key action "The Healthy Building", whose overriding goal was to halve the number of indoor environment related health problems and the risks of incorrect actions in design, construction and building management that may result in indoor environment related health problems (Abel et al, 2002; Formas, 2004). Connected to the key action, Hult (2002) presents a method to assess and ensure indoor environment quality in buildings during the program, design and management phases. Different tools are proposed to collect data for the assessment and to structure decision-making by focusing on indoor environment quality in the planning process.

In the research school "The Building and its Indoor Environment" at Lund Institute of Technology, Nordberg (2004) investigated if occupants living in buildings with quality labelled indoor environments experience better indoor environments than occupants in buildings with normal planning and construction. The aim of another project has been to analyse the complex of problems with indoor air quality and to indicate ways to reduce problems in future buildings (Hammargren, 2003).

An interdisciplinary Nordic workshop for a better indoor climate was held in Copenhagen in 1999, with the discussion concerning the economic, legal and user oriented decision base and procurement tools that clients and authorities need for a good and resource efficient indoor climate. The need for models to help decision makers during the different stages in the building process was pointed out (Bakke and Lindvall, 1999). Jönsson (2000) has studied the possibility to include indoor climate issues as an impact category in the life-cycle assessment of building products (LCA). She suggests that risk assessment is a more suitable method, since only very limited aspects of indoor climate can be addressed in LCA. In the doctoral thesis *Green Procurement of Buildings*, Sterner (2002) presents a tender evaluation model integrating life-cycle cost with environmental impact as a monetary term. By using the model, clients can award contractors who develop cost-effective buildings with low environmental impact. A model for performance contract and performance based procurement is developed and presented in Lagerqvist (1996) and Lagerqvist and Johansson (2004) who include a proposal of the specification with performance requirements based on the Act and the Decree on technical requirements for construction work and the Swedish Building Regulations.

Efforts have been made to develop indices as measures of indoor environmental quality. Sekhar et al (2003) have developed the Indoor Pollutant Standard Index (IPSI), where measured concentration levels of physical, chemical and biological pollutants are compared with relevant local and international standards/guidelines to establish the indoor air quality (IAQ) status of the building. Sofuoglu and Moschandreas (2003) have developed the Indoor Air Pollution Index (IAPI) for office buildings, which includes eight pollutants in the index formulation: bacteria, carbon monoxide, carbon dioxide, formaldehyde, fungi, $PM_{2.5}$, PM_{10}, radon, and TVOC. The published papers have caused debate about the usefulness of indices. Mendell (2003) stated that protecting human health from adverse environmental exposure based on adequate information is challenging and that building managers and operators still lack validated tools and strategies to identify and remedy indoor environment quality (IEQ) problems likely to cause symptoms in occupants. However, sufficient information is presently unavailable to construct a useful IEQ index based on specific indoor contaminant concentrations. Mølhave (2003) stated the use of a substitute measure since the variable of interest cannot be measured for practical, economical, or principal reasons. Finally, Wolkoff (2003) stated that no relationships between indoor volatile organic compounds (VOCs) and human health have been established to support the causality of short-term complaints, like eye and airway irritation, except for a few biologically reactive compounds, e.g. formaldehyde. Similarly, the scientific community has recognised that TVOC has no predictable health value. Wolkoff ends the contribution stating “We should have in mind that the human pattern(s) of complaints also depends on psychological exposures, in addition to many other external work related risk factors, and gender differences.”

4.2 Identifying undesirable indoor events, random variable Y_{env}

The objective of the hazard identification is to identify undesirable indoor events, i.e. the random variable Y_{env}, which combines an environmental impact with the design or construction of the building, or a combination thereof. The general mandatory provision in the Swedish Building Regulations (BFS 2002:19) concerning hygiene, health and environment which is in accordance with section 5 in the Decree on Technical Requirements for Construction Works, etc. (SFS 1994:1215), states:

> “Buildings shall be designed so that quality of air, light and water, moisture and temperature conditions, and hygiene conditions, are satisfactory with respect to public health requirements.”

Regulations concerning the quality of indoor air states, “Buildings shall be designed so that the quality of air is satisfactory in the occupied zone in rooms or parts of rooms where persons are present other than occasionally”, and continue with mandatory provisions regarding emissions (gases and particles), microorganisms and ionising radiation.

As mentioned earlier, the Swedish Commission on Environmental Health pointed out areas of concern to human health to be indoor air with a focus on radon and “sick buildings” (SOU 1996:124), and was followed-up by the Environmental Health Reports (IMM, 2001; IMM, 2005). The Nordic workshop in Copenhagen for a better indoor climate established as factors of particularly high concern in the indoor environment to be moisture and radon and factors of high concern to be volatile organic compounds (Bakke and Lindvall, 1999). A Nordic interdisciplinary expert-group (NORDDAMP) reviewed the scientific literature on damp buildings and health, and concluded that strong correlations not only exist in the scientific literature between damp buildings and health, but also factors pertaining to building design, such as concrete slab on ground and PVC-flooring together with dampness, presence of mould and exposure to chemicals, increased risks. An update of the review performed by a European group (EUROEXPO) verified that dampness in buildings is a risk factor for health effects, such as cough, wheeze, asthma and airway infections. The literature is inconclusive regarding causative agents in such buildings, but suggested agents are mites, microbiological agents and organic chemicals from degraded materials (Bornehag et al, 2001; Bornehag and Sundell, 2002; Sundell and Nordling, 2003; Abel et al, 2002). The compiled research results from the program “The Healthy Building” show that the understanding of numerous unexplained building related health problems had advanced. Several risk factors in the indoor environment contributing to adverse health effects have been identified, e.g. risk factors for allergic symptoms are i.a. dampness and low ventilation rate, with some of these risk factors originating from mistakes in design, construction and maintenance of buildings (Abel et al, 2002; Formas, 2004; Bornehag et al, 2004).

The overall undesirable indoor event Y_{env} has to be identified and the conclusion drawn from the reviewed investigations is that the main indoor problems comprise different emissions (gases and particles), microorganisms or substances from microorganisms, and ionising radiation that can also be derived from the mandatory provisions stated in the Swedish Building Regulations. The undesirable indoor event, Y_{env}, i.e. the top event in the fault tree, is defined as “Indoor air pollutants in buildings causing an unhealthy indoor environment to humans”. The top event is made more specific by the input events (1) “Radon concentrations in indoor air” (2) “Emissions in indoor air” and (3) “Microorganisms and/or substances from microorganisms in indoor air”, shown in Figure 4.1. The sub-top events pass through an OR-gate, since the separate or combined events are the unhealthy indoor environments.

Another conclusion drawn from the investigations is that human actions are needed for the undesirable indoor events to occur, i.e. the system includes some fault due to human actions that together with the environmental impact cause an unhealthy indoor environment. This is illustrated in the fault tree in Figure 4.1 with the two events “Environmental impact” and “Fault due to human action” passing through an AND-gate, since the events need to be combined to cause the undesirable sub-top events.

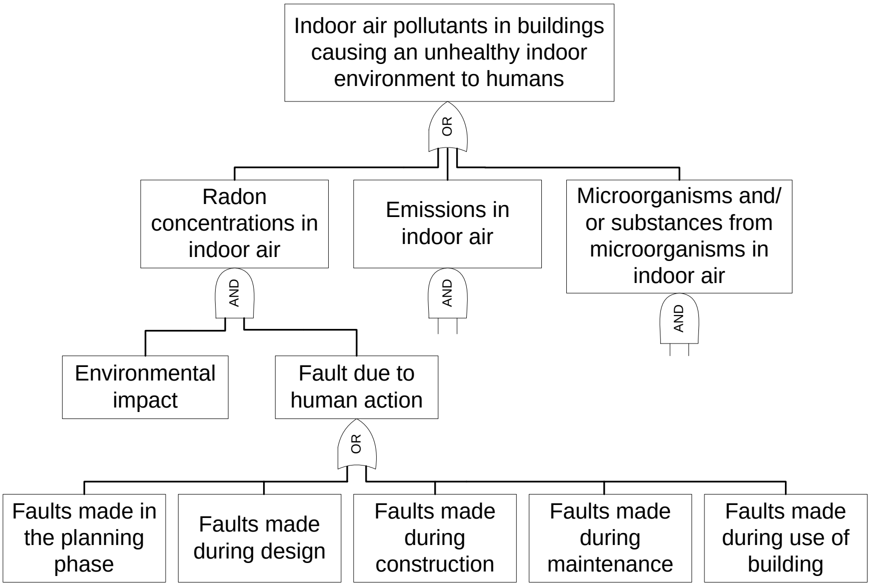


Figure 4.1 Definition of top event and sub-top events in the fault tree.

Faults due to human actions can be made in several phases and levels of the building process, such as a bad choice of foundation system in the planning phase, incorrect use of building materials in the design phase, or gluing the carpet too early in the construction phase. Therefore, the event “Fault due to human action” is made more specific in Figure 4.1, with input events that separately or in combination may be the cause of system failure.

This work will continue to focus on and further investigate undesirable indoor events caused by ionising radiation and microorganisms.

4.3 Identifying dose-response relationships, random variable X_{env}

The objective of the initial consequence evaluation is to find the occurrence of specific human health effects related to the undesirable indoor events and the dose-response relationship between exposure and humans becoming unhealthy, i.e. the random variable X_{env}.

Kolluru (1996c) shows that most of us spend 90 to 95 % of our time indoors, being exposed extensively to indoor pollutants. Berglund et al (2001) define exposure as "the contact of a chemical, physical or biological agent with the outer boundary of an organism". The way an agent enters an organism is referred to as an exposure route with inhalation, ingestion and dermal contact being the three major exposure routes to humans. Distinctions must be made between environmental concentration, exposure concentration and dose. Environmental concentration refers to the presence of an agent in a particular carrier medium, exposure concentration refers to its presence in its carrier medium at the point of contact, and finally, the dose refers to the amount of a pollutant actually entering the human body.

In the public health debate and research of building related health problems, two different terms are commonly used, namely "Sick Building Syndrome" (SBS) and "Building Related Illness" (BRI). The World Health Organisation has defined SBS as a combination of general symptoms and symptoms present in the mucosal membranes and skin. Inherent in the definition is that the symptoms are related to a residence or working in a certain building. Physical status, laboratory tests and other medical examinations are as a rule normal. Symptoms of SBS can be, e.g. irritation of the eyes, nose and throat, experience of dry skin, fatigue or headache. BRI, on the other hand, is defined as diseases related to buildings that can be recorded objectively, Table 4.1 (Thörn, 1999).

Table 4.1 Examples of Building Related Illnesses (BRI) and corresponding exposure (Thörn, 1999).

BRI	**Exposure**
Asthma	Mould, mites, dander
Allergic alveolitis	Mould, other protein antigens
Humidifier fever	Endotoxins
Legionnaires' disease	Bacteria (*Legionella pneumophila*)
Lung cancer	Radon / radon daughters

Several Swedish studies concern the indoor environment and health. The ELIB-study from 1991/1992 was mentioned at the beginning of this chapter (Norlén and Andersson, 1993). An epidemiological study was presented in 1993, where the relationship between radon concentrations in residential buildings and lung cancer had been investigated (Pershagen et al, 1993). A more recent study that began in 1999 is the interdisciplinary epidemiological study including more than 10 000 children, called "Dampness in Buildings and Health" (DBH-study) with the overall aim to identify health-relevant exposure in damp buildings (e.g. Bornehag et al, 2002). In a study (BAMSE) conducted to examine the impact of building characteristics and indoor air quality on recurrent wheezing in infants, 4089 children were followed during their first two years of life (e.g. Emenius et al, 2004). They found, for example, that living in private homes with a crawl space or concrete slab foundation was associated with an increased risk of recurrent wheezing. The Environmental Health Report 2001 was preceded by a national environmental health survey (NMHE 99) involving 11 233 respondents and the Environmental Health Report 2005 was preceded by an environmental health survey of children (BMHE 03) (IMM, 2001; IMM, 2005).

Despite extensive research, dose-response relationships of specific human health effects related to undesirable indoor events may be difficult to find. Some threshold values, e.g. for ionised radiation, can be derived from the mandatory provisions stated in the Swedish Building Regulations (BFS 2002:19). Swedish guiding values on indoor environments can be found in, e.g. Samuelsson et al (1998), VVS-tekniska föreningen (2000) and in Svenska Inneklimatinstitutet (1991).

From international work on the indoor environment, the World Health Organisation (WHO) has published *"Air quality guidelines for Europe"*, where the aim is to provide guiding values as a basis to eliminate or reduce exposure to pollutants that are known or likely to be hazardous to human health (WHO, 2000). The International Council for Research and Innovation in Building and Construction (CIB) together with the International Society of Indoor Air Quality and Climate (ISIAQ) have published *"Performance criteria of buildings for health and comfort"* with the objective to deal with the importance of a good indoor climate by considering all aspects, such as ventilation, building material, quality of design and construction work, in all the stages of the building process (CIB report, 2004).

4.4 Ionising radiation

4.4.1 Introduction

Ionising radiation occurs when particles are emitted during disintegration of a substance. The particles are absorbed into material striking out electrons from atoms or molecules leaving ions behind. The radiation of particles is called alpha or beta radiation, depending if the protons, neutrons or electrons are emitted. Gamma and X-ray radiation are also included in ionising radiation despite their short waved electromagnetic radiation.

Humans are, to varying degrees, constantly exposed to ionising radiation primarily from natural radiation in our environment. The decay series starting with uranium-238, thorium-232 and uranium-235 cause the predominant radiation, present in bedrock, soil, water, air and in some building material. Sweden is one of the countries with high risk of ionising radiation indoors depending on geology and climate (Clavensjö and Åkerblom, 2004; Radiation Protection Authorities, 2000). The Swedish Building Regulations (BFS 2002:19) states that:

> "Buildings shall be designed so that the annual mean value of the radon content does not exceed 200 Bq/m^3 and the level of gamma radiation does not exceed 0,5 µSv/h in rooms where persons are present other than occasionally."

Three different isotopes of radon, radon-222, radon-220 and radon-219 are products of the decay series mentioned above. This section will focus on radon-222, commonly known as radon in buildings. Some parts, i.a. the production and transportation of radon, is summarised from Ljungquist (2003).

4.4.2 Radon concentrations in buildings

4.4.2.1 Origin

Radon (Rn-222), identified by Marie Curie and at a time when it was called radium emanation, is a radioactive inert gas and a product from the disintegration of radium (Ra-226) of the decay series starting with uranium (U-238). When radon disintegrates into its decay products, polonium-218, lead-214, bismuth-214 and polonium-214, called radon daughters, alpha radiation with short ranges are sent out. In turn, the radon daughters disintegrate sending out alpha, beta and gamma radiation.

There is a constant disintegration of radium to radon in Swedish soil and the amount of radon generated depends on the radium concentration in soils and rocks. The fraction of radon leaving the generation point and entering the pore space is called emanation coefficient and depends on the grain size, the structure of the soil and the water ratio. Table 4.2 shows the normal levels of radium and radon in different types of Swedish soil (Clavensjö and Åkerblom, 2004; Johansson, 1996; Medici and Rybach, 1994; Åkerblom et al, 1988).

Table 4.2 Normal levels of radium-226 and radon-222 in different types of Swedish soil, measured at a depth of 1 metre (Clavensjö and Åkerblom, 2004).

Type of soil	Ra-226 (Bq/kg)	Rn-222 (Bq/m^3)
Moraine, normal	15 – 50	5000 – 50 000
Moraine with granite	30 – 75	20 000 – 60 000
Moraine with uranium rich granite	75 – 350	40 000 – 200 000
Gravel and coarse sand from glaciofluvial sediment	20 – 75	10 000 – 150 000
Sand and coarse silt	5 – 25	4000 – 20 000
Clay	25 – 100	10 000 – 120 000
Soil containing alum shale	175 – 2500	50 000 - > 1 000 000

Radon, measured in Becquerel (disintegrations per second) per cubic metre (Bq/m^3), has a relatively short half-life (3,8 days) and therefore a mobility of high importance. Radon must be able to be transported through the soil by diffusion or by flowing air or water. The possibility of transportation by diffusion depends on the permeability of the soil, which in turn depends on the particle size distribution, the degree of compaction and the water ratio. Permeable soils like gravel contain about 40 % air making diffusion almost as easy as in air. Tight soils like clay are usually not permeable to soil air but radon can be transported via, e.g. water pipes and the permeable material normally placed under and around the foundation as a drainage layer. The transportation length by diffusion is limited to five centimetres in water, two metres in sand and five metres in air (Clavensjö and Åkerblom, 2004).

The radon concentration at ground level is usually lower than deeper down in the soil depending on diffusion and the affect of the wind. This concentration also depends on the time of year with high and stable contents during the winter when the ground is frozen to half the contents during the early summer and thereafter a strong fluctuation depending on the choppy conditions of wind and precipitation (Åkerblom et al, 1988; Clavensjö and Åkerblom, 2004). A study in Switzerland by Johner and Surbeck (2001) support the hypothesis that a top layer of high permeability is ventilated by air, whereas a top layer with low permeability gives enough time to build up large amounts of radon in the ground. They also show that rain strongly decreases the permeability of the top layer when saturated with water.

4.4.2.2 Undesirable indoor events, random variable Y_{env}

A review of Swedish radon history by Swedjemark (2004), tells us i.a. that the first measurements of radon concentrations indoors in Sweden were performed in the early 1950s, and from the unsuccessful attempts in the 1970s to inform concerned authorities about the health risks with high radon concentrations indoors. However, interest increased in the late 1970s after exposure of Swedish houses to several thousands of Bq/m^3 indoors covering front-pages by the mass media. In 1993, a Swedish epidemiological study (Pershagen et al, 1993) showed that the variations in radon concentration indoors was approximately lognormal distributed with the geometric mean 60,5 Bq/m^3 and the arithmetic mean 106,5 Bq/m^3.

Today, the Radon Commission (SOU 2001:7) and the following Swedish Government proposition on certain indoor environmental issues (Prop. 2001/02:128), state that humans are not to be exposed to radon concentrations indoors above 200 Bq/m^3. The natural amount of radon in Swedish soil makes it impossible to set goals of a radon free indoor environment even in a very long perspective, though the recommendation is to always use radon protected performance even in low risk areas.

Table 4.3 Radon classification of soil in Sweden and measurements taken in design (from Åkerblom et al, 1988; Neovius, 1999).

Classification according to risk	Bq/m^3	Share of ground in Sweden	Measurements
Low risk area	<10 000	20 %	Traditional design
Normal risk area	10 000 – 50 000	70 %	Radon protected design
High risk area	>50 000	10 %	Radon proof design

The ground in Sweden is divided into three risk classes according to the radon concentration in the soil; hence, the Swedish municipalities have the obligation to establish drawings of the risk areas. Depending on the level of risk the foundation of the building is recommended to be designed with different degrees of protection, Table 4.3.

The government proposition concludes, as also stated in e.g. Åkerblom et al (1988), that the amount of radon indoors mainly depends on the level of radon in the soil and the soil permeability, the indoor air pressure compared to outdoor, the possibility of leakage through the foundation and the tightness, and air changes of the building. Results from a study in Norway (Sundal et al, 2004) show a significant correlation between radon levels indoors and geological factors. Radium content and soil permeability were used as indicators of production and transportation of radon together with building foundation and ventilation habits. Sundal et al (2004) state that important information for the classification of risk areas can be obtained from already mapped geological parameters.

However, high radon concentrations indoors even in low risk areas may occur, as became obvious during an investigation in the municipality of Hudiksvall. Residential buildings built after 1980 were measured concerning radon levels indoors and the amount of buildings, with radon levels above 200 and 400 Bq/m^3 respectively, were approximately the same independent of risk area (SOU 2001:7). A study in Norway (Rydock et al, 2001) experienced the same results when radon measurements were made in a new housing development built in an area previously not associated with elevated radon concentrations. Of 21 houses, 4 (or 19 %) exhibited annual average radon concentrations indoors over 200 Bq/m^3. Rydock et al suggested that site investigations may be of limited value in determining where to include radon protection measures in new housing.

The above mentioned may be explained by the fact that building a house is like with putting a lid over the ground where the concentration of radon under the foundation may rise to levels closely to maximum regarding the concentration in the soil. However, the risk of radon indoors assumes that the foundation is built on a permeable soil layer of approximately one metre or more to be able to store the necessary volume of soil air. A foundation on silt and clay usually gives low risk of radon indoors depending on the low permeability, despite the high radon concentration. However, the risk may increase significantly if the clay is dried out. Radon transported by groundwater is assumed to not be the source of radon entering the building due to the limited transportation length and though performed measurements show a comparable radon concentration in the groundwater regarding the type of soil (Clavensjö, 1997; Åkerblom et al, 1988).

Radon can be transported through the building foundation by diffusion or advection. Diffusion occurs through the slab when the radon concentration below the foundation is larger than indoors. Urošević and Nikezić (2003) have simulated and experimentally tested the diffusion transport of radon for different types of concrete and describe a method to estimate the diffusion coefficient. The diffusion coefficient for the type of concrete used (type 50) was estimated to 4,3 x 10^{-8} m^2/s. However, Clavensjö and Åkerblom (2004) state that the radon concentration in the soil air needs to be approximately 500 000 Bq/m^3 to reach indoor levels above the threshold value 200 Bq/m^3 by diffusion.

Advection mainly occurs through cracks when pressures below and above the foundation differ. Cracks and narrow openings are found i.a between different building components, in the concrete and in construction joints. Other ways for radon to enter the building are, e.g. via lead-throughs and floor drains, Figure 4.2 (Clavensjö, 1997; Åkerblom et al, 1988).

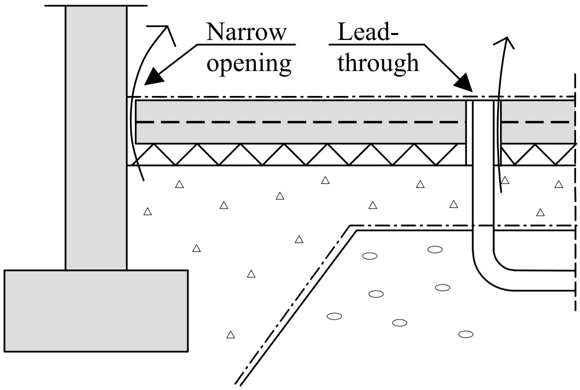


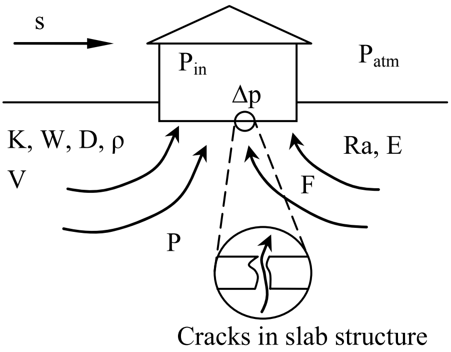
Figure 4.2 Examples of narrow openings and lead-throughs.

The amount of air leakage into the building through cracks can be calculated using Darcy’s law, and if the crack passes through a thick board compared to the crack width, laminar flow can be assumed according to Equation 4.1 (Nevander and Elmarsson, 1994). The same equation is used in Nielson et al (1997) and in Betonghandboken - Material (1994), where water and gas flow through cracks in the concrete is estimated.

$$R = \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t} \qquad [m^3/s] \qquad (4.1)$$

η	dynamic viscosity, Ns/m^2
Δp	pressure difference, Pa
t	depth of flow through, m
l	length of flow through, m
w	crack width, m

The crack width is critical since a crack growth from 0,1 mm to 1 mm represents a 1000 times higher gas flow through the component. Clavensjö and Åkerblom (2004) state that a crack width of approximately 0,5 mm is enough to allow leakage, and Nielson et al (1997) found that a 1,8 mm slab crack had a normalised air flow of 1,9 x 10^{-4} m^3/s m Pa across a 0,09 m thick concrete slab.



P_{in} : air pressure indoors
P_{atm} : air pressure outdoor
Δp: P_{atm} – Pin
P : pressure in soil
K: air permeability in soil
D : diffusion coefficient
ρ : porosity
E : emanation coefficient of soil
F: radon flux
W : water content of soil
S : wind strength and direction
Ra : radium content
V : grain size distribution in soil

Figure 4.3 General overview of the physical quantities involved in radon generation and transportation (adapted from Medici and Rybach, 1994).

Different types of ventilation lead to different ratios between indoor and outdoor air pressures. Depending on difference in temperature, the difference in air pressure of self-draught ventilation changes throughout the year from 2-10 Pascal (Pa) in the winter to 0 Pa in the summer. A simple rule in Sweden, according to Nevander and Elmarsson (1994), is that the difference in air pressure with respect to the indoor and outdoor difference in temperature can be approximated with 1 Pascal per meter (Pa/m) building height. Exhaust air ventilation normally gives an indoor air pressure of 5-15 Pa lower than outdoors, and exhaust air-air supply ventilation is able to keep a difference in air pressure of 0-1 Pa.

The radon concentration in a building caused by advection can be calculated using equation (Åkerblom et al, 1988; Clavensjö and Åkerblom, 2004):

$$C_{\mathrm{build}} = \frac{C_{\mathrm{t}} \cdot R}{V_{\mathrm{build}} \cdot (\ell + \lambda)} \qquad [\mathrm{Bq/m^3}] \qquad (4.2)$$

C_t radon concentration in the air volume under the building, Bq/m^3
R amount of air leakage into the building, m^3/h
ℓ air changes in the building, ach/h
λ disintegration constant for Rn-222, h^{-1} (7,55 x 10^{-3} h^{-1})
V_{build} building inside volume, m^3

The radon concentration under the building C_t, is calculated using the maximum radon concentration in soil, while also considering the ventilation effect.

$$C_t = C_{max} \cdot \frac{\lambda}{(n+\lambda)} \tag{4.3}$$

C_{max} radon in air volume under the building with 0 ach/h, Bq/m^3
R amount of air leakage into the building, m^3/h
n air changes in the volume, ach/h
λ disintegration constant of Rn-222, h^{-1} (7,55 x 10^{-3} h^{-1})

Nielson et al (1997) have studied the radon penetration by diffusion ($\Delta p = 0$) and combined advection and diffusion ($\Delta p > 0$) of concrete slabs containing cracks, joints, pipe penetrations and sealants. The physical characteristics that influence radon transport by diffusion are the porosity, permeability and the diffusion coefficient of the building component. The equivalent diffusion coefficient for the different slabs was 6,5 x 10^{-8} m^2/s, with a standard deviation of only 8 %. Undisturbed lead-throughs did not increase the advection; however, disturbed pipe-slab joints, for example, were estimated to be equivalent to 2 x 10^{-4} m wide cracks with an effective area of 1,1 x 10^{-7} m^2.

Radon from soil is the most common cause to radon concentrations indoors, though it may also originate from stone based building material in particular, since almost all stone based material in Sweden contains radium. Alum shale concrete is no longer a problem in new construction and the radium concentration in modern building material is usually small and insignificant. However, countrywide investigations of concrete ballast have showed radium contents of 167 Bq/kg in macadam samples as well as concrete with ballast from bedrocks with high uranium contents able to emit radon daughter concentrations over 70 Bq/m^3 (Betonghandboken - Material, 1994). The ballast used in concrete may be the cause to radon concentrations indoors. The contribution to indoor air is often small compared to radon concentrations in soil air, but has to be considered when not only designing the foundation of the building with concrete, but also the walls and roof (Junker, 1999; Clavensjö and Åkerblom, 2004). The contribution of radon from a surface, e.g. building material or rock, is calculated with equation (4.4) (Clavensjö and Åkerblom, 2004; Åkerblom et al, 1988).

$$C_{\text{surface}} = \frac{1}{\lambda + n} \cdot \frac{E \cdot F}{V} \qquad [\text{Bq/m}^3] \qquad (4.4)$$

where

λ	disintegration constant for radon, 7,55 x 10^{-3} h^{-1}
n	amount of air changes in the volume, ach/h
E	exhalation of radon, Bq/m^2h
F	surface area, m^2
V	volume, m^3

A third way to get radon concentrations indoors occurs when radon contaminated groundwater is used as drinking water. Radon from contaminated drinking water emanates to the indoor air and may give high levels of radon indoors. This is usually not a problem when potable water is distributed from a municipality water works, though drinking water distributed from drilled wells in uranium rich bedrocks may cause high levels of radon indoors. Drinking water with a radon concentration of 1000 Bq/l is roughly estimated to cause a radon concentration in a single-family dwelling of 100-200 Bq/m^3 (Clavensjö and Åkerblom, 2004).

4.4.2.3 Consequences to humans, random variable X_{env}

Radon-222 disintegrates into decay products, also known as radon daughters, which in turn disintegrate sending out alpha, beta and gamma radiation. The radon daughters have a high tendency to stick to airborne particles that are easily inhaled into the lungs. The radiation affects the lung cells and may eventually cause lung cancer (Hus & Hälsa, T6:2000; Johansson, 1996; Åkerblom et al, 1988). The Swedish National Board of Health and Welfare (SoS), i.e. the supervisory authority of radiation in the existing building stock, issues general advices concerning radon concentrations indoors regarding sanitary inconvenience to humans (SOSFS 1999:22). In 2004, the general advices were revised in accordance with the Swedish Government proposition on certain issues of indoor environment (Prop. 2001/02:128), changing the guiding value of sanitary inconvenience from 400 Bq/m^3 to 200 Bq/m^3 (SOSFS 2004:6), i.e. the same as the threshold value in the Swedish Building Regulations for new buildings. Approximately 280000 residential buildings are assumed to have radon concentrations indoors above 200 Bq/m^3 and the SoS conclude that radon concentrations indoors is a health risk of great concern and important to reduce (Socialstyrelsen, 2005). The Swedish Radiation Protection Authority (SSI), which has the overall responsibility to protect humans against harmful effects of ionising radiation, has estimated the number of deaths in lung cancer connected to radon indoors to approximately 500 cases per year (Mjönes and Falk, 2001). In IMM (2001) the estimation is that 400 out of 2800 cases of lung cancer per year in Sweden depend on exposure to radon where 350 are smokers and 50 non-smokers.

The risk of suffering from lung cancer caused by radon exposure is proportional and depends on the radon concentration and time with a latency of 15-40 years (Clavensjö and Åkerblom, 2004). A Swedish national epidemiological study investigated the relationship between radon concentrations in dwellings and lung cancer (Pershagen et al, 1993), and estimated the increase in the risk of lung cancer depending on radon to be 10 % per 100 Bq/m^3 during 32,5 years of exposure considering both smokers and non-smokers. The estimated increase in relative risk of suffering from lung cancer is 3,4 % per 1000 Bq/m^3 and year, which also includes those who sleep with an open window in the bedroom. The study considered the time spent at home indoors to be 60 %, according to former Swedish studies. A later study about residential radon and lung cancer was performed among never-smokers also suggesting a relative risk of 10 % per 100 Bq/m^3 average radon concentration. However, never-smokers exposed to environmental tobacco smoke constituted the majority of the increase in risk (Lagarde et al, 2001). The results have been supported by a performed collaborative analysis of radon data from 13 European case-control studies (Darby et al, 2005), and after correcting for uncertainties in measuring the radon concentrations, the risk corresponded to an increase of 16% per 100 Bq/m^3 increase in radon. The dose-response relation seemed to be linear with no evidence of a threshold dose, and with a significant dose-response relation even below the recommended action levels.

4.5 Microorganisms

4.5.1 Introduction

Microorganisms are very small (< 0,1 mm) living organisms not visible to the human eye. They include for example protozoa, many algae, fungi and bacteria and exist everywhere in nature where they are of vital importance to plants and animals. However, some microorganisms may be infectious to man, called pathogens. The ability to cause disease is called virulence and is often defined as an infection dose, i.e. the number of microorganisms needed to become ill, measured in colony forming units per volume (e.g. cfu/ml). Virulence differs between microorganisms, with some species being very virulent especially those transmitted by aerosol (Sunesson, 1995; Ström et al, 1990; Thougaard et al, 2001).

A building or its services are never completely free of microorganisms. Already during the production of building material and construction of the building itself, a number of microorganisms occur, or are being introduced on/in the building material. The Swedish Building Regulations (BFS 2002:19) states:

> "Buildings and their services shall be constructed of such materials and designed in such a way that the risk of unhealthy growth of microorganisms is limited."

Microorganisms are often mentioned apart from the above cited section, e.g. buildings shall be designed without any microbial growth due to moisture, and any harmful growth of microorganisms in the water supply shall be prevented. This section will focus on two types of problems caused by microorganisms in buildings. The first is microbial growth in building components and the second is microbial growth in water installations.

4.5.2 Microbial growth in the building components

4.5.2.1 Growing conditions

Mould fungi are a group of microorganisms built up with long branching strings called hyphae forming the mycelia. From the mycelia, pinhead-like structures are developed, called sporangiophores or conidiophores, depending on how the fungi reproduce. These structures are the reproductive organs forming spores/conidia that are liberated into the air. Bacteria, belonging to the genus *Streptomyces*, also have a fungi-like structure with branching hyphae and spore-bearing structures (Sunesson, 1995; Thougaard et al, 2001; Viitanen, 1996).

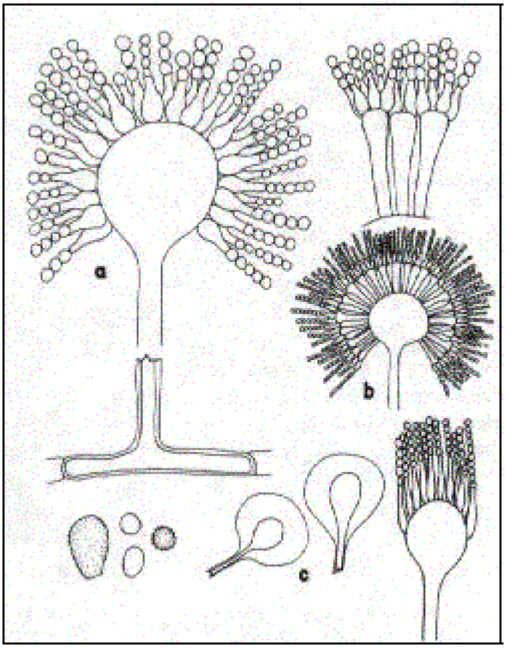


Figure 4.4 Structure of the mould fungi Aspergillus versicolor

To be able to grow, fungi need sufficient nutritive substances, moisture and the right temperature range to permit germination, hyphal growth and sporulation. Mould fungi show a great ability to adjust and develop at temperatures from 5 to 40°C. Optimum temperatures for most fungi species range between 20 and 30°C. The limits depend on the fungal species, substrates and other environmental conditions (Sunesson, 1995; Viitanen, 1996). Microbial growth and deterioration of building materials starts as soon as water activity a_w (the relative humidity at equilibrium divided by 100) achieves a minimum limit of approximately 0,7, corresponding to 70 % RH (Hyvärinen et al, 2002; Sunesson, 1995).

4.5.2.2 Secondary metabolism

During growth, microorganisms produce a variety of necessary substances called primary metabolites, used as an energy source and building material or for reproduction. In contrast to primary metabolites, secondary metabolites are produced during either slow growth or the stationary growing phase, since they have a lower priority to the organism than growth. Microorganisms generally produce more secondary metabolites under conditions of nutritional stress and production often starts after active growth has ceased. Mould fungi and mycelia producing bacteria primarily produce secondary metabolites. The purpose of the production to the organisms is unknown, but may, if released into the air, be odorous or toxic to humans.

Numerous products are generated during the secondary metabolism, e.g. antibiotics, allergens, mycotoxins, endotoxins and volatile substances. Volatile substances produced during the secondary metabolism include e.g. alcohols, ketons and organic acids, also known as fungal volatile metabolites or microbial volatile organic compounds (MVOC) (Gravensen and Nielsen, 2000; Johansson, 2000; Murtoniemi et al, 2003; Rylander, 2002; Rylander, 2004a; Ström et al, 1994; Sunesson, 1995; Thougaard et al, 2001).

4.5.2.3 Fungal spores

Depending on species, the reproduction of fungi is made by the means of spores in different ways. Fungal spores are present everywhere in both indoor and outdoor environments, and are very resistant and able to survive long periods of drought. Most fungal spores are 2-20 µm in size and are measured in number of established colony forming units per cubic metre air (cfu/m^3). The outdoor concentration of airborne fungal spores in Sweden varies from 10 cfu/m^3 during the winter to around 30 000 cfu/m^3 in the autumn. The number of viable airborne micro-organisms in indoor air is significantly lower compared to outdoor air and in houses where no health complaints associated with the indoor environment are reported, the air normally contains $10^1 – 10^3$ cfu/m^3 (Gravesen et al, 1994; Ström et al, 1990; Sunesson, 1995; Thougaard et al, 2001).

Spores can act as carriers of compounds produced by microorganisms. This is of special interest, since the spores are sufficiently small in size to reach the alveoli. It has been demonstrated that mycotoxins can be located inside as well as on the surface of the spores (Gravesen et al, 1994), and Murtoniemi et al (2003) demonstrated that microbial spores serve as carriers of bioactive compounds produced by microorganisms. For example, *Stachybotrys chartarum* produce several biologically potent mycotoxins that are carried along with spores.

4.5.2.4 Undesirable indoor events, random variable Y_{env}

One of the primary causes to microbial growth in construction is moisture at the wrong place, e.g. a relative humidity above 75 % increases the risk for mould growth on wood and wood based material (Samuelsson et al, 1998; Sundell, 2000). The expert-group NORDDAMP concluded from a review of scientific literature on damp buildings and health the main reasons for damp buildings are (Bornehag et al, 2001):

- rain, snow or soil dampness leaking into the building components,
- dampness produced by tenants and their activities,
- dampness from the construction site, and
- unknown leakage from installations.

To prevent microbial growth in buildings, measurements against moisture at the wrong places in the construction have to be taken. Land and Must (2004) showed, e.g. that plasterboards during transportation from the manufacturer to the building site could already be exposed to enough levels of relative humidity to initiate mould growth caused by condensation inside the wrapping. Damage from moisture also depends on actions taken by tenants or owners, from activities like showering or rebuilding without sufficient knowledge, e.g. adding insulation in a misdirected wish to lower the energy use. To change the floor covering on an old concrete floor may involve a moisture risk especially if the new flooring is impermeable (Sjöberg and Nilsson, 2002). Floor heating may also put the construction at risk. If the insulation under the concrete slab on the ground is thin and the heating is turned off during part of the year or if the heating coils are installed deep down in the slab, a redistribution of the residual water in the construction with a high moisture level at the surface of the concrete will occur as a result (Sjöberg and Nilsson, 2002). However, this subject will not be examined more deeply, since excellent information about how to prevent moisture damage during the design, construction and maintenance of a building can be found in publications and computer programs produced by the Moisture Research Centre at Lund Institute of Technology (e.g. Harderup, 1993; Harderup, 2000; Fuktcentrum).

Mould fungi can grow on the surface of many different materials. The various building materials present in houses invariably include sufficient nutrients for at least some fungal species, with the building temperatures being normally within the limits of fungal growth (Sunesson, 1995). However, they differ in their capacities to support growth, depending on, e.g. nutrient availability and their moisture absorbing potential. Nevertheless, it should be emphasised that even materials such as mineral-based insulation or ceramics may provide conditions for fungal growth (Hyvärinen et al, 2002). In a study by Hyvärinen et al (2002), *Penicillium* was the most common genus in moisture damaged building materials. This was also the only species found on the wood samples exposed to alternating humidity conditions by Viitanen (1996). *Penicillium* show a capability to resume growth after returning from low to high humidity and are not very demanding regarding nutrients and moisture. The *Aspergillus* and *Penicillium* species are primary colonizers, able to grow at the lowest humidity ($a_w < 0,8$) (Sunesson, 1995).

Hyvärinen et al (2002) also found, for example, *Cladosporium* in high concentrations and most frequently in paper and mineral insulation. *Aspergillus versicolor* and *Acremonium* were favoured by ceramic products, paints and glues. Andersson et al (1997) and Murtoniemi et al (2003) also observed *Stachybotrys* on plasterboards, where *S. chartarum* grew faster than other microbes. It should be mentioned that the growth occurs only on the liners, not in the core. *Stachybotrys* was also observed frequently in paper material samples. Bacteria found in buildings belong to the genera *Streptomyces*. More mould fungi species have been tabulated in the literature and in papers, e.g. Ström et al (1990), Samson et al (1994) and Sunesson (1995).

Several attempts have been made to indicate and model mould growth. Rowan et al (1999) present critical limits for the growth of, e.g. the indoor fungi *Aspergillus versicolor* and *Stachybotrys chartarum* mathematically described in terms of growth limit curves (isopleths) that define the minimum combination of temperature (T) and relative humidity (RH) at which growth will occur using a third-order polynomial equation of the form $RH = a_3T^3 + a_2T^2 + a_1T + a_0$.

Table 4.4 Minimum RH supporting growth of test fungi over the temperature range 20 to 25 °C (parts of Table from Rowan et al, 1999).

Fungus	Min RH (%) supporting growth Avg ± SD
Aspergillus versicolor	79,3 ± 2
Penicillium brevicompactum	81,3 ± 1,7
Penicillium spinulosum	79,5 ± 0,7
Stachybotrys chartarum	93,6 ± 0,5

Hukka and Viitanen (1999) present a mathematical model to simulate mould growth on wooden material based on regression models for mould growth on sapwood of pine and spruce. Consisting of differential equations, the model describes the growth rate in different fluctuating conditions. Haverinen et al (2001: 2003a; 2003b) have developed an empirical moisture damage index, simulated as a continuous variable, which may provide a tool to estimate moisture damage intensity quantitatively and more objectively, with the purpose to clarify the association between moisture damage induced exposure and the occupant's health. It may also be useful for maintenance of buildings, decision-making (e.g. for estimating the need for repair) and risk assessment. In a study, Boutin-Forzano et al (2004) show that a simple measurement of wall RH can be used as an index for discarding and suspecting *S. chartarum* infestation in dwellings.

The levels of microbial compounds found in indoor air can be expected to be low (µg/m^3-levels). Swedish investigations into affected buildings show the numbers of airborne microorganisms seldom to differ from the levels detected in unaffected control buildings. The reason for this might be because the growth of microorganisms primarily occurs within the building construction, e.g. in insulation materials, and since the organisms are sealed in the tight construction, no significant transport of fungal or bacterial cells to the indoor environment occurs (Blomquist and Andersson, 1994; Ström et al, 1990; Ström et al, 1994). However, studies in Finland show a difference in species between buildings with and without health problems among the residents (Nevalainen et al, 1994). In a study by Airaksinen et al (2004a; 2004b), the objective was to determine whether microbes are transported from the crawl space to the indoor air. Previous studies provided the background to the study by showing that particles ranging from 1,0-2,5 µm are penetrating easily through cracks. This was an interesting result, since the median of the aerodynamic diameter of fungal spore is typically 2,0-3,0 µm in indoor air and is very suitable for penetration. The study showed a clear linkage between fungal spores in the indoor air and crawl space with penetration occurring even at a lower pressure difference, for which it is highly dependent.

Research is performed to find fungi specific MVOC for the detection of mould growth in buildings. However, the problem is that several substances can originate from both microbial activity as well as being emitted from building materials. Claeson et al (2002) found that the production of fungal metabolites to also vary greatly between different growths media and this difference in metabolite production makes it difficult to find single specific MVOCs as microbial tracer compound. The alcohol 3-methyl-1-butanol is a common compound and is emitted from various species of, e.g. *Aspergillus, Penicillium* and *Streptomyces*, which are common mould fungi and bacteria found in moisture damaged buildings. Other common alcohols are 2-methyl-1-propanol (also from species of e.g. *Aspergillus, Penicillium* and *Streptomyces*) and 1-octen-3-ol (from species of e.g. *Aspergillus, Penicillium*) (Sunesson, 1995; Wilkins et al, 2000).

Geosmin (1,10-dimethyl-*trans*-9-decalol) has an earthy odour and is an important potential indicator to microbial growth in buildings, since its only known origin is from microorganisms. The major producers of geosmin are *Streptomycetes* but it could also be emitted from species of, e.g. *Aspergillus* and *Penicillium* (Ström et al, 1990; Sunesson, 1995).

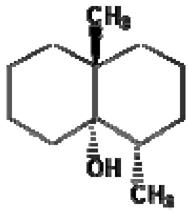


Figure 4.5 Chemical structure of geosmin

Another agent found indoors is (1→3)-β-D-glucan, a polyglucose structure present in the cell walls of moulds, some bacteria and plants. It is also toxic after the death of the organism (e.g. Rylander and Lin, 2000; Beijer et al, 2003; Rylander, 2002; Rylander, 2004b). In the study by Anderson et al (1997), on construction materials of interior walls in moisture damaged buildings, high contents of i.a. endotoxin and glucan was found on water damaged plasterboard, whereas none was found on the material from non-water damaged areas.

4.5.2.5 Consequences to humans, random variable X_{env}

Moulds contain a variety of antigens and their capacity to induce an immunological response is well recognised. When exposed to spore dust liberated from mould fungal or bacteria, different types of allergies may be the result. Exposure to organic dust, i.e. particles of microbial, plant or bacterial origin, is known from, e.g. farmers to be dangerous to human health causing inflammation in the airways. However, symptoms reported in connection with the indoor environment and mould are not always of an allergic origin, but reflect a non-specific airway inflammation. Adverse health outcomes associated with moisture-damaged buildings probably originate from an exposure consisting of complex interactions between various microbial species and other indoor pollutants. The concentrations and proportions of microbial components in such environments can vary greatly with growth conditions (e.g. Gravesen et al, 1994; Rylander and Lin, 2000).

Extensive research is searching for explanations, with the hypothesis being that products from microorganisms may be hazardous to humans. Penttinen et al (2005) have evaluated the effects of simultaneous exposure to *Streptomyces californicus* and *Stachybotrys chartarum* on inflammatory responses. Murtoniemi et al (2002) cultured *Stachybotrys chartarum*, *Aspergillus versicolor*, *Penicillium spinulosum*, and *Streptomyces californicus* on liners and cores of plasterboards to examine the microbial growth and the resulting bioactivity that was assessed as the ability of microbial spores to induce inflammatory responses. Jussila et al (2002) exposed mice to a single dose of *A. versicolor* spores isolated from the indoor air of a moisture-damaged building. Rand et al (2005) have examined the exposure of animals to metabolites from *Penicillium* species common to damp building materials and found significant inflammatory responses. Kelman et al (2004) have modelled a continuous exposure to a high concentration of mould spores containing the maximum reported concentration of mycotoxins. However, none of the maximum doses modelled were sufficiently high to cause any adverse effect. The conclusion from these studies is that the inflammatory response pattern in lungs differs depending on fungal species, while no dose-response relationship is yet available.

Bacterial endotoxin, found on fragments of cell walls, is one agent in organic dust that causes i.a. airway inflammations in humans when inhaled. Endotoxins have been found indoors in, e.g. dust, and are expressed in ng/m^3. Based on toxicological data and experience from field studies, proposals have been made for guidelines of non-effect levels of endotoxins to 0,2-0,5 ng/m^3. (1→3)-β-D-glucan may also induce an inflammatory response and a suggested threshold value is 2 ng/m^3 (e.g. Rylander and Lin, 2000; Beijer et al, 2003; Rylander, 2002; Rylander, 2004a; Rylander, 2004b).

4.5.3 Microbial growth in water installations

4.5.3.1 Introduction

The harmful growth of microorganisms in the water supply system accounted for in this section is the growth of the bacteria *Legionella*, which may cause Legionnaires' disease among humans. Most bacteria exhibit three stages of growth. The first phase is the lag that can be seen as the time to adapt to the environment. The second phase is the exponential growth phase yielding a straight line on a logarithmic scale. The growing rate is expressed as generation time, i.e. the time needed to double the number of bacteria. The exponential growth slows down and eventually ceases either because the required nutrient is limited or because of the accumulation of inhibitory metabolic products. In the next phase, the stationary phase, the number of produced cells will be equal to the number that dies. The final phase is the declination phase where the number of living cells is halved during a specific time. To a microbiologist, a bacterium is considered dead when it has lost the power to reproduce (Brundrett, 1992; Thougaard et al, 2001).

A chain of events must occur before humans suffer from Legionnaires' disease, beginning with an environmental source of *Legionella*. The next two events in the chain are the factors needed to enable amplification, and the transmission of the organism to susceptible people. These two steps in the chain can be influenced by engineering design and maintenance practice. Subsequent events are influenced by the health of the individual and include the inoculation of the organism at a site in humans where infection may occur, and a person who is susceptible and unable to fight off the infection (Millar et al, 1997; Geary, 2000; Darelid, 2003).

4.5.3.2 Environmental source of Legionella

The aerobic gram-negative bacteria *Legionella* are microorganisms (1-3 µm in length) present in lakes, rivers and streams. Certain species may also be found in wet soil. The family *Legionellaceae* consists of a single genus *Legionella*, established in 1979 after the occurrence of a large outbreak of pneumonia among members of the American Legion three years earlier. *Legionella* consists of 48 known species, comprising 70 subgroups called serogroups. The specie associated with Legionnaires' disease, a severe disease involving pneumonia, is *Legionella pneumophila* serogroup 1, also responsible for Pontiac fever, a less severe self-limited flu-like illness.

The presence of *Legionella* in natural freshwater constitutes the occurrence also in man-made water systems, since the bacteria pass through the conventional water treatment process with little reduction. However, the concentration of bacteria is generally very low with only a few organisms per litre. The presence of these few *Legionella* in distribution water does not necessarily pose a health threat. Rather, it is the threat of amplification that is of public health concern (Millar et al, 1997; Thougaard et al, 2001; de Jong and Kallings, 2003; Darelid, 2003; Geldreich, 1996; Fields et al, 2002; US EPA, 1999).

4.5.3.3 Factors enabling amplification

Amplification is the growth process of *Legionella*, where certain conditions have to be fulfilled. Storey et al (2004a; 2004b) have investigated factors that may enhance *Legionella* amplification and transmissibility within man-made water systems. Four main "ecological" factors of *Legionella* were identified:

1. their interaction with thermophilic amoebae,
2. accumulation within biofilms,
3. resistance to conventional disinfection and
4. detachment of biofilm.

The bacteria survive and replicate as intracellular parasites in protozoa (e.g. amoebae is a group of protozoa) that serve as host. A single protozoan cell may harbour up to 1000 *Legionella* bacteria. The host provides nutrients and shelter for unfavourable conditions such as high temperature, disinfection procedures and drying, making *Legionella* more tolerant than many other microorganisms. In the final stage of amplification *Legionella* kill its host cells and the bacteria are released into the water in great numbers (Cooper et al, 2004; Geary, 2000; Darelid, 2003; Fields et al, 2002; Storey et al, 2004a).

The amplification is favoured by biofilm, a thin layer of microorganisms present on the inner surfaces of the water pipes. The biofilm offers protection from high temperatures and chemicals in the water. Nutrients available in biofilms have lead to the hypothesis that *Legionella* may multiply even in the biofilm outside a host cell (Cooper et al, 2004; Geary, 2000; Geldreich, 1996; Fields et al, 2002; Storey et al, 2004a). The ability to grow extracellular in the absence of protozoa has, according to Fields et al (2002), only been documented on laboratory media. A study by Murga et al (2001) showed that *L. pneumophila* could survive without protozoa in biofilm, though the protozoa were needed for multiplication.

Water temperature is an important condition. *L. pneumophila* multiplies in water between 25°C and 42°C, with an optimal growth temperature of 35°C. A common way to destroy pathogens is by using heat treatment, i.e. pasteurisation, and for *L. pneumophila*, multiplication slows down at temperatures above 40°C and ceases at 44-46°C. Therefore, this is the critical temperature for death (Yee and Wadowsky, 1982; Brundrett, 1992; Fields et al, 2002; Szewzyk and Stenström, 1993; Kusnetskov et al, 1996). The bacteria survive below 20°C, but do not replicate, above 50°C they rapidly decline and at 60°C the decimal reduction time, i.e. 90 % reduction in cell population is 1-11 minutes depending on species and 2-5 minutes for *Legionella pneumophila* sg1 (Brundrett, 1992; Rogers et al, 1994). However, these temperatures presuppose *Legionella* in a planktonic phase. Storey et al (2004a) show that interaction with both biofilm and amoebae increase the resistance to thermal disinfection. Another explanation to heat resistance may be the presence of dead pipe ends that are not reached by the hot water (Rogers et al, 1994).

The pH-value for reproduction is between 5,5 and 9,2, which can be compared with the threshold limits 7,5-9,0 for drinking water according to the Swedish National Food Administration (Szewzyk and Stenström, 1993; SLFVS 2001:30). However, Szewzyk and Stenström (1993) found no correlation between pH-value or water hardness and the presence of *Legionella* in their study.

The *Legionella* bacteria need time to grow and reproduce, and stationary or slow flowing water, for example, constitute excellent growing conditions. In a laboratory environment, *L. pneumophila* have a mean generation time, i.e. time to double the number of cells, of 2 hours. Multiplication in tap water is much slower due to the limited quantity of nutrients present and the mean generation time becomes nearer to a day, cf. Figure 4.6. The exponential growth rate can be expressed as (Brundrett, 1992; Thougaard et al, 2001):

$$\frac{dN}{dt} = \mu \cdot N \tag{4.5}$$

where

N	number of cells
t	time
μ	constant of specific growth rate

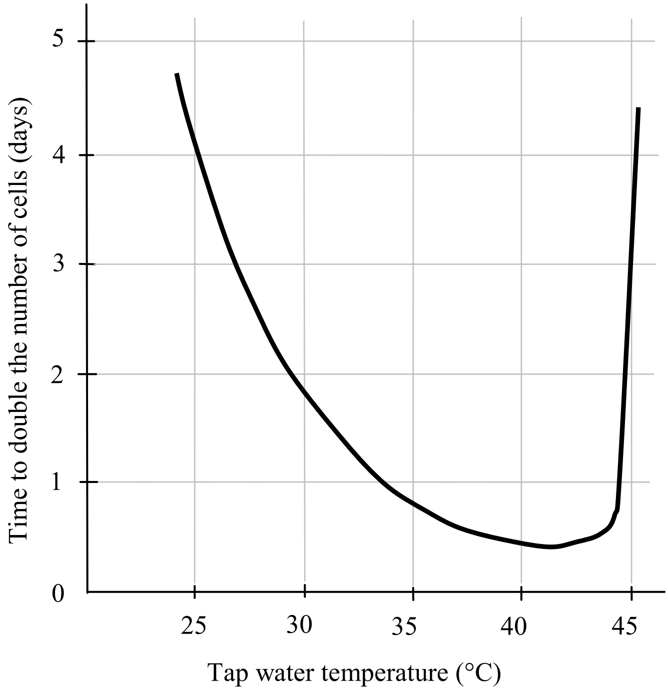


Figure 4.6 *An estimation of mean generation time of Legionella pneumophila in tap water (based on data from Yee and Wadowsky, 1982) (adapted from Brundrett, 1992).*

Legionella colonisation is more common in large and complex water distribution systems probably due to the fact that a large and complex pipe network provides larger surfaces with more biofilm formation as well as more peripheral stagnant water areas with lower temperatures (Szewzyk and Stenström, 1993; Darelid, 2003).

4.5.3.4 Transmission of Legionella indoors

The third link in the *Legionellae* chain is the transmission of the organism from the reservoir to susceptible people. Since the amplification of *Legionella* occurs in water the bacteria is transmitted through small water droplets, so called aerosols. Several ways of generating aerosols exist, like condensation of air streams on airborne particles, breaking up of free falling water, the impact of drops on surfaces, and bursting of bubbles on the water surface (Brundrett, 1992). Water droplets smaller than 5 µm in diameter behave very similarly to bulk air movements.

Diameter	*Description*	*Terminal velocity*
1 mm	Rain drops	4 m/s
100 µm	Fine drizzle	1 m/s
10 µm	Cloud droplets	0.02 m/s
1 µm	Aerosols	0.0002 m/s

Figure 4.7 Examples of naturally formed water droplets (Brundrett, 1992).

The indoor sources most commonly associated with aerosol-producers are, e.g. whirlpool baths, humidifiers, fountains and shower heads. According to Brundrett (1992), bubbles “collect” particles in the water as they rise to the surface, making the aerosols richer in contamination than the bulk fluid. Other aerosol producing sources are cooling towers that disseminate aerosols to the outdoor air or to the indoor air through the ventilation system, and hot spring water.

4.5.3.5 Undesirable indoor events, random variable Y_{env}

Amplification of *Legionella* occurs, i.a., in the building water supply system including all piping and other installations, e.g. calorifiers, from where the water enters the building. *Legionella* can colonise a variety of plumbing materials, including polyvinyl chloride (PVC), steel, wood and copper (Darelid, 2003; Geldreich, 1996). In a study by Rogers et al (1994), the survival and growth of *Legionella pneumophila* were investigated at different temperatures on both plastic and copper surfaces. The pathogen was able to survive in biofilms on the surface of the plastic material at 50°C, but was absent from the copper surface at the same temperature, Table 4.5. Copper was also less bio contaminated than PVCc at all examined temperatures. However, the effect of copper in pipe works on *Legionella* growth seems to decrease with time and cease five years after installation (Szewzyk and Stenström, 1993).

Table 4.5 Comparison of the colonisation of different plumbing materials at different temperatures (adapted from Rogers et al, 1994).

Temp (°C) and material		Mean colonisation (cfu/cm^{-2})		Colonisation ratio
		Total flora	*L. pneumophila*	*L. pneumophila*
20	Copper	$2{,}16 \times 10^5$	BD	1
	PVCc	$1{,}81 \times 10^6$	$2{,}13 \times 10^3$	2132
40	Copper	$8{,}04 \times 10^4$	$1{,}97 \times 10^3$	1
	PVCc	$3{,}67 \times 10^5$	$6{,}84 \times 10^4$	34,7
50	Copper	$2{,}26 \times 10^4$	BD	1
	PVCc	$1{,}22 \times 10^5$	$6{,}00 \times 10^1$	60
60	Copper	$4{,}47 \times 10^2$	BD	
	PVCc	$5{,}19 \times 10^3$	BD	

BD = below detection limit of 10 cfu/cm^{-2}

In a Swedish study with the aim to increase knowledge of *Legionella*, 25% of the hot tap water tests from different types of buildings (from single-family dwellings to hospitals) were positive (1104 ± 3233 cfu/100 ml) compared to only 4% of the cold water tests (26 ± 49 cfu/100 ml) (Szewzyk and Stenström, 1993). *Legionella* were also found in all calorifiers with an outgoing temperature below 50°C as well as in all calorifiers larger than 1000 litres without water circulation, independent of outgoing water temperature, the latter probably due to thermal stratification. Temperatures below 50°C at the tap showed positive tests of *Legionella* even if the temperature in the calorifier was 60°C.

In 1991, a large outbreak of nosocomial Legionnaires' disease occurred at Värnamo hospital. The hospital's hot water was stored in a large 15 000-litre calorifier and delivered to the taps of the wards at less than 45°C. The growth of *Legionella* in the water samples ranged from 5 – 1500 cfu/100 ml with a mean value of 565 cfu/100 ml. It was also concluded that the only source of exposure came from the hospital showers. An abundance of slime was found in the shower equipment that was partly made of plastic material (Darelid, 2003).

In a report by Det Norske Veritas (2004), technical risk factors supporting the growth of *Legionella* were identified using technical inventories of buildings on occurred cases of Legionnaires' disease during a two-year period. Twenty-four technical risk factors were identified based on the inventory protocols, including the risk of, e.g. stagnant water (88 % of the cases), taps seldom used (81%), temperature of circulating hot water <50°C (75 %), and risk of cold water >18°C (65 %). Further potential risk factors were the lack of protocols of the temperature measurements (91 % of the cases), up-to-date drawings of the water supply system (58 %) and hot water operator instructions (58 %).

Disinfection measures like, e.g. chlorination, hot-water flushing or copper-silver ionisation, have little effect on the long term control of *Legionella* and once the disinfection is completed, recolonisation is likely to occur. In already colonised water systems, periods of non-usage or ongoing construction work are technical risk factors. However, a surveillance study in Värnamo hospital has shown that keeping the hot water temperature above 55°C is effective in reducing the risk of nosocomial Legionnaires' disease (Darelid, 2003). A complete eradication of *Legionella* from the water system is probably an unrealistic goal. Focus should be put on diminishing *Legionella* growth by eliminating areas of water stagnation, known as "dead ends" (pipes not used and longer than one pipe diameter) and keeping "hot water hot and cold water cold" (e.g. Darelid, 2003; Geary, 2000; VVS Tekniska föreningen, 2004).

4.5.3.6 Consequences to humans, random variable X_{env}

Approximately one-half of the 48 species of *Legionella* have been associated with human disease. However, as already mentioned, the specie *Legionella pneumophila* sg 1 is associated with most reported cases of legionellosis, e.g. Legionnaires' disease and Pontiac fever (Darelid, 2003; Fields et al, 2002). The last links in the chain of events, to suffer from Legionnaires' disease, are influenced by the individual's health and include inoculation of the organism at a site where the human can be infected, and that the person is susceptible to the infection. Legionnaires' disease occurs when water droplets containing *Legionella* bacteria are inhaled deeply into the lungs. A person's susceptibility depends, on e.g. the exposure dose, age, underlying chronic illness, smoking, and weakened immunity (Millar et al, 1997; Darelid, 2003; Geary, 2000; de Jong and Kallings, 2003; EWGLI, 2002).

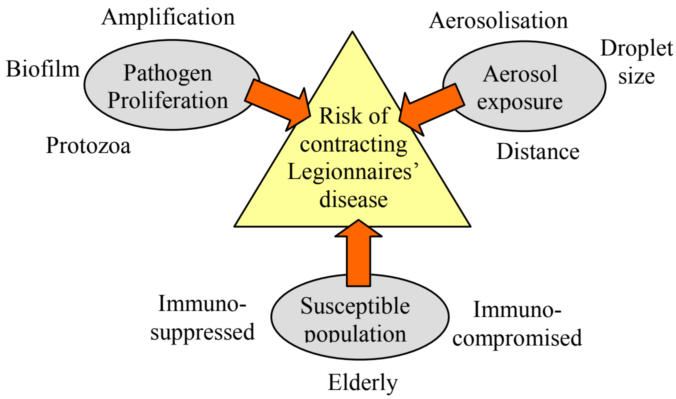


Figure 4.8 Factors that affect legionellosis risk (Cooper et al, 2004).

Legionnaires' disease occurs in epidemics and as sporadic cases. Approximately 50 domestic cases of illness are reported in Sweden each year, giving an incidence of about 0,6 cases per 100 000 inhabitants. The total annual cases including travel associated are about 100. However, despite the obligation to report cases of Legionnaires' disease according to the Communicable Disease Act (SFS 2004:168), the incidence is assumed to be ten times higher, since all cases are probably not correctly diagnosed (de Jong and Kallings, 2003).

Cooper et al (2004) define the risk of legionellosis as the probability that disease will occur as a consequence of exposure to the causative agent. Studies have been conducted to quantify the risk of exposure and disease. An attempt to develop a simplistic quantitative microbial risk assessment (QMRA) for *Legionella* was done in a study by Storey et al (2004b). A log-normal distribution of human exposure to aerosols was used, assuming the average person would inhale approximately 57,5 ± 35,8 μL during 10 minutes in the shower. The probability of infection resulting from the inhalation of a certain number of organisms (*D*) was simulated using the model:

$$P_{\inf} = 1 - e^{-rD} \qquad (4.6)$$

i.e. the single-hit model with fixed probability of infection *r*. This means that exposure to one infectious unit causes illness, i.e. $r = 1$ (Haas et al, 1993; Teunis and Havelaar, 2000). This model has been used in risk assessment of virus in drinking water; however no study confirming the relationship between humans and *Legionella* bacteria has been found.

Guiding values have been found from the United States Environmental Protection Agency, US EPA, (US EPA, 1999), which refer to Shelton et al (1993), suggesting immediate disinfection of all equipment if potable water has *Legionella* concentrations above 100 cfu/ml and “a low but increased level of concern” when being above 1 cfu/ml. From EWGLI, the European Working Group for *Legionella* Infections (EWGLI, 2002), action levels following *Legionella* sampling in hot and cold water systems are tabulated where disinfection should be considered upon finding between 1000 – 10 000 cfu/litre. If more than 10 000 cfu/litre are found in the system, an immediate identification of remedial actions should be performed including possible disinfection of the system.

However, assumptions are still required due to the lack of basic information regarding *Legionella* pathogenicity, population susceptibility and the extent of exposure. Sufficient information is not available to support a dose-response relationship and the threshold infective dose, i.e. the dose required to produce an infection of *Legionella* (e.g. Cooper et al, 2004; US EPA, 1999).

4.6 Summary of chapter 4

Environmental impacts with the potential to cause an undesirable indoor event of concern to human health were identified to be microorganisms and substances from microorganisms, emissions, and ionising radiation. The top event and the sub-top events defined in section 4.2 were based on the reviewed investigations and compilations of research results, see Figure 4.1. The following identification of causes to undesirable indoor events focused on microorganisms, both in building components and water supply system, and ionising radiation.

The risk analysis process proposed in chapter 3 will know be applied to the foundation of a single-family dwelling in chapter 5, and to the water supply system of a tenant-owned dwelling in chapter 6, using the different environmental impacts and dose-response relationships found in chapter 4.

5 RISK ANALYSIS OF ENVIRONMENTAL IMPACT TO THE FOUNDATION

5.1 Scope definition

The risk analysis procedure proposed in chapter 3 will be applied to the foundation of a single-family dwelling. The main purpose is to evaluate the possibility to qualitatively establish the causes of undesirable indoor events caused by environmental impacts and the design and construction of the foundation, and to quantitatively compare the undesirable indoor events with the occurrence of specific human health effects and dose-response relationships.

The failure/success criteria to be used are primarily, if available, threshold values from the Swedish Building Regulations, guiding values found in authoritative advices or published research.

5.2 System definition

This fictitious example of a single-family dwelling has a building area of 110 m^2 (b = 8,00 m, l = 13,75 m). The foundation is built on undisturbed soil of glaciofluvial sand, and the groundwater level is more than 1,0 meter under the excavated rock floor. Common foundation methods of single-family dwellings in Sweden are concrete slabs on the ground and crawl spaces with different solutions for ventilation of the space under the base floor. Regardless of which type, the foundation consists of different discrete elements that interact forming an entity whose purpose is to act as a passive barrier and protect the indoor environment from environmental impacts, assuming proper design and construction. The case analysis will be performed when the building is founded on a concrete slab on the ground. However, similarities and differences between the different foundation methods will be discussed throughout the qualitative analysis.

The design of the concrete slab on the ground is shown in Figure 5.1, and includes from the bottom a geotextile placed on the excavated rock floor to separate the undisturbed soil from the 150 mm well-washed macadam layer (8-32 mm), serving as a drainage layer and a capillary barrier sealing. The necessary insulation thickness is 22 mm regarding the required 3°C difference in temperature above and below the insulation to avoid moisture transport (Harderup, 1993; Harderup, 2000). The chosen insulation thickness is 50 mm Paroc ground board 389-00 made of stone wool (λ = 0,036 W/m°C) and available for commercial use. Calculations are accounted for in Appendix B.

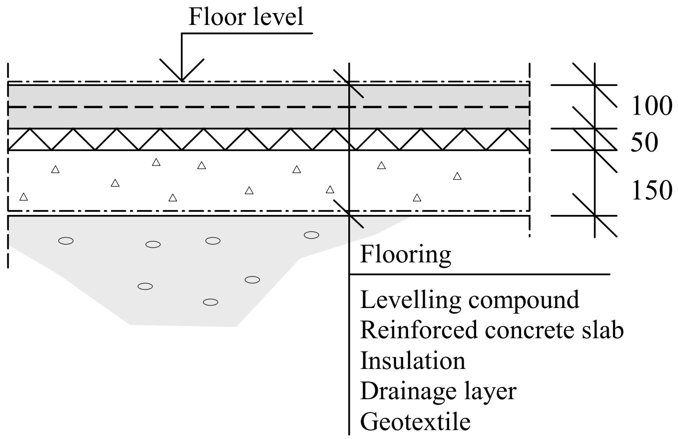


Figure 5.1 Component to be analysed – concrete slab on the ground.

Using concrete K30, the reinforced concrete slab is 100 mm thick with a characteristic design value of the compressive strength f_{cck} = 21,5 MPa, the tensile strength f_{ctk} = 1,60 MPa, and the modulus of elasticity E_{ck} = 30,0 GPa (BBK 94), standard cement suitable for concrete flooring in residential buildings, manufacturing class II and *vct* = 0,6 (Betonghandboken - Arbetsutförande, 1992). The slab is reinforced with a welded mesh reinforcement ϕ6 s 150 NPs500 placed in the centre of the concrete slab. The characteristic design value of the reinforcement yield strength f_{st} = 500 MPa.

The concrete slab is membrane cured, and the surface is levelled with a low-alkali floor-levelling product. The type of flooring is not considered in this analysis, since the flooring may change over the years depending on renovation and maintenance. However, it is important to consider the type of flooring as well as the possible change of flooring when performing a proper analysis, where a tight material will lower the amount of incoming environmental impact versus, for example, a ceramic material that will allow cracks and the possibility of incoming air pollutants. Pipes for potable water and waste water pass through the slab.

5.3 Hazard identification and initial consequence evaluation

5.3.1 Undesirable indoor events, random variable Y_{env}

Environmental impacts were identified in the hazard identification in chapter 4, with the potential to cause undesirable indoor events. In section 4.4, ionising radiation was considered and the environmental impacts with the potential to cause undesirable indoor events from the foundation of a building were identified to be radon contaminated soil air under the building that leaked into the indoor air, and radon originating from stone based building material, e.g. from the concrete in the foundation slab.

In section 4.5 microbial growths in building components were considered with the primary cause of mould growth being moisture in the wrong place. Mould growth in the crawl space under a building may cause leakage of airborne fungal spores into the building. Further, mould growth may occur when insulation is placed on the top of a concrete slab on the ground together with a wooden framework. This may not be the cause of airborne fungal spores in indoor air, but substances, e.g. volatile organic compounds, produced by the mould during the secondary metabolism.

5.3.2 Dose-response relationships, random variable X_{env}

When radon and its decay products disintegrate, they emit radiation that may affect the lung cells and cause cancer. Swedish Building Regulations (BFS 2002:19) stipulate the threshold value for radon concentrations indoors of 200 Bq/m^3 to not be exceeded. A dose-response relationship has been estimated in a Swedish epidemiological study for radon concentrations indoors to be linear with no threshold dose and with an increase in relative risk of 3,4 % per 1000 Bq/m^3 and year.

Airborne fungal spores and other substances from indoor mould growth may cause different types of allergy and inflammatory responses. However, according to the literature review, dose-response relationships are not yet available.

5.4 Construction of the fault tree

In the hazard identification from chapter 4 two environmental impacts, radon concentrations and airborne fungal spores were identified with the potential to cause undesirable indoor events through the foundation. The fault tree in Figure 5.2 will constitute the basis for further reasoning about the construction and development of the fault tree. Effort will be placed on developing the causes of radon concentrations indoors. The branch with airborne fungal spores will only serve as an example of the possibility to include several pollutants in the analysis, since no dose-response relationship is available to complete the branch analysis.

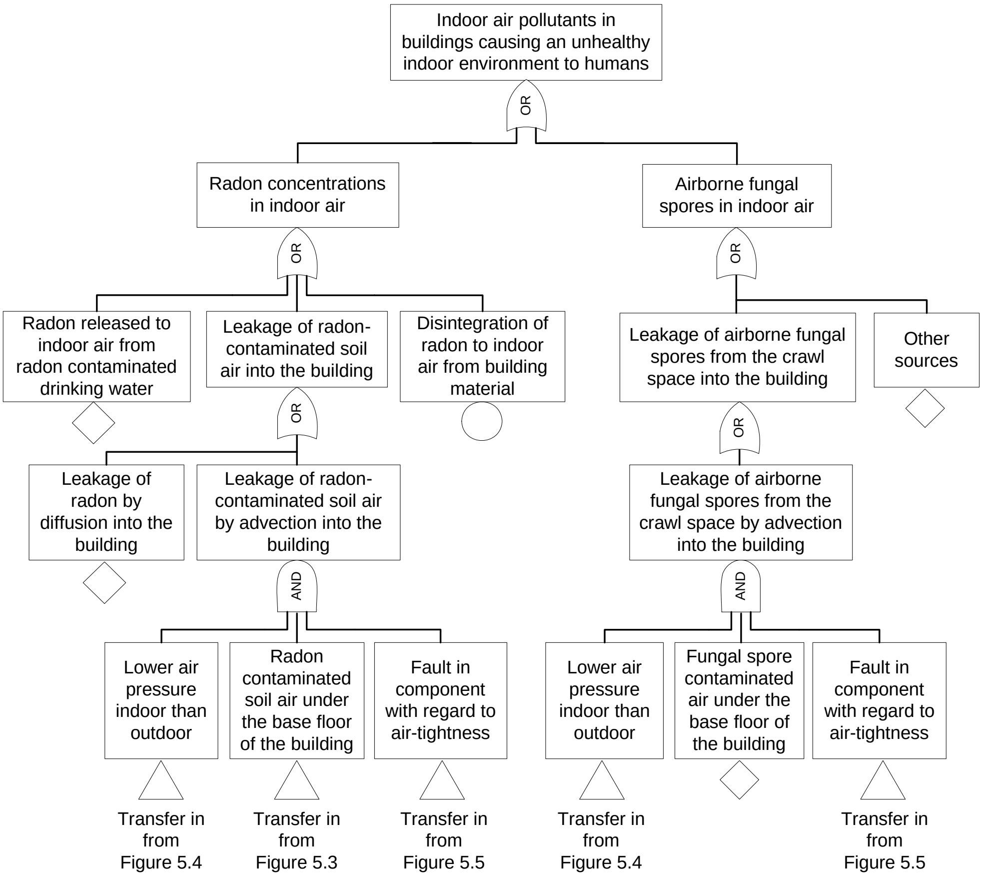


Figure 5.2 Causes to indoor air pollutants from radon and airborne fungal spores.

Both radon and airborne fungal spores indoors may depend on different types of sources. Radon contaminated soil air or airborne fungal spores from the crawl space may enter the building through the foundation illustrated in the fault tree in Figure 5.2. The two events pass through an OR-gate and can occur separately or in combination with other sources as indoor air pollutants. Other sources of airborne fungal spores will not be considered further. Concerning radon concentrations indoors three events with the potential to cause the sub-top event “Radon concentrations in indoor air” were identified in chapter 4 to be (1) release of radon from radon contaminated drinking water, (2) leakage of radon contaminated soil air into the building, and (3) disintegration of radon from the building material. Radon released from the drinking water may temporarily cause high radon concentrations indoors, though it is not of interest in this analysis and the event is not further developed, as symbolised with a diamond. The event “Disintegration of radon to indoor air from building material” can be of interest when using concrete and is considered to be a basic event, since measurements can be performed about the contribution of radon from the building material to the indoor environment. The most important contribution to high levels of radon indoors is ”Leakage of radon contaminated soil air into the building”, and the causes of which will be further developed in the fault tree.

Depending on their characteristics, air pollutants can enter the building through the building component by advection, diffusion, or both. Airborne fungal spores can only enter the building by advection with air, whereas radon gas may enter the building by both diffusion and advection, shown in Figure 5.2, where the two events pass through an OR-gate. Diffusion depends on the permeability of the component and the difference in the concentration of air pollutants below and above the component. The literature review in chapter 4 shows that only minor amounts of radon gas enter the building by diffusion through a concrete slab. Because of its limited contribution to the total amount of radon concentrations indoors, the event is not further developed, as indicated in the fault tree with a diamond.

To get a leakage of air pollutants by advection through the foundation an environmental impact is needed to affect the base floor of the building. In this case, base floor refers to either a concrete slab on the ground or the floor of a crawl space, i.e. the nearest floor to the ground independent of foundation type. The environmental impact consists of radon contaminated soil air, fungal spore contaminated air, or both under the base floor of the building. Further, a “fault” in the building component has to leak air from beneath the base floor into the building, and it has to be a lower air pressure indoors compared to outdoors. These three events pass through an AND-gate, since they have to occur in combination to get radon concentrations or airborne fungal spores in the indoor air.

The event “Radon contaminated soil air under the base floor of the building” from Figure 5.2 occurs when (1) the material under the building contains radium disintegrating into radon, and (2) the material is permeable enough to allow transportation of soil air. This is visualised in Figure 5.3 where the two events pass through an AND-gate.

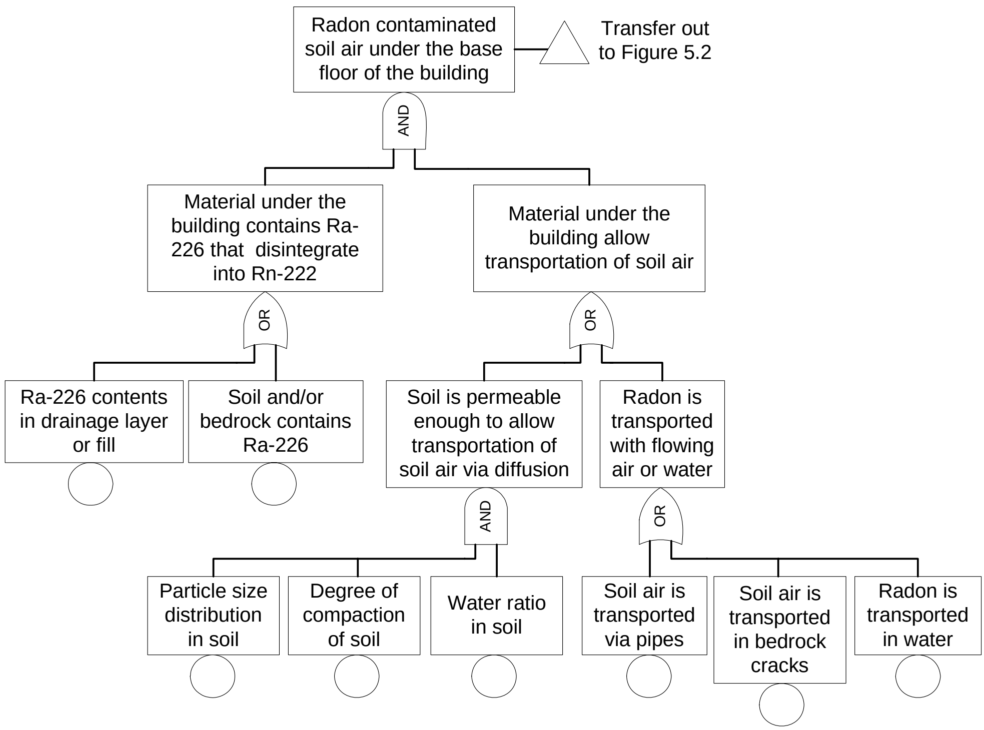


Figure 5.3 Causes to ”Radon contaminated soil air under the base floor of the building”.

Radium in the material under the building can originate from the soil, bedrock, or both having high levels of radium concentrations or/and from complementary material, e.g. sand or blasted rock, used for drainage layer or fill. The latter occurs when the fill or drainage layer has the dimension to store large amounts of soil air. This is visualised in the fault tree in Figure 5.3 with the two events considered to be basic events pass through an OR-gate. In the case of the capillary barrier sealing and drainage layers, experience has shown that the layer needed to be at least 0,3 meter and have a radium content of 200 Bq/kg, before the contribution needs to be included in a risk estimation (Junker, 1999).

Material containing radium has to come in combination with the allowance for transportation of radon, achieved by diffusion, advection, or both. Diffusion of soil air occurs when the soil is permeable enough, depending on the particle size distribution, the degree of compaction and the water ratio. Transportation of radon by advection using flowing air requires air to be transported via pipes in the soil, e.g. water pipes and telecom cables, pulled through casings, or in bedrock cracks. Radon may also be transported with flowing water but has a very limited transportation length due to disintegration.

The event “Lower air pressure indoors than outdoors” from Figure 5.2 depends on the difference in temperature between indoor and outdoor air, the type of ventilation used, the wind pressure or a combination thereof. In Figure 5.4, the three input events pass through an OR-gate, since they may cause the output event separately or in combination. The events constitute basic events. The event “Lower air pressure indoors than outdoors” occurs in both branches of the fault tree and depends on the same input events. The event may then be considered a common-cause that has to be analysed if the different environmental impacts occur simultaneously.

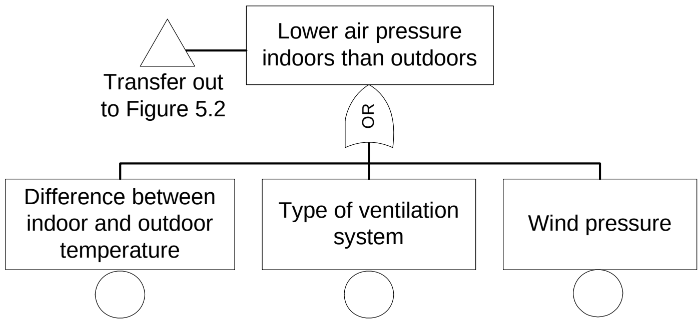


Figure 5.4 Causes to “Lower air pressure indoors than outdoors”.

The event “Fault in component with regard to air-tightness” in Figure 5.2 is developed further, and the possibility for air pollutants to enter the building by advection can occur by the events (1) air leakage through narrow openings, (2) air leakage through cracks in the component material, and (3) air leakage caused by a too permeable material. In Figure 5.5, these events pass through an OR-gate, since they may, separately or together, be the cause of leakage into the building. Narrow openings can exist between different building components, e.g. between foundation and wall, in construction joints or where pipes pass through the building component, c.f. Figure 4.2 in chapter 4. Cracks in the component material occur, i.a. in concrete by shrinkage. Any important advection through permeable material only occurs via e.g. mineral wool. Concrete and wood are too solid to allow any leakage by advection.

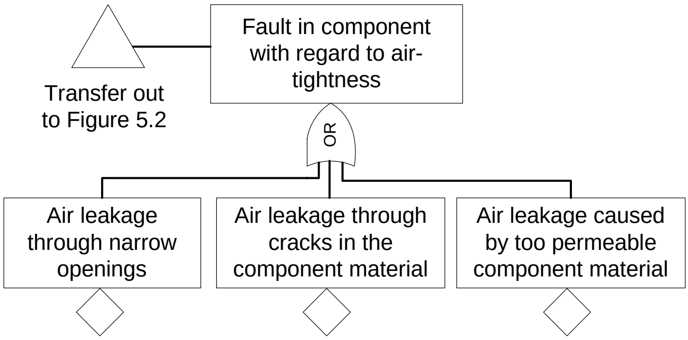


Figure 5.5 Developed event ”Fault in component with regard to air-tightness”

The event “Fault in component with regard to air-tightness” occurs in both branches of the fault tree, depends on the same input events, and may therefore, be considered a common-cause that has to be analysed if the different environmental impacts occur simultaneously. The development of the causes to the event “Fault in component with regard to air-tightness” has not lead to the establishment of basic events. Instead, the branches in the tree are finished with undeveloped events, i.e. signed with diamonds, since every event could possibly be developed further, but include human influence. When deductive reasoning comes down to human influence, many different causes may come in question, e.g. knowledge, skill, commitment etc. Human reliability analysis was highlighted in section 2.6, where it was concluded that at least certain faults would be possible to include in a fault tree with assigned probabilities. However, this is a research area of its own and will not be considered further in this analysis.

The construction of the fault tree concerning radon concentrations in indoor air is completed. The other branch of the fault tree with “Airborne fungal spores in indoor air” can be developed down to its basic events in accordance with radon. However, this will not be performed in this work.

5.5 Qualitative examination of the fault tree

The fault tree has been developed down to levels where experimental data is difficult to find and the tree structure is reduced according to the shaded events in Figure 5.6 to evaluate the top event.

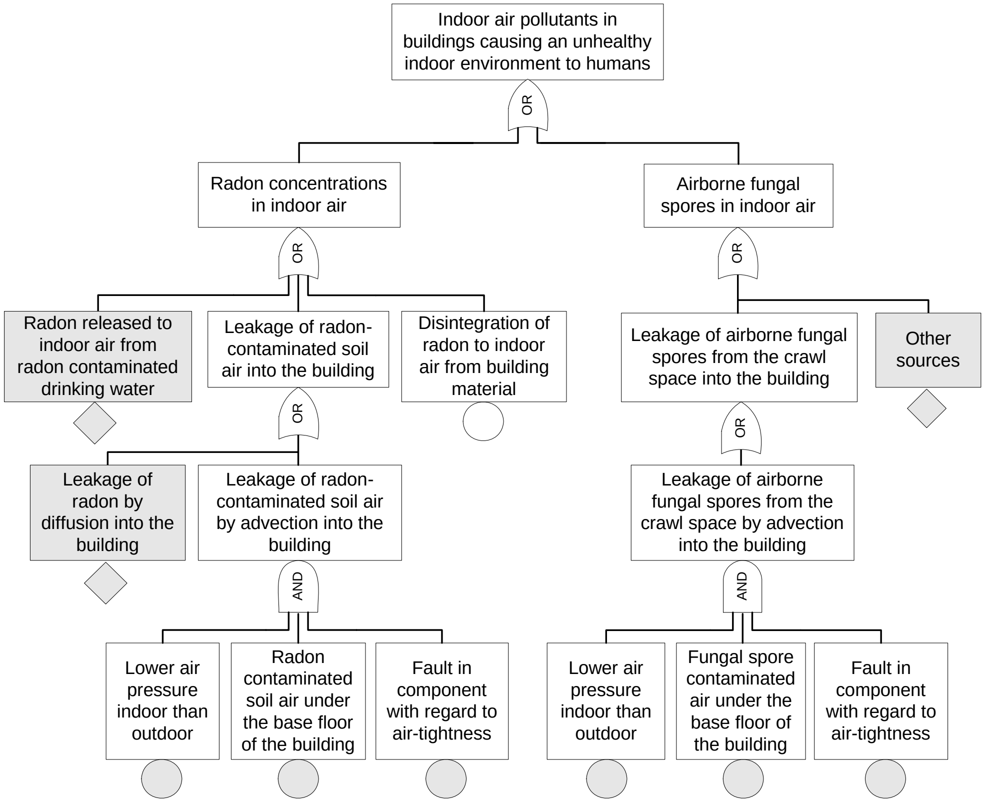


Figure 5.6 Events (marked with shaded colour) in the original fault tree which are reduced or changed in properties.

Three events have been disregarded from the fault tree. The event "Radon released….from drinking water" is not of interest in this analysis and therefore considered to have the probability $p_f = 0$ of occurrence. The event "Leakage…by diffusion" was removed from the tree, since the contribution can be neglected by using a concrete slab on the ground, i.e. the probability of occurrence is $p_f = 0$. The event "Other sources" concerning airborne fungal spores has not been considered at all, since the pollutant is only used in the tree as an example. The three input events passing through the AND-gates have been reduced to basic events to manually evaluate the fault tree easier. Uncertainty incorporated in the reduction can be handled using structural reliability analysis, since several random variables can be considered in a single basic event. The fault tree in Figure 5.6 is reorganised in accordance with Figure 5.7, where the fault tree events are characterised with capital letters and numbers when looking for minimal cut sets. The basic events (symbolised with circles) are characterised with B, fault events (symbolised with rectangles) with E, the sub-top events with ST, and the top event is symbolised with T.

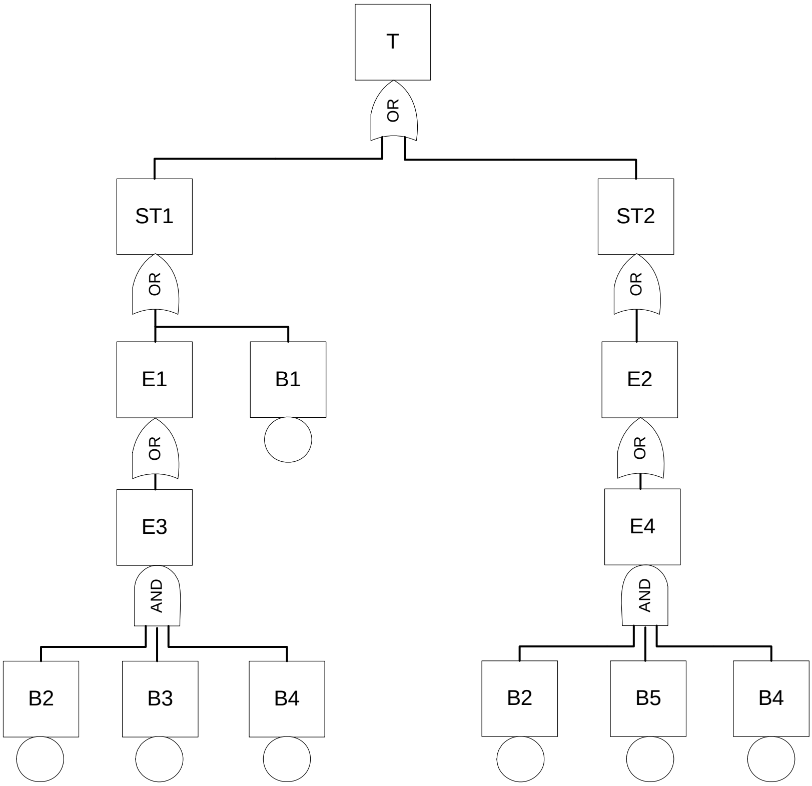


Figure 5.7 Reduced tree according to Figure 5.6 where the events are characterised with letters and numbers.

To determine the minimal cut sets of the fault tree, the events are first translated to its equivalent Boolean equations from the top of the tree down to the bottom and the basic events. Here, the basic events B2 and B4 are considered to be common-cause failures, though this may not be correct and has to be analysed separately when performing an analysis with several environmental impacts.

$$\begin{aligned}&T=ST1\cup ST2\\&ST1=E1\cup B1\\&E1=E3=B2\cap B3\cap B4\\&ST2=E2=E4=B2\cap B5\cap B4\end{aligned} \tag{5.1}$$

The next step is to express each fault event in terms of the basic events starting from the bottom and up in the tree. To eliminate any mistakes caused of the similarity between the symbols of union and intersection, union will be marked with + and intersection with $\cdot$.

$$\begin{aligned}&T=B1+(B2\cdot B3\cdot B4)+(B2\cdot B5\cdot B4)=\\&\ \ =B1+B2\cdot B4\cdot(B3+B5)\end{aligned} \tag{5.2}$$

The top event T is the union of the three minimal cut sets B1, (B2 B3 B4) and (B2 B5 B4) where the two latter are the intersection of a combination of three basic events each. The top event will occur if B1 occurs or B2 and B4 occur in combination with B3 and/or B5.

In chapter 3, the undesirable indoor event Y_{env}, was defined as a function of the environmental load q_{env} together with the design and construction of the building component, denoted D_{env}. In the case of the foundation in this chapter, the environmental load q_{env} includes disintegration of radon from building material q_{B1}, radon contaminated soil air under the building q_{B3}, and fungal spore contaminated air under the base floor of the building q_{B5}. The variables possible to influence during the building process include the event B2, the pressure difference Δp, and the event B4, fault in component with regards to air-tightness, i.e. the occurrence of cracks and narrow openings with an area A.

$$Y_{\mathrm{env}}=f\left(q_{\mathrm{B1}},q_{\mathrm{B3}},q_{\mathrm{B5}},\Delta p,A\right) \tag{5.3}$$

However, the undesirable indoor event cannot be immediately compared with the dose-response relationship, since the measurable units differ. Instead, the sub-top events have to be separately evaluated in the quantitative evaluation and compared with the dose-response relationship of interest.

$$Y_{\mathrm{ST1}}=f\left(q_{\mathrm{B1}},q_{\mathrm{B3}},\Delta p,A\right) \tag{5.4}$$

$$Y_{\mathrm{ST2}}=f\left(q_{\mathrm{B5}},\Delta p,A\right) \tag{5.5}$$

If measures of probabilities instead of probability density functions are used, the probability of the undesirable indoor event can be calculated without regarding the cause to the unhealthy indoor environment. However, the estimated probability cannot be compared with any threshold value or dose-response relationship.

5.6 Quantitative evaluation of the fault tree

The occurrence of the sub-top event ST1, concerning radon concentrations in indoor air, depends on the occurrence of the basic event B1, or the intersection of the basic events B2, B3 and B4, i.e. the fault event E3. However, since the fault tree was reduced every basic event may depend on several random variables and by using structural reliability analysis (SRA), functions can be used to express the event space and the relationship between the set of random variables.

5.6.1 Definition of the basic event B1

The basic event B1 is defined as "Disintegration of radon to indoor air from building material". The contribution of radon from a surface, e.g. building material or rock, can be calculated using equation (4.4) in chapter 4. With this equation, the basic event B1 can be described as a set of random variables logically connected with a function describing the condition under which the event will happen where the random variables of interest can be expressed by probability density functions.

$$G(\mathbf{Y}_{\mathrm{B1}}) = \frac{1}{\lambda + n} \cdot \frac{E \cdot F}{V} \qquad [\mathrm{Bq/m^3}] \qquad (5.6)$$

where

- λ disintegration constant for radon, 7,55 x 10^{-3} h^{-1}
- n amount of air changes in the volume, ach/h
- E exhalation of radon, Bq/m^2h
- F surface area, m^2
- V volume, m^3

The random variable of interest is the exhalation of radon, *E*, from different material. To estimate a probability density function and statistical parameters for the basic event, measurements on the exhalation of radon from different surfaces are needed. However, the contribution to the total radon concentration indoors from the concrete included in the analysed foundation with a slab can be considered to be very small compared to the contribution from radon in the soil, and the basic event is therefore neglected in estimating the sub-top event.

5.6.2 Definition of the fault event E3

The fault event E3, "Leakage of radon-contaminated soil air by advection into the building", depends on the intersection of the basic events B2, B3 and B4. Radon concentration indoors caused by leakage of radon contaminated soil air through cracks and narrow openings in the building components, and regarding the effect of radon disintegration or ventilation in the soil layer, can be calculated using the equations (4.2) and (4.3) in chapter 4.

$$C_{\text{build}} = C_{\max} \cdot \frac{\lambda}{(n+\lambda)} \cdot \frac{R}{V_{\text{build}}(\ell + \lambda)} \qquad [\text{Bq/m}^3] \qquad (5.7)$$

$C_{\max}$ radon concentration in the air volume under the building, Bq/m^3
ℓ air changes in the building, ach/h
λ disintegration constant for Rn-222, h^{-1} ($7{,}55 \times 10^{-3}\ h^{-1}$)
V_{build} building volume indoors, m^3
n air changes in the volume under the base floor, ach/h

R is the amount of soil air leaking into the building given by:

$$R = \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t} \qquad [\text{m}^3/\text{s}] \qquad (5.8)$$

η dynamic viscosity, Ns/m^2
Δp pressure difference, Pa
t depth of flow through, m
l length of flow through, m
w crack width, m

The disintegration constant, λ, is smaller than the air changes in the building, ℓ, and, according to Clavensjö and Åkerblom (2004), can be often neglected. The function for the vector $\mathbf{Y}_{E3}$, expressing the relationship between the random variables, is given by:

$$G(\mathbf{Y}_{E3}) = C_{\max} \cdot \frac{\lambda}{(n+\lambda) \cdot V_{\text{build}} \cdot \ell} \cdot \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t} \qquad [\text{Bq/m}^3] \qquad (5.9)$$

The event E3 is the intersection, i.e. the product, of the basic events B2, B3 and B4. The random variables of interest in the analysis are the pressure difference between indoor and outdoor air, Δp, the maximal radon concentration in soil air, $C_{\max}$, and the width and extension of cracks and narrow openings in the base floor, depending, e.g. on material properties and work performance.

5.6.3 *Estimation of the pressure difference,* Δp

A difference in air pressure can arise because of, e.g. a difference in temperature between indoor and outdoor air, type of ventilation in the building, wind pressure, or a combination thereof. The analysed building is self-draught ventilated and the pressure difference in the analysis will only depend on the difference in temperature between indoor and outdoor air given by (Nevander and Elmarsson, 1994):

$$\Delta p = g \cdot (\rho(T_\mathrm{u}) - \rho(T_\mathrm{i})) \cdot h \qquad [\mathrm{N/m^2}] \qquad (5.10)$$

where

$$\rho(T) = 1{,}29 \cdot \frac{273}{273 + T} \qquad (5.11)$$

g acceleration of gravity, $\mathrm{m/s^2}$
ρ air density, $\mathrm{kg/m^3}$
T temperature, °C
h building height, m

The acceleration of gravity, g, the building height, h, and the temperature indoors, T_i, are considered to be deterministic values, while the temperature outdoors, T_u, is a random variable represented by a probability density function and described by the statistical parameters mean, m, and standard deviation, s.

Data of the outdoor temperature is collected from a report by Rosén et al (1997), where radon concentrations at two different locations, Slaka and Börje, close to the municipality of Linköping, were recorded during two years of time. Several other parameters were also recorded, including the outdoor temperature. The data used is from the location Slaka. Data available and used is from January 1, 1994 to December 28, 1994, with missing data from July 15 to August 5. The temperature was measured 96 times a day in January and 24 times a day the remainder of the year and it is assumed that every observation was measured independently. The mean outdoor temperature per day has been calculated and sorted in ascending order illustrated in the histogram in Figure 5.8. The cause of the lower frequency in the histogram between daily mean values of 6 – 10°C is unclear. It is, however, unlikely to be caused by lack of data during a short period in the summer, since these daily mean values ought to be higher.

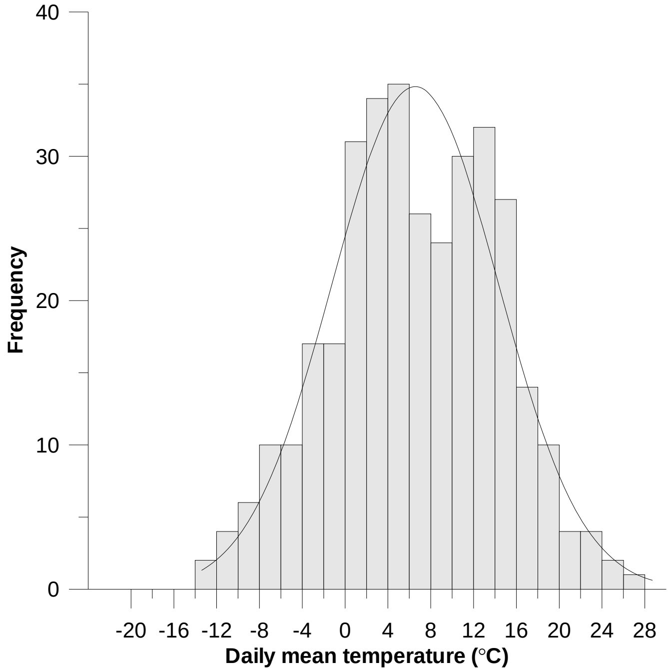


Figure 5.8 Histogram and normal probability density function for daily mean temperature outdoors at Slaka during 1994.

The data is tested for normality using @Risk (2004) distribution fit giving the P-P-plot in Figure 5.9. It is assumed that the mean outdoor temperature at Slaka is normal distributed with the statistical parameters mean m = 6,6°C and standard deviation s = 7,8°C. The temperature indoors is considered constant over the entire year with T_i = 20,9°C, collected from the ELIB-report as a mean value of the temperature indoors in single-family dwellings (Norlén and Andersson, 1993). The difference in height between the spots of air leakage in the building is approximated to h = 2,5 m and the acceleration of gravity g = 9,81 m/s^2.

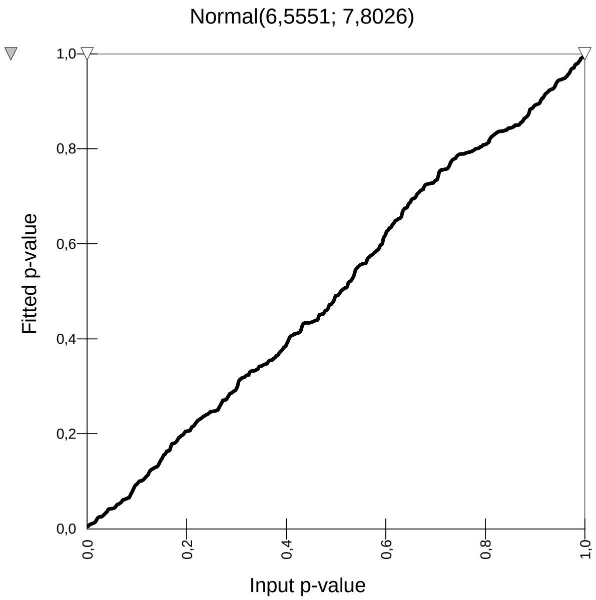


Figure 5.9 *Normal distribution P-P-plot for the daily mean temperature outdoors at Slaka during 1994.*

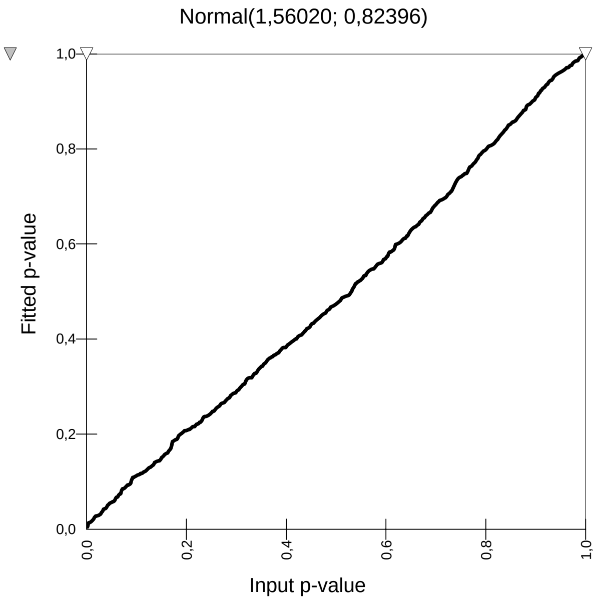


Figure 5.10 *Normal distribution P-P-plot from simulation of difference in air pressure Δp.*

The difference in pressure Δp is simulated using @Risk (2004) and the Monte Carlo simulation. The input random variable T_u is defined with the distribution N(6,6; 7,8) (°C), and the other inputs are considered deterministic. The simulation is made using an auto-stop when the mean and standard deviation converge between the iterations. The simulation stops after 700 iterations and the P-P-plot of the pressure difference being normally distributed is shown in Figure 5.10. It is assumed that the pressure difference between indoor and outdoor air is approximately normally distributed N(1,53; 0,86) (Pa) and the estimated coefficient of variation v = 0,56.

5.6.4 Estimation of the radon concentration in soil air, C_{max}

The report by Rosén et al (1997) provides the data for the radon concentration in soil air. The radon concentration in soil air was recorded during a two-year period at two different locations, Slaka and Börje. The data used here is from Slaka and was recorded between November 1993 and November 1995 in glaciofluvial sand at three different depths, of 0,7 meter, 1,0 m and 1,5 m. The measurements used are from 1,0 m, Figure 5.11, since the radon classification depending on risk area, is based on this depth.

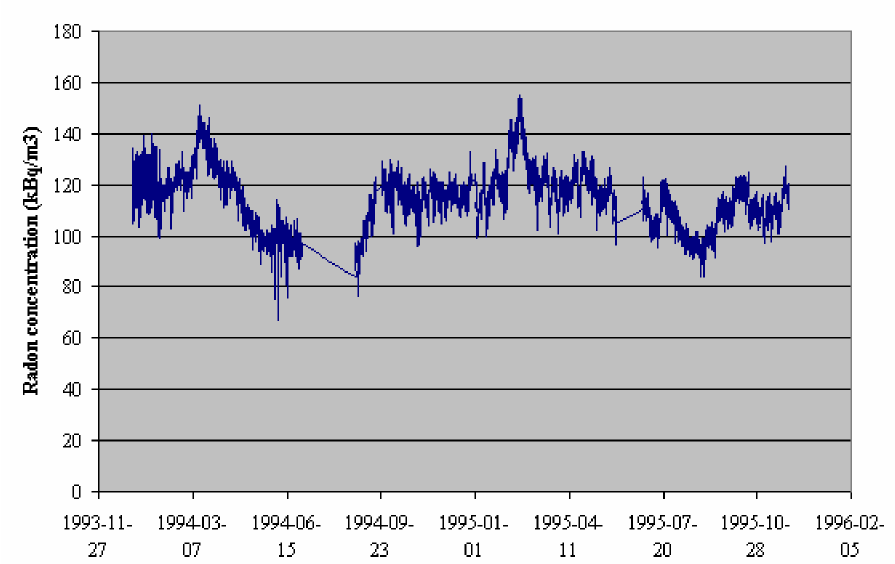


Figure 5.11 Radon concentration at 1,0 m depth in soil at Slaka from November 1993 to November 1995.

Data was recorded automatically from instruments permanently installed in the ground. In 1994 a stroke of lightning hit the equipment resulting in considerable damage. Therefore, almost two months of recording is missing from that year. In June 1995 a calculated stop in measurements was made from June 1 to June 26. The data used was measured 24 times per day between December 1, 1994 to November 30, 1995, and the daily mean values are estimated, see appendix C. The assumption is that every observation was made independently. (Note that the temperature data are from the year before, since data were unavailable this year.) The data is sorted in ascending order to form a histogram on radon concentration in soil air at 1,0 meter depth, Figure 5.12.

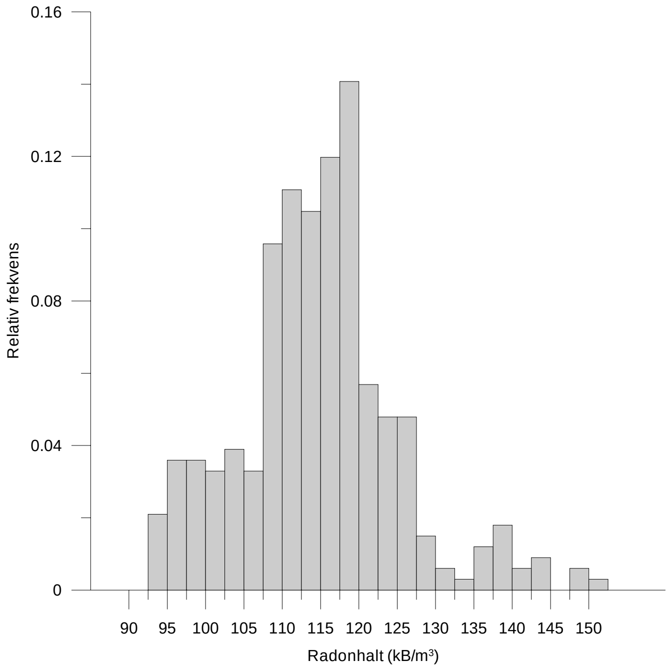


Figure 5.12 Histogram of observed radon concentration in soil air at 1,0 m depth at Slaka.

The measurements missed during June would, if present, be sorted around 110 Bq/m^3, giving a minor adjustment of the peak to the right. The mean value of the observations' daily mean values m = 114,72 kBq/m^3 and standard deviation s = 10,37. The spread is estimated using the coefficient of variation:

$$v = \frac{s}{m} = \frac{10370}{114720} = 0,09 \tag{5.12}$$

The data is tested for normality by comparing the measurements against the calculated values and plotted in a P-P-plot shown in Figure 5.13. The measurements differ slightly from the calculated values.

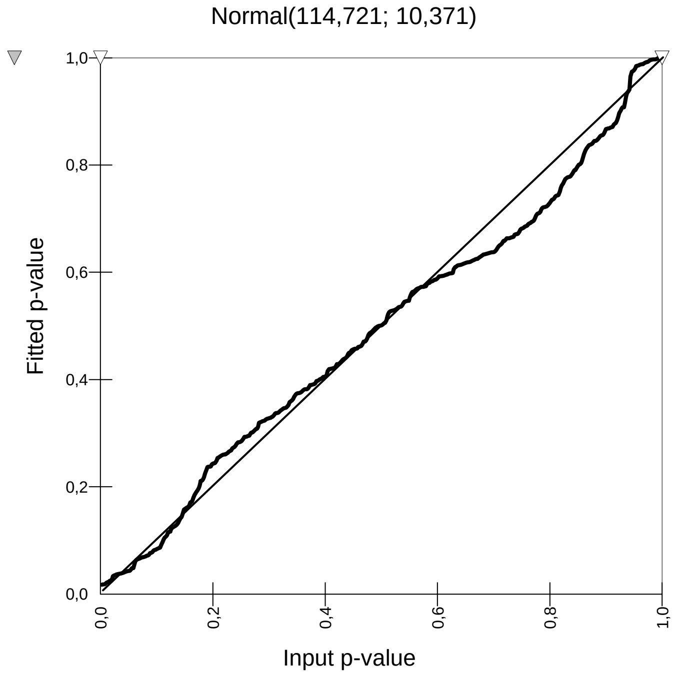


Figure 5.13 Comparison between measurements and calculated values of radon concentrations in soil air with N(114 720, 10 370).

The correctness in the assumption of normality is tested using a chi-square-test and the computer software @Risk.

$$\chi^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i} = 38,60 \tag{5.13}$$

If $\chi^2_\alpha > 38,60$, the hypothesis that the random variable C_{max} is normally distributed is not rejected. According to @Risk χ^2_α = 42,31 (α = 0,001). The level of significance is low. However, transformation of the measurements does not give a better agreement. Therefore, it is assumed that the radon concentration in soil air at 1,0 m depth is approximately normally distributed N(114 720; 10 370) (Bq/m^3), and the estimated coefficient of variation $v = 0,09$.

5.6.5 Estimation of cracks and narrow openings

The basic event B3, "Fault in component with regard to air-tightness", depends on cracks and narrow openings in the base floor and the basic variables width *w*, length *l*, and the depth *t* throughout the component. Narrow openings depend on design and work performance. In this analysis, the number of pipes passing through the base floor, appearance of e.g. floor-wall connections, and the existence of construction joints has to be estimated.

The propagation of cracks depends on, e.g. settlements and material properties. Estimations often have to be made from experience since knowledge about the relationship between the variables is insufficient, e.g. the relative humidity (RH) affects the propagation of cracks, which in the case of a concrete slab on the ground makes it important whether the insulation is placed above or below the concrete slab. In a concrete slab on the ground, narrow openings mainly occur where pipes pass the slab. As mentioned in chapter 4, Nielson et al (1997) found that undisturbed lead-throughs did not increase the advection, however, the slab will be affected by, e.g. settlements, and the pipe-slab joints will be disturbed over time by concrete-to-pipe bond breakage. The widths and lengths of the openings around lead-throughs and from the settlements have to be approximated. The total amount of cracks and narrow openings through the base floor is given by:

$$\sum w^3 \cdot l = w_{\mathrm{sh}}^3 \cdot l_{\mathrm{sh}} + w_{\mathrm{settl}}^3 \cdot l_{\mathrm{settl}} + w_{\mathrm{pipe}}^3 \cdot l_{\mathrm{pipe}} \tag{5.14}$$

The crack propagation caused by shrinkage in the concrete slab occurs when the tensile strength in the concrete is exceeded. The width of the cracks is reduced with reinforcement that distributes the stress causing more cracks with less width. The mean width w_{m} of cracks in the concrete slab can be estimated according to the Swedish code BBK 04.

$$w_{\mathrm{m}} = \nu \cdot \frac{\sigma_{\mathrm{s}}}{E_{\mathrm{s}}} \cdot s_{\mathrm{rm}} \tag{5.15}$$

$$\nu = 1 - \frac{\beta}{2,5 \cdot \kappa_1} \cdot \frac{\sigma_{\mathrm{sr}}}{\sigma_{\mathrm{s}}} \quad , \quad \nu \geq 0,4 \tag{5.16}$$

where

E_s modulus of elasticity of reinforcement (E_s = 200 GPa)
s_{rm} mean value of distance between cracks ($s_{rm} = s$ for welded mesh reinforcement)
β coefficient considering long term loads (β = 0,5)
κ_1 coefficient considering reinforcement bond (κ_1 = 1,6 for welded mesh reinforcement)
v coefficient considering contribution of tensile strength in concrete between cracks
σ_s the reinforcement tensile stress

The reinforcement tensile stress σ_{sr} is the stress present immediately after crack propagation and is proportional to the ultimate concrete tensile strength f_{ct}.

$$\sigma_{sr} = f_{ct} \cdot \frac{E_s}{E_c} \tag{5.17}$$

where E_c is the modulus of elasticity of the concrete. The reinforcement tensile strength σ_s is equal to the product of the shrinkage strain and the modulus of elasticity of the reinforcement. Equation (5.15) can be rewritten as:

$$w_m = \left(1 - 0{,}125 \cdot \frac{f_{ct} \cdot E_s}{E_c} \cdot \frac{1}{E_s \cdot \varepsilon_{sh}}\right) \cdot \frac{E_s \cdot \varepsilon_{sh}}{E_s} \cdot s \tag{5.18}$$

$$w_m = \left(1 - 0{,}125 \cdot \frac{f_{ct}}{E_c \cdot \varepsilon_{sh}}\right) \cdot \varepsilon_{sh} \cdot s \tag{5.19}$$

The shrinkage ε_{sh} can be approximated by the basic drying shrinkage strain $\varepsilon_{cd,\infty}$ for concrete given in Eurocode 2 that also considers the relative humidity (RH):

$$\varepsilon_{cd,\infty} = 0{,}85 \cdot \left[\left(220 + 110 \cdot \alpha_{ds1}\right) \cdot \exp\left(-\alpha_{ds2} \cdot \frac{f_{cm}}{f_{cmo}}\right)\right] \cdot 10^{-6} \cdot \beta_{RH} \tag{5.20}$$

$$\beta_{RH} = -1{,}55 \cdot \left[1 - \left(\frac{RH}{RH_0}\right)^3\right] \tag{5.21}$$

where:

f_{cm} mean compressive strength (MPa)
f_{cmo} = 10 MPa
α_{ds1} coefficient which depends on type of cement
= 3 for slowly hardening cement
= 4 for normal or rapidly hardening cement
= 6 for rapidly hardening high-strength cement
α_{ds2} coefficient which depends on type of cement
= 0,13 for slowly hardening cement
= 0,12 for normal or rapidly hardening cement
= 0,11 for rapidly hardening high-strength cement
RH the ambient relative humidity (%)
RH_0 = 100 %

This gives for normal hardening cement:

$$\varepsilon_{cd,\infty} = 870 \cdot \exp\left(-0,012 \cdot f_{cm}\right) \cdot 10^{-6} \cdot \left[1 - \left(\frac{RH}{100}\right)^3\right] \tag{5.22}$$

The definitions of the random variables for concrete and reinforcement are collected from the Probabilistic Model Code compiled by the Joint Committee on Structural Safety (JCSS, 2001). The tensile strength, f_{ct}, for concrete is given by:

$$f_{ct} = 0,3 \cdot f_c^{2/3} \qquad \text{[MPa]} \tag{5.23}$$

where f_c is the in situ compressive strength for concrete. Tests of the in situ compressive strength have yielded f_c = 40 MPa for concrete class K30 (Betonghandboken – Arbetsutförande, 1992), which according to JCSS is lognormal distributed with a coefficient of variation v = 0,06. According to JCSS, the tensile strength is lognormal distributed with a coefficient of variation v = 0,3. The modulus of elasticity E_c for concrete is given by:

$$E_c = 10,5 \cdot f_c^{1/3} \cdot \left(\frac{1}{1 + \beta_d \cdot \varphi(t,\tau)}\right) \qquad \text{[GPa]} \tag{5.24}$$

where β_d is the ratio of the permanent load to the total load, usually 0,6 – 0,8. The creep coefficient $\varphi(t, \tau)$ is assumed to be deterministic and depends, i.a. on RH. According to JCSS, the modulus of elasticity is lognormal distributed with a coefficient of variation ν = 0,15. This gives with β_d = 0,8 and $\varphi(t, \tau)$ = 2 (RH = 75 %, BBK 04):

$$E_c = \frac{10,5}{2,6} \cdot f_c^{1/3} \tag{5.25}$$

Calculating the coefficient ν according to equation (5.16) gives ν ≈ 0,99; the coefficient will therefore be approximated as equal to 1. The relationship between crack width and shrinkage strain is then given by:

$$w_m = \varepsilon_{sh} \cdot s \tag{5.26}$$

where

$$\varepsilon_{sh} = 870 \cdot \exp\left(-0,012 \cdot f_{cm}\right) \cdot 10^{-6} \cdot \left[1 - \left(\frac{RH}{100}\right)^3\right] \tag{5.27}$$

The random variable f_{cm} is defined with the lognormal distribution LN(40; 2,4) (MPa), and the other inputs are considered deterministic. The relative humidity when the insulation is placed below the slab is *RH* = 60 % and the distance between reinforcement bars *s* = 150 mm.

5.6.6 Estimating the undesirable indoor event Y_{env}

The sub-top event ST1 "Radon concentrations in indoor air" occur if event B1 or event E1 = E3 = B2B3B4 occur. The relationship between the events is given by the union of the functions of the event B1 and the event E1:

$$G(\mathbf{Y}_{ST1}) = G(\mathbf{Y}_{B1}) \cup G(\mathbf{Y}_{E1}) = \left(\frac{1}{\lambda + n} \cdot \frac{E \cdot F}{V}\right) + \left(\frac{C_{max} \cdot \lambda}{(\lambda + n) \cdot V_{build} \cdot \ell} \cdot \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t}\right) \tag{5.28}$$

The basic event B1, regarding the exhalation of radon from the building material will be neglected in the analysis, since the contribution of radon from the building material in the present case can be assumed to be negligible compared to the contribution of radon from soil leaking into the building. Hence, the analysis will consider the sub-top event ST1 as equal to the event E1, and the undesirable indoor event Y_{env}.

$$G(\mathbf{Y}_{\text{env}}) = \frac{C_{\max} \cdot \lambda}{(\lambda + n) \cdot V_{\text{build}} \cdot \ell} \cdot \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t} \qquad [\text{Bq/m}^3] \qquad (5.29)$$

The random variables have been defined and the deterministic variables have to be established. The building volume is approximated using an indoor height of 2,4 m, to V = 264 m^3, giving the air changes indoors ℓ = 0,5 ach/h, according to the Swedish Building Regulation. The dynamic viscosity η = 18,1 x 10^{-6} Ns/m^2 in an air temperature of 20°C (Nevander and Elmarsson, 1994). The disintegration constant for radon λ = 7,55 x 10^{-3} h^{-1}.

The amount of air changes under the base floor of the building, n, can be calculated for each type of air volume. In the case of a concrete slab on the ground, the amount of air changes depends on the volume and the porosity of the fill, and the amount of air leakage into the building R, since the soil is assumed to be unventilated under the building:

$$n = \frac{R}{V_{\text{fill}} \cdot p} \qquad [\text{h}^{-1}] \qquad (5.30)$$

V_{fill} volume of fill and drainage layer under the building, m^3
p soil porosity
R amount of soil air leaking into the building, m^3/s

The building is founded on a concrete slab on the ground with a 150 mm macadam layer that is assumed to be extended 1,0 m outside the concrete slab and with a porosity p = 0,4 (40 %). The fill volume becomes V_{fill} = 24 m^3. The amount of air leakage into the building has to be estimated.

Estimating cracks from shrinkage by incorporating deterministic values in equation (5.14) gives w_{m} = 0,06 mm. The length of the cracks from shrinkage (l = 1135 m) is an approximation made where cracks are present between the reinforcement bars in both directions at the part of the slab that is 100 mm thick, i.e. the edge-supporting beams excluded. Cracks from settlements in the ground are approximated with a crack propagating in the short direction (l = 8,0 m) of the slab with a width w = 1,0 mm. Openings around pipes passing through the slab are estimated to width w = 0,5 mm and the length l = 0,8 m (two pipes with ϕ 110 mm).

$$\sum w^3 \cdot l = (0{,}06 \cdot 10^{-3})^3 \cdot 1135 + (1{,}0 \cdot 10^{-3})^3 \cdot 8 + (0{,}5 \cdot 10^{-3})^3 \cdot 0{,}8 = 8{,}3 \cdot 10^{-9} \ \text{m}^3$$

$$R = \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t} = \frac{1{,}53 \cdot 8{,}3 \cdot 10^{-9}}{12 \cdot 18{,}1 \cdot 10^{-6} \cdot 0{,}1} \cdot 3600 = 2{,}12 \ \ \mathrm{m^3/h} \tag{5.31}$$

The undesirable indoor event is estimated with the following random variables: radon concentration in soil air $C_{\max}$ N(114 720; 10 370) (Bq/m^3), the pressure difference Δp N(1,53; 0,86) (Pa), and the crack propagation from shrinkage where the concrete compressive strength f_c is LN(40; 2,4) (MPa), together with deterministic values on the other variables. However, to avoid negative radon concentrations, which theoretically could occur due to a negative pressure difference in the left tail, the distribution of the pressure difference will be truncated to zero in the left tail before the simulation. The Monte Carlo simulation (@Risk, 2004) is performed using 10 000 iterations to estimate the undesirable indoor event Y_{env}, Figure 5.14.

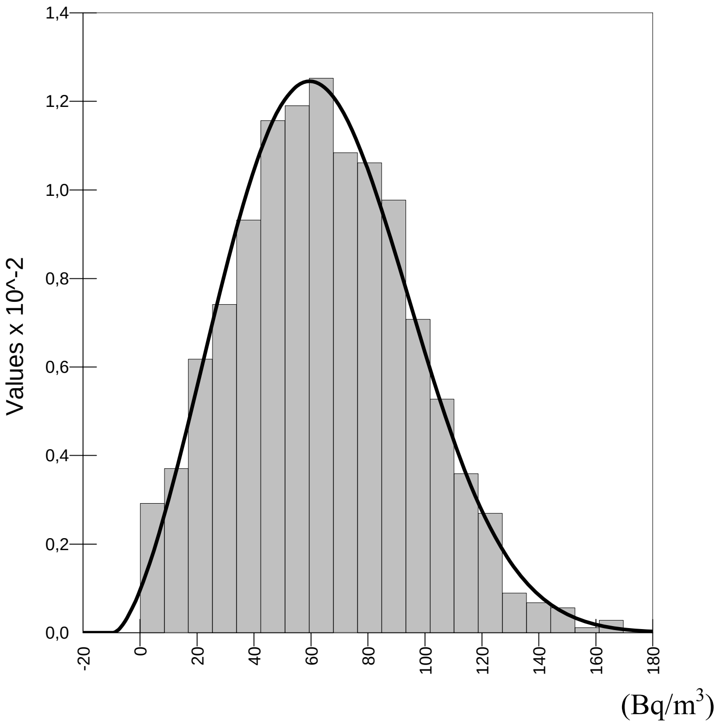


Figure 5.14 *Histogram of the simulated undesirable indoor event Y_{env} "Radon concentrations in indoor air" on high risk area C_{max} = 114 720 Bq/m^3.*

The distribution fit reveals the simulated data for radon concentration indoors can be described by a lognormal distribution, corresponding to the results from the epidemiological study (Pershagen et al, 1993). The simulation gives the statistical parameters mean m = 64 Bq/m^3 and standard deviation s = 31 Bq/m^3. It is assumed that the radon concentration indoors, i.e. the undesirable indoor event Y_{env}, is approximately lognormal distributed LN(64; 31) (Bq/m^3).

5.7 Risk estimation

5.7.1 Definition of random variables

Risk is estimated under the assumption of living in the analysed single-family dwelling founded on high risk ground from a radon concentration perspective. The undesirable indoor event Y_{env} should be compared with the dose-response relationship X_{env}. From chapter 3, risk is defined as violating the limit state function given by Eq. 3.8:

$$M_{\text{env}} = G(X_{\text{env}}, Y_{\text{env}}) = X_{\text{env}} - Y_{\text{env}} < 0$$

The undesirable indoor event Y_{env} can be described either by the equation (5.29) or by the lognormal distributed probability density function LN(64; 31) (Bq/m^3) estimated in the previous section. The lognormal probability density function of the random variable Y_{env} is given by:

$$f_{Y_{\text{env}}}(x) = \frac{1}{\sqrt{2\pi} \cdot x \cdot \varepsilon} \cdot e^{-\frac{1}{2}\cdot\left(\frac{\ln x - \lambda}{\varepsilon}\right)^2} \quad , \qquad 0 \leq x < \infty \tag{5.32}$$

where

$$\lambda = \ln\left[\frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}}\right] \quad , \qquad \varepsilon = \sqrt{\ln\left[\frac{\sigma^2 + \mu^2}{\mu^2}\right]} \tag{5.33}$$

The dose-response relationship between the exposure of radon concentrations in dwellings and the risk of lung cancer is linear, with an increase in risk of 3,4 % per 1000 Bq/m^3 and year. The probability density function of a linear distribution function is normally described by a uniform distribution. However, estimating the probability of small ranges regardless of dose gives the same frequency of the population suffering from lung cancer. This does not seem correct, since the sensitivity among people ought to show more variation in response conditional to the dose. A normal or lognormal distribution would probably be more accurate in describing the variation in sensitivity of the population. However, since the linear dose-response relationship is the generally accepted distribution function, the uniform distribution of the probability density function will be used from now on in this work. The probability density function is given by:

$$f(x) = \begin{cases} \dfrac{1}{b-a} & , \quad a < x < b \\ 0 & , \quad \text{elsewhere} \end{cases} \tag{5.34}$$

The lower limit a = 0. The upper limit of the probability density function can be expressed in different ways depending on time of radon exposure and what risk one wants to calculate. The annual risk gives $b = 1/0{,}034 \times 10^{-3}$ per Bq/m^3.

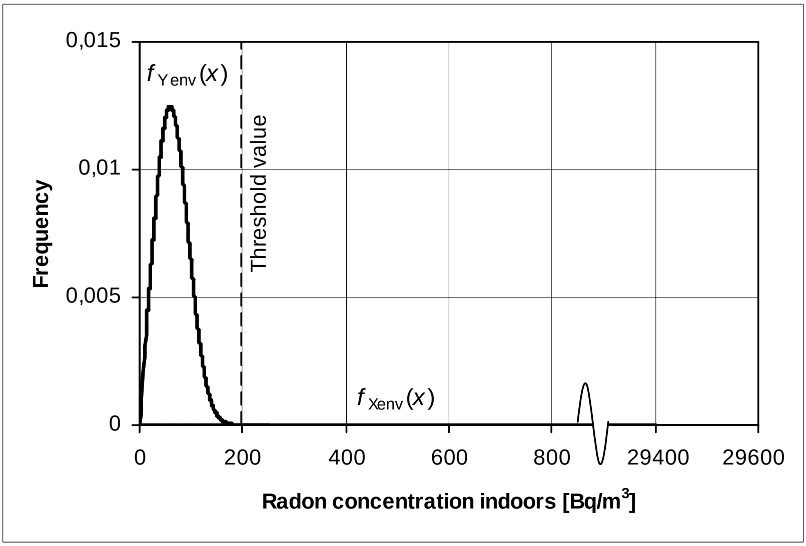


Figure 5.15 *The probability density function f_{Yenv} of the undesirable indoor event Y_{env} radon concentration indoors on a high risk area (C_{max} = 114 720 Bq/m^3) and the probability density function of the dose-response relationship f_{Xenv}.*

The probability density function f_{Yenv} of the undesirable indoor event and the probability density function f_{Xenv} of the annual dose-response relationship are compared in Figure 5.15. The probability density function of the dose-response relationship is a straight line with a frequency of $0{,}034 \times 10^{-3}$ making it difficult to visualise together with the undesirable indoor event.

When X_{env} and Y_{env} are statistically independent, Eq. 3.9 from chapter 3 obtains the total failure probability p_{f} :

$$p_{\mathrm{f}} = P(X_{\mathrm{env}} - Y_{\mathrm{env}} < 0) = \int_{0}^{\infty} F_{\mathrm{X_{env}}}\left(x\right) f_{\mathrm{Y_{env}}}\left(x\right) dx$$

However, the integration over the failure domain can be a difficult task to perform analytically and the comparison is often made using a simulation or FOSM.

5.7.2 Risk estimation using simulation

The estimation of risk, i.e. the probability of violating the limit state function can be made using the Monte Carlo simulation and Eq. 3.8.

$$M_{\mathrm{env}} = G(X_{\mathrm{env}}, Y_{\mathrm{env}}) = X_{\mathrm{env}} - Y_{\mathrm{env}} < 0$$

The random variables are compared using the assumed probability density function f_{Xenv} of the dose-response relationship, with equation (5.29) describing the undesirable indoor event Y_{env}.

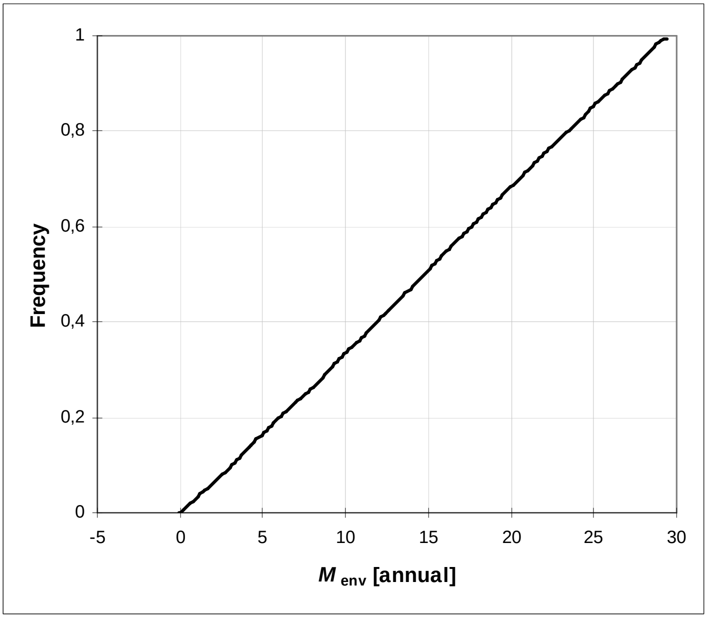


Figure 5.16 *The cumulative distribution function of the limit state function when the undesirable indoor event is compared with the dose-response relationship.*

The comparison is made using @Risk, and the resulting cumulative distribution function when the dose-response relationship is based on the annual risk is shown in Figure 5.16. According to the @Risk calculations, the total failure probability p_f = 0,0025, i.e. the annual probability of suffering from illness living in the analysed single-family dwelling.

The failure/success criterion used is the threshold value 200 Bq/m^3, as stipulated in the Swedish Building Regulations (BFS 2002:19), to not be exceeded. The undesirable indoor event is compared with the threshold value as failure criteria, Figure 5.17.

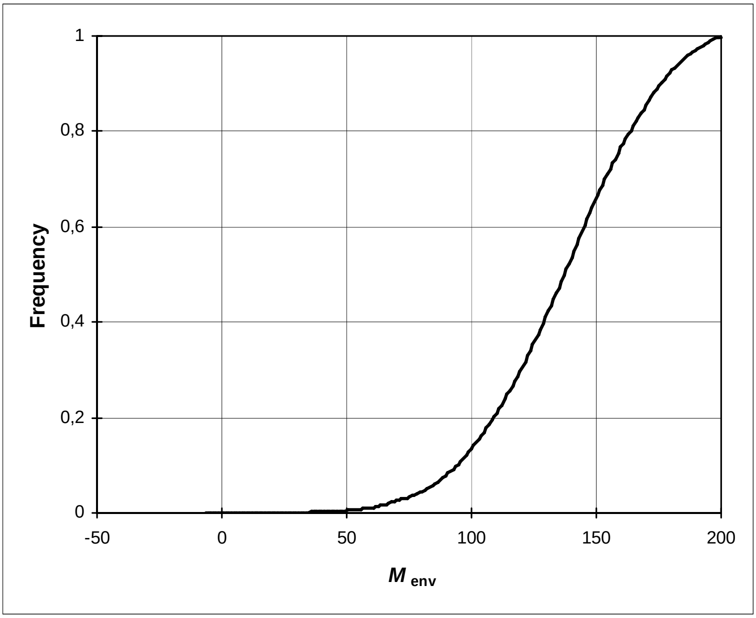


Figure 5.17 Cumulative distribution function of the limit state function when X_{env} is equal to the threshold value.

Calculations in @Risk yield the probability p_f = 0,0001 = 0,1 x 10^{-3} that the indoor radon concentration will exceed the threshold value in the analysed single-family dwelling.

5.7.3 Risk estimation using FOSM

The estimation of risk can be made using the first-order second-moment theory (FOSM). The limit state function separating the safe region from the failure region is given by:

$$M_{\text{env}} = G\left(X_{\text{env}}, Y_{\text{env}}\right) = X_{\text{env}} - Y_{\text{env}} = 0 \tag{5.35}$$

The calculations can be performed using either the threshold value to estimate the probability to exceed this value, or the probability density function describing the random variable X_{env}. To simplify the calculations, X_{env} is only considered using the threshold value:

$$X_{\text{env}} = 200 \text{ Bq/m}^3 \tag{5.36}$$

The undesirable indoor event Y_{env} is given by:

$$Y_{\text{env}} = \frac{C_{\max} \cdot \lambda}{(\lambda + \dfrac{R}{V_{\text{fill}} \cdot p}) \cdot V_{\text{build}} \cdot \ell} \cdot \frac{\Delta p}{12\eta \cdot t} \cdot (\sum w^3 \cdot l) \tag{5.37}$$

where Eq. (5.38):

$$\sum w^3 \cdot l = (870 \cdot 10^{-6} \cdot \exp\left(-0{,}012 \cdot f_{\text{cm}}\right) \cdot \left[1 - \left(\frac{RH}{100}\right)^3\right] \cdot s) \cdot l_{\text{sh}} + (w_{\text{se}}^3 \cdot l_{\text{se}}) + (w_{\text{p}}^3 \cdot l_{\text{p}})$$

Substituting the deterministic basic variables defined in Table 5.1 gives the limit state function:

$$\begin{aligned} M_{\text{env}} = 200 - &\frac{C_{\max} \cdot 0{,}00755}{(0{,}00755 + \dfrac{2{,}12}{24 \cdot 0{,}4}) \cdot 264 \cdot 0{,}5} \cdot \frac{\Delta p \cdot 3600}{12 \cdot 18{,}1 \cdot 10^{-6} \cdot 0{,}1} \cdot \\ &\cdot \left[\left(870 \cdot 10^{-6} \cdot \exp\left(-0{,}012 \cdot f_{\text{cm}}\right) \cdot \left[1 - \left(\frac{60}{100}\right)^3\right] \cdot 0{,}150\right)^3 \cdot 1135 + \right. \\ &\left. + ((1.0 \cdot 10^{-3})^3 \cdot 8.0) + ((0.5 \cdot 10^{-3})^3 \cdot 0.8)\right] = 0 \end{aligned} \tag{5.39}$$

$$M_{\mathrm{env}} = 200 - 41{,}5 \cdot 10^{3} \cdot C_{\max} \cdot \Delta p \cdot \left[(1{,}2 \cdot 10^{-9} \cdot \exp(-0{,}036 \cdot f_{\mathrm{cm}})) + 8{,}1 \cdot 10^{-9} \right] = 0 \tag{5.40}$$

Table 5.1 Definition of basic variables

Variable	μ$_i$	σ$_i$	v	Distr.
x_{radon}	200 Bq/m^3	0		D
Δp	1,53 N/m^2	0,86 N/m^2	0,56	N
η	18,1 x 10^{-6} Ns/m^2	0		D
V_{build}	264 m^3	0		D
ℓ	0,5 ach/h	0		D
λ	7,55 x 10^{-3} h^{-1}	0		D
$C_{\max}$	114 720 Bq/m^3	10 370 Bq/m^3	0,09	N
R	2,12 m^3/h	0		D
V_{fill}	24 m^3	0		D
p	0,4	0		D
s	0,150 m	0		D
f_{cm}	40 MPa	2,4 MPa	0,06	LN
RH	60 %	0		D
l_{sh}	1135 m	0		D
w_{se}	1,0 x 10^{-3} m	0		D
l_{se}	8,0 m	0		D
w_{p}	0,5 x 10^{-3} m	0		D
L_{p}	0,8 m	0		D
t	0,1 m	0		D

D = deterministic, N = normal, LN = lognormal distributed

The basic variables described in Table 5.1 by their mean and standard deviation are normalised into the z-coordinated system giving:

$$Z_{C_{\max}} = \frac{C_{\max} - \mu_{C_{\max}}}{\sigma_{C_{\max}}} \tag{5.41}$$

$$Z_{\Delta p} = \frac{\Delta p - \mu_{\Delta p}}{\sigma_{\Delta p}} \tag{5.42}$$

$$Z_{f_{cm}} = \frac{\ln f_{cm} - \mu_{\ln f_{cm}}}{\sigma_{\ln f_{cm}}} \tag{5.43}$$

where:

$$\sigma_{\ln i} = \sqrt{\ln(\nu_i^2 + 1)} \quad \text{and} \quad \nu_i = \frac{\sigma_i}{\mu_i} \tag{5.44}$$

$$\mu_{\ln i} = \ln \mu_i - \frac{1}{2}\ln(\nu_i^2 + 1) = \ln\left[\frac{\mu_i}{\sqrt{\nu_i^2 + 1}}\right] \tag{5.45}$$

If the coefficient of variation ν < 0,25 the following approximations can be made:

$$\sqrt{\nu_i^2 + 1} \approx 1 \quad \text{and} \quad \sqrt{\ln(\nu_i^2 + 1)} \approx \nu_i \tag{5.46}$$

The basic variables are expressed as:

$$C_{max} = \mu_{C_{max}} + Z_{C_{max}} \cdot \sigma_{C_{max}} \tag{5.47}$$

$$\Delta p = \mu_{\Delta p} + Z_{\Delta p} \cdot \sigma_{\Delta p} \tag{5.48}$$

$$f_{cm} = \frac{\mu_{f_{cm}}}{\sqrt{\nu_{f_{cm}}^2 + 1}} \cdot \exp\left(Z_{f_{cm}} \cdot \sqrt{\ln(\nu_{f_{cm}}^2 + 1)}\right) = \mu_{f_{cm}} \cdot \exp(Z_{f_{cm}} \cdot \nu_{f_{cm}}) \tag{5.49}$$

The limit state surface in the normalized z-coordinate system is given by:

$$g(Z) = 200 - \Big[41,5 \cdot 10^3 \cdot (\mu_{C_{max}} + Z_{C_{max}} \cdot \sigma_{C_{max}}) \cdot (\mu_{\Delta p} + Z_{\Delta p} \cdot \sigma_{\Delta p}) \cdot \\ \cdot \Big[(1,2 \cdot 10^{-9} \cdot \exp(-0,036 \cdot \mu_{f_{cm}} \cdot \exp(Z_{f_{cm}} \cdot \nu_{f_{cm}}))) + 8,1 \cdot 10^{-9}\Big]\Big] = 0 \tag{5.50}$$

$$g(Z) = 200 - \Big[41,5 \cdot 10^3 \cdot (114720 + 10370 \cdot Z_{f_{cm}}) \cdot (1,53 + 0,86 \cdot Z_{\Delta p}) \cdot \\ \cdot \Big[(1,2 \cdot 10^{-9} \cdot \exp(-0,036 \cdot 40 \cdot \exp(0,06 \cdot Z_{f_{cm}}))) + 8,1 \cdot 10^{-9}\Big]\Big] = 0 \tag{5.51}$$

$$g(Z) = 200 - \Big[(7,3 + 0,7 \cdot Z_{\mathrm{C_{max}}} + 4,1 \cdot Z_{\Delta \mathrm{p}} + 0,4 \cdot Z_{\mathrm{C_{max}}} \cdot Z_{\Delta \mathrm{p}}) \cdot 10^{9} \cdot \\ \cdot \Big[(1,2 \cdot 10^{-9} \cdot \exp(-1,44 \cdot \exp(0,06 \cdot Z_{\mathrm{f_{cm}}}))) + 8,1 \cdot 10^{-9} \Big] \Big] = 0 \tag{5.52}$$

The design point on the limit state surface is given by:

$$(Z_{\mathrm{C_{max}}}, Z_{\Delta \mathrm{p}}, Z_{\mathrm{f_{cm}}}) = (\alpha_{\mathrm{C_{max}}} \cdot \beta, \alpha_{\Delta \mathrm{p}} \cdot \beta, \ \alpha_{\mathrm{f_{cm}}} \cdot \beta) \tag{5.53}$$

where

$$\alpha_{C_{\mathrm{max}}} = \frac{-\dfrac{\partial g}{\partial Z_{\mathrm{C_{max}}}}}{\sqrt{\left(\dfrac{\partial g}{\partial Z_{\Delta \mathrm{p}}}\right)^2 + \left(\dfrac{\partial g}{\partial Z_{\mathrm{C_{max}}}}\right)^2 + \left(\dfrac{\partial g}{\partial Z_{\mathrm{f_{cm}}}}\right)^2}} \tag{5.54}$$

$$\alpha_{\Delta \mathrm{p}} = \frac{-\dfrac{\partial g}{\partial Z_{\Delta \mathrm{p}}}}{\sqrt{\left(\dfrac{\partial g}{\partial Z_{\Delta \mathrm{p}}}\right)^2 + \left(\dfrac{\partial g}{\partial Z_{\mathrm{C_{max}}}}\right)^2 + \left(\dfrac{\partial g}{\partial Z_{\mathrm{f_{cm}}}}\right)^2}} \tag{5.55}$$

$$\alpha_{\mathrm{f_{cm}}} = \frac{-\dfrac{\partial g}{\partial Z_{\mathrm{f_{cm}}}}}{\sqrt{\left(\dfrac{\partial g}{\partial Z_{\Delta \mathrm{p}}}\right)^2 + \left(\dfrac{\partial g}{\partial Z_{\mathrm{C_{max}}}}\right)^2 + \left(\dfrac{\partial g}{\partial Z_{\mathrm{f_{cm}}}}\right)^2}} \tag{5.56}$$

Differentiating the equation (5.52) regarding the normalised basic variables and substituting Z_{i} with $\alpha_{\mathrm{i}} \cdot \beta$ gives:

$$\frac{\partial g}{\partial Z_{\mathrm{C_{max}}}} = -(0,7 + 0,4 \cdot \alpha_{\Delta \mathrm{p}} \cdot \beta) \cdot 10^{9} \cdot \\ \cdot \Big[(1,2 \cdot 10^{-9} \cdot \exp(-1,44 \cdot \exp(0,06 \cdot \alpha_{\mathrm{f_{cm}}} \cdot \beta))) + 8,1 \cdot 10^{-9} \Big] \tag{5.57}$$

$$\frac{\partial g}{\partial Z_{\Delta p}} = -(4,1 + 0,4 \cdot \alpha_{\mathrm{Cmax}} \cdot \beta) \cdot 10^{9} \cdot \left[(1,2 \cdot 10^{-9} \cdot \exp(-1,44 \cdot \exp(0,06 \cdot \alpha_{\mathrm{f_{cm}}} \cdot \beta))) + 8,1 \cdot 10^{-9} \right] \tag{5.58}$$

$$\frac{\partial g}{\partial Z_{\mathrm{f_{cm}}}} = 0,1 \cdot (7,3 + 0,7 \cdot \alpha_{\mathrm{Cmax}} \cdot \beta + 4,1 \cdot \alpha_{\Delta p} \cdot \beta + 0,4 \cdot \alpha_{\mathrm{Cmax}} \cdot \alpha_{\Delta p} \cdot \beta^{2}) \cdot \left[\exp(0,06 \cdot \alpha_{\mathrm{f_{cm}}} \cdot \beta) \cdot \exp(-1,44 \cdot \exp(0,06 \cdot \alpha_{\mathrm{f_{cm}}} \cdot \beta)) \right] \tag{5.59}$$

Substituting equations (5.57) – (5.59) with the equations (5.54) – (5.56) gives the sensitivity factors α_i for the basic variables. The safety index β is estimated using Newton-Raphson method:

$$\beta_{n+1} = \beta_{n} - \frac{g(\beta)}{\partial g / \partial \beta} \tag{5.60}$$

$$\begin{aligned} \frac{\partial g}{\partial \beta} = &-(0,7 \cdot \alpha_{\mathrm{Cmax}} \cdot \beta + 4,1 \cdot \alpha_{\Delta p} \cdot \beta + 0,8 \cdot \alpha_{\mathrm{Cmax}} \cdot \alpha_{\Delta p} \cdot \beta) \cdot 10^{9} \cdot \\ &\cdot \left[(1,2 \cdot 10^{-9} \cdot \exp(-1,44 \cdot \exp(0,06 \cdot \alpha_{\mathrm{f_{cm}}} \cdot \beta))) + 8,1 \cdot 10^{-9} \right] \\ &+ 0,1 \cdot (7,3 + 0,7 \cdot \alpha_{\mathrm{Cmax}} \cdot \beta + 4,1 \cdot \alpha_{\Delta p} \cdot \beta + 0,4 \cdot \alpha_{\mathrm{Cmax}} \cdot \alpha_{\Delta p} \cdot \beta^{2}) \cdot \\ &\cdot \left[\alpha_{\mathrm{f_{cm}}} \cdot \exp(0,06 \cdot \alpha_{\mathrm{f_{cm}}} \cdot \beta) \cdot \exp(-1,44 \cdot \exp(0,06 \cdot \alpha_{\mathrm{f_{cm}}} \cdot \beta)) \right] \end{aligned} \tag{5.61}$$

The safety index β and the sensitivity factors α_i are solved iteratively by choosing starting values and calculating new values using the equations (5.54 – 5.61). The calculations are made in Excel and accounted for in Appendix C. This gives:

$$\alpha_{\Delta p} = 0,917 \qquad \alpha_{\mathrm{C_{max}}} = 0,398 \qquad \alpha_{\mathrm{f_{cm}}} = -0,013$$

$$\boxed{\begin{aligned} &\beta = 3,62 \\ &P = \Phi(-\beta) = 0,147 \cdot 10^{-3} \end{aligned}}$$

From the sensitivity factors α_i the pressure difference Δp can be concluded to be of importance. However, as previously stated, the crack width is also critical, though is not expressed in the sensitivity factors since only the importance of the concrete quality is reflected.

5.8 Application of the model on available data

In Ljungquist (2003) the model was applied to available data from the municipality of Hudiksvall where measurements of indoor radon concentrations were made on more than 8000 buildings. The data was received from the Environment and Health Protection Office at Hudiksvall, and the foundation design were collected from the archives of building permission documents. From the observations, 167 buildings founded on concrete slab on the ground and ventilated with self-draught, exhaust air-air supply, or exhaust air were selected. The classification of risk area was done using a map where low, normal, and high risk area were illustrated. The buildings are founded on risk area and ventilated according to Table 5.2.

Table 5.2 Radon risk area and ventilation system of the 167 buildings in Hudiksvall founded on concrete slab on the ground.

Risk area	Self-draught ventilation	Exhaust air ventilation	Exhaust air-supply air ventilation	∑
Low risk	1	1	9	11
Normal risk	9	32	72	113
High risk	12	8	23	43
∑	22	41	104	167

The data are plotted in a diagram in Figure 5.18 regarding risk area and independent of ventilation system.

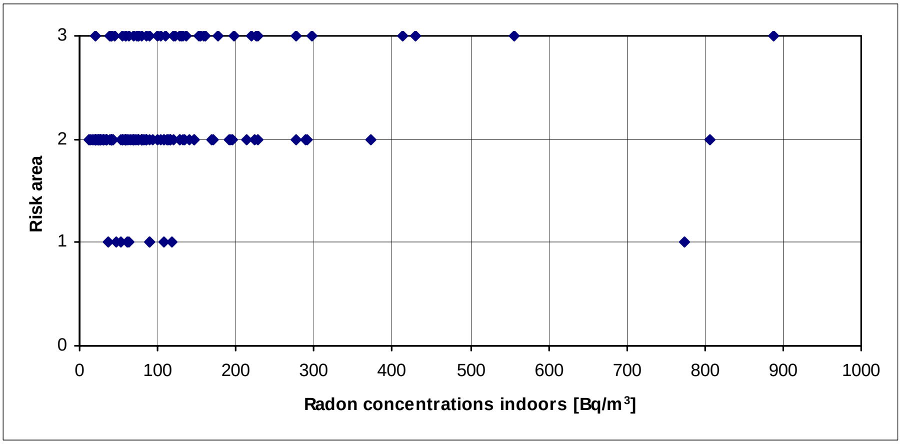


Figure 5.18 Radon indoors in the 167 buildings founded on concrete slab on the ground in Hudiksvall independent of ventilation system. 1 = low risk, 2 = normal risk and 3 = high risk area.

Twenty-eight indoor measurements are only reported to be below 100 Bq/m^3 because of the used measurement method. In this analysis, an approximation is made and the 28 buildings are divided in 4 groups with an indoor radon concentration of 20, 40, 60 and 80 Bq/m^3. The data of the indoor radon concentrations in the 167 buildings independent of risk areas and ventilation systems are tested in @Risk with the proposed distribution being a lognormal distribution LN(111; 131) (Bq/m^3), see Figure 5.19. This corresponds to the estimated distribution in the epidemiological study by Pershagen et al (1993). The probability of exceeding the threshold value 200 Bq/m^3 is 13,8 % for the observations and 14,3 % for the proposed lognormal distribution.

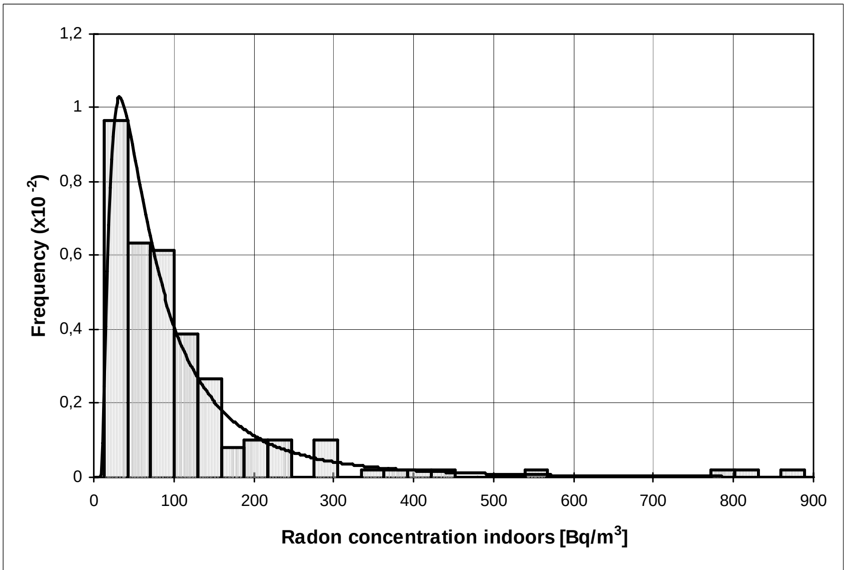


Figure 5.19 Distribution of indoor radon concentrations in the 167 buildings founded on concrete slab on the ground in Hudiksvall independent of ventilation system and risk area.

The data for low, normal and high risk areas are tested independent of the ventilation system, shown in Figure 5.20. The distribution fit gives a lognormal distribution LN(93; 109) (Bq/m^3) for the normal risk area and a lognormal distribution LN(156; 160) (Bq/m^3) for the high risk area. The probability of exceeding the threshold value for the normal risk area is 8,0 % for the observations and 9,4 % for the proposed lognormal distribution, and for high risk area 20,9 % for the observations and 22,8 % for the proposed lognormal distribution. The low risk area only contains 11 buildings, considered too small to get an accurate distribution fit that can be seen when the probability of exceeding the threshold value is compared giving 9,1 % for observations and 37,5 % for the proposed distribution.

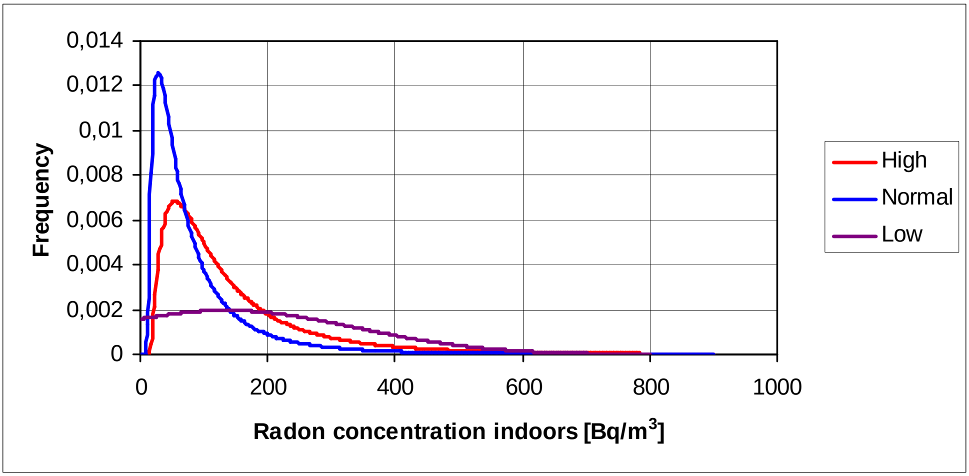


Figure 5.20 *Distribution of radon concentrations indoor independent of ventilation system in buildings in Hudiksvall founded on concrete slab on the ground on low, normal and high risk area.*

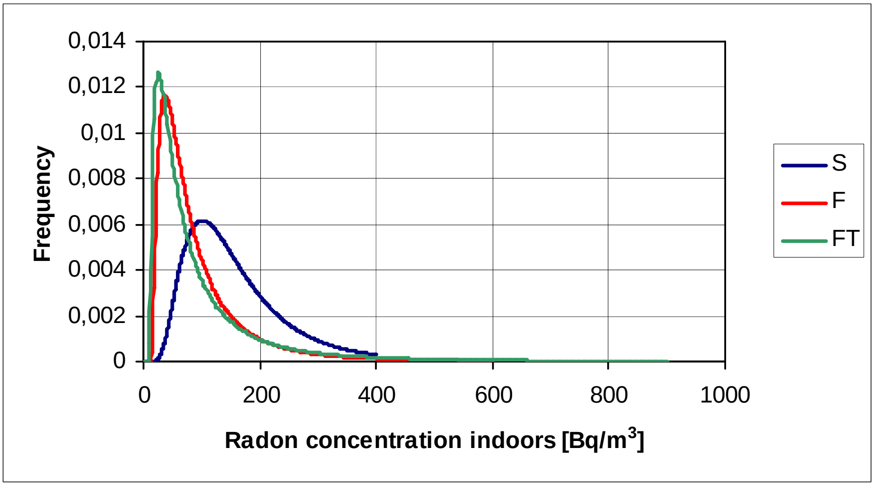


Figure 5.21 *Distribution of radon concentrations indoor in different ventilated buildings in Hudiksvall founded on concrete slab on the ground and independent of risk area. FT = exhaust air-air supply, F = exhaust air, S = self-draught.*

The data of the indoor radon concentrations in the buildings with self-draught, exhaust air and exhaust air - air supply ventilation are tested in @Risk independent of risk area, Figure 5.21. The distribution fit for exhaust air- air supply ventilation gives a lognormal distribution LN(105; 143) (Bq/m^3), and for exhaust air ventilation a lognormal distribution LN(98; 96) (Bq/m^3). The probability of exceeding the threshold value for exhaust air-air supply ventilation is 9,6 % for the observations and 11,8 % for the proposed lognormal distribution, and for exhaust air ventilation 7,3 % for the observations and 9,3 % for the proposed lognormal distribution. Only 22 buildings have self-draught ventilation considered too small to get an accurate distribution fit. However, the probability of exceeding the threshold value is 27,3 % for observations and 25,6 % for the proposed distribution which is lognormal LN(163; 99) (Bq/m^3).

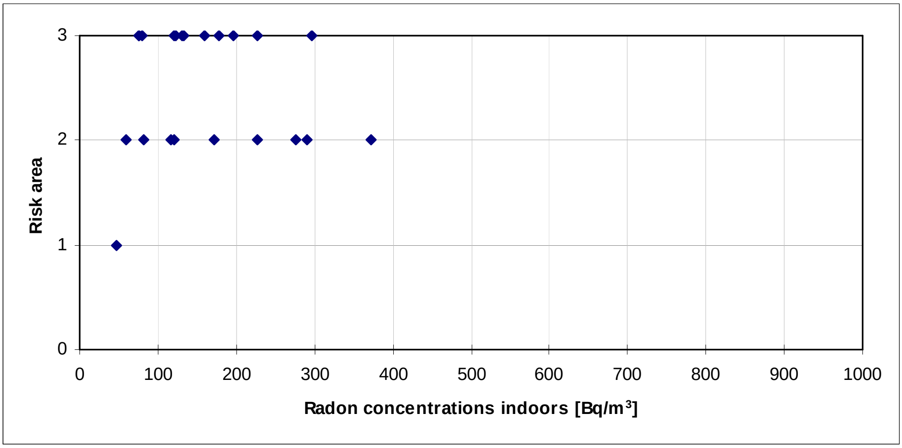


Figure 5.22 Radon concentrations indoor in self-draught ventilated buildings in Hudiksvall founded on concrete slab on the ground. 1 = low risk, 2 = normal risk and 3 = high risk area.

From the 167 single-family dwellings founded with concrete slab on the ground, 22 were selected because they were self-draught ventilated. The distribution of the radon concentrations indoors compared to risk area is shown in Figure 5.22. The intention of collecting available data was to verify the accuracy of the model. However, the indoor radon concentration in buildings founded on normal risk and high risk areas have approximately the same range of concentration, and since the pattern of the data is incoherent, in situ investigations are needed to explain the somewhat confusing distribution of the data and to apply the data correctly to the model. The problem with in situ investigations of a concrete slab on the ground is that the flooring hides the question of interest here, namely the cracks and narrow openings allowing radon concentrations in soil air to enter the indoor environment.

Different sizes and ranges of cracks and narrow openings is one explanation of the data distribution. Another explanation is that the mapping of risk areas of radon concentrations in soil air does not reveal possible cracks in the bedrock that may transport larger amounts of radon gas, i.e. a building assumed to be founded on a normal risk area may be placed on a spot which could be characterised as a high risk area. The mean value of the observations are also higher than the estimated undesirable indoor event which may depend on the fact that measurements of indoor radon concentrations are performed from late autumn (October, November) until spring (February, Mars). The radon concentrations in the ground are then reaching the highest values during the year depending on snow and water. The estimated undesirable event used the radon distribution over the entire year.

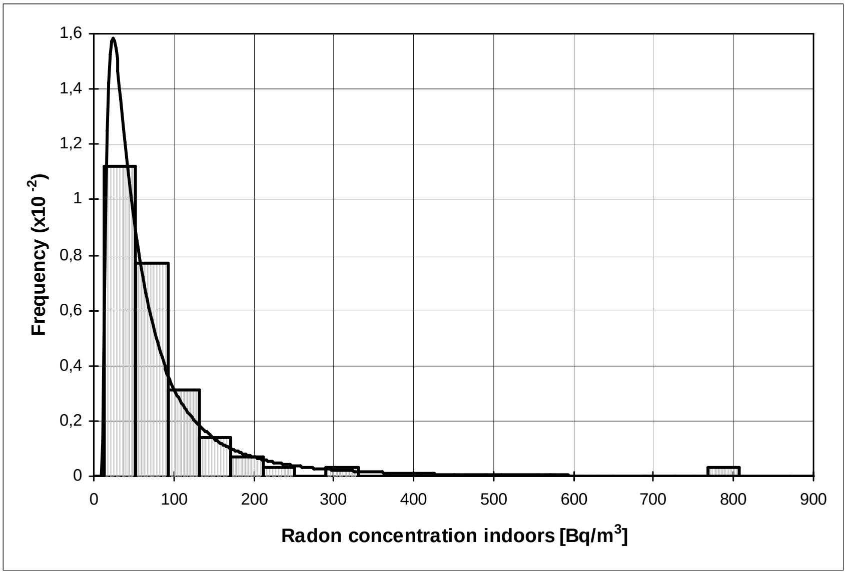


Figure 5.23 Distribution of indoor radon concentrations in 72 buildings founded on concrete slab on normal risk ground in Hudiksvall with exhaust air-air supply ventilation system.

According to Table 5.2 the group founded on a normal risk area and equipped with exhaust air- air supply ventilation probably contains enough observations to estimate an accurate distribution. The observations are tested with @Risk and the proposed distribution is lognormal LN(81; 101) (Bq/m^3), see Figure 5.23. The probability of exceeding the threshold value 200 Bq/m^3 is 4,2 % for the observations and 7,3 % for the proposed lognormal distribution. By comparing the mean value and standard deviation of the observations from Hudiksvall and the estimation of the undesirable indoor event Y_{env} using the proposed model, the yielded mean value is higher for the observations, even though the undesirable indoor event is estimated using a high risk area. Two explanations can be that the concrete slabs in the observations contain larger openings, as well as the soil locally includes higher radon concentrations than described by the map used.

However, risk estimation can be made by comparing the proposed lognormal distribution as the undesirable indoor event Y_{env} with the dose-response relationship X_{env}. The comparison is made using @Risk, and the resulting distribution function when the dose-response relationship is based on the annual risk is shown in Figure 5.24. The estimations in @Risk yield the total failure probability $p_f = 0{,}003$ as the annual risk of suffering from lung cancer. The total failure probability is probably too high, since the tail of the proposed distribution gives a higher probability of exceeding the threshold value than the observations.

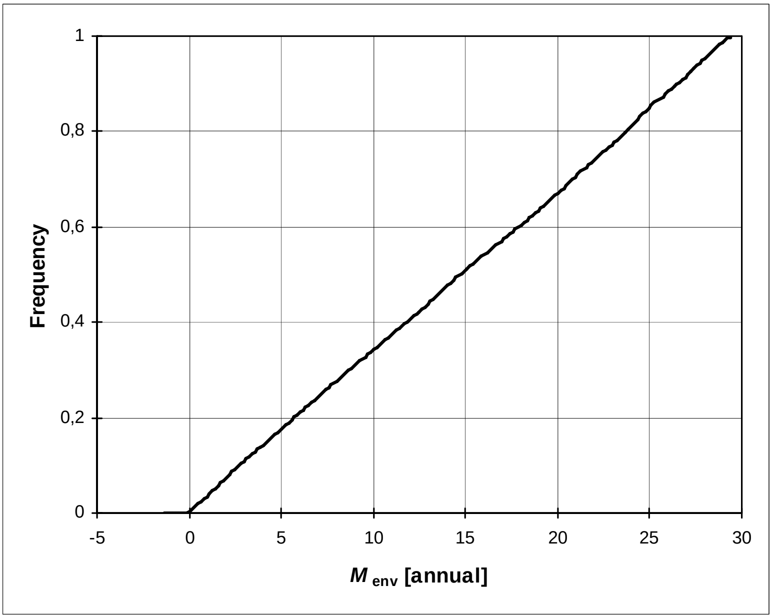


Figure 5.24 The distribution function of the limit state function when the undesirable indoor event is compared with the dose-response relationship.

The risk estimation can be performed with other by @Risk proposed distributions to estimate the total failure probability, i.e. distributions with a better agreement in the important right tail. However, the purpose of the collection of the observations was to apply the available data to the model for verification which became impossible due to the incoherence in the observations between the different risk areas.

5.9 Summary of chapter 5

The risk analysis process proposed in chapter 3 has been applied to a single-family dwelling founded on a concrete slab on the ground performed in agreement with common praxis. The dwelling is built in an area with high levels of radon concentrations in the soil regarded as a high risk area. The purpose of the analysis is to evaluate the comparing of the undesirable indoor event caused by the environmental radon impact and the increased risk to humans described by the dose-response relationship, i.e. similar comparison as the load effect and resistance are compared in structural reliability analysis.

The qualitative evaluation of finding the basic events that contribute to the occurrence of the undesirable indoor event “Radon concentrations in indoor air”, was done using fault tree analysis, with the events of interest being the level of radon concentration in the soil under the building, the difference in air pressure between indoor and outdoor air, and the possibility of air leakage through the foundation regarding narrow openings, cracks etc. The relationship between the random variables describing the undesirable indoor event was expressed by:

$$G(\mathbf{Y}_{\text{env}}) = C_{\max} \cdot \frac{\lambda}{(n+\lambda)\cdot V_{\text{build}} \cdot \ell} \cdot \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t} \quad [\text{Bq/m}^3]$$

The radon concentration in soil air was estimated from data recorded at Slaka giving $C_{\max}$ approximately normally distributed N(114 720; 10 370) (Bq/m^3). The air pressure was only considered by using the difference in temperature between indoor and outdoor air since the building was self-draught ventilated. Outdoor temperature data were collected from the radon measurements in Slaka and the difference in air pressure was calculated and considered to be normally distributed N(1,53; 0,86) (Pa). Air leakage through the foundation was accounted for using cracks caused by shrinkage and settlements, and narrow openings caused by pipes passing the concrete slab. The compressive strength of the concrete was considered to be lognormal distributed LN(40; 2,4) (MPa). All other inputs were considered deterministic. The quantitative evaluation of the undesirable indoor event Y_{env} was made using the Monte Carlo simulation with the computer software @Risk. The distribution fit suggested the event to be lognormal distributed LN(64; 31) (Bq/m^3), which is in line with investigations made on indoor radon concentrations.

The dose-response relationship is considered to be linear with no threshold dose and the increased risk of suffering from lung cancer caused by radon indoors is estimated to 3,4 % per 1000 Bq/m^3 and year. A uniform distribution is used to describe the probability density function of the random variable X_{env}.

Risk is defined as the violation of the limit state function, and the dose-response relationship X_{env} and undesirable indoor event Y_{env} are compared according to:

$$M_{env} = G(X_{env}, Y_{env}) = X_{env} - Y_{env} < 0$$

The comparison using @Risk gave the probability of an analysed limit state violation living in the analysed single-family dwelling to be:

$p_f = 0{,}0025$ per year

The undesirable indoor event was also compared with the failure/success criterion 200 Bq/m^3 which is the threshold value stipulated in the Swedish Building Regulations (BFS 2002:19) to not be exceeded. The comparison using @Risk gave the probability:

$p_f = 0{,}1 \times 10^{-3}$ to exceed the threshold value 200 Bq/m^3.

The comparison between the undesirable indoor event Y_{env} and the threshold value was also made using the first-order second-moment theory (FOSM), and the safety index β was estimated by iteration to be:

$\beta = 3{,}62 \quad \rightarrow \quad P(X_{env}-Y_{env}<0) = 0{,}14 \times 10^{-3}$

The intention of collecting available data from the municipality of Hudiksvall was to verify the accuracy of the model. The data was received from the Environment and Health Protection Office, and the foundations designs were collected from the archives of building permission documents. However, the indoor radon concentration in the selected 22 buildings with self-draught ventilation founded on a normal risk and a high risk area had approximately the same range of concentration. Different sizes and ranges of cracks and narrow openings is one explanation of the data distribution. Another explanation is that the mapping of risk areas of radon concentrations in soil air does not reveal possible cracks in the bedrock that may transport larger amounts of radon gas, i.e. a building founded on a normal risk area may be placed on a spot which could be characterised as a high risk area. Risk estimation was made of the 72 buildings with the proposed lognormal distribution LN(81; 101) (Bq/m^3), exhaust air-air supply ventilation and founded on a normal risk area. The risk of limit state violation was estimated using the dose-response relationship X_{env} yielding the total failure probability p_f = 0,003, i.e. the annual probability of suffering from illness.

The performed analysis includes several uncertainties in both the qualitative evaluation and the quantitative estimation, since simplifications were necessary throughout the work due to a lack of data or scientific knowledge. However, the purpose of the analysis has been to evaluate the possibility to compare the undesirable indoor events caused by the environmental impact radon and the increased risk to humans described by the dose-response relationship, i.e. similar comparison as the load effect and resistance are compared in structural reliability analysis. A more thorough discussion about the results and uncertainties will be performed in chapter 7.

6 RISK ANALYSIS OF ENVIRONMENTAL IMPACT TO THE WATER SUPPLY SYSTEM

6.1 Scope definition

The risk analysis procedure proposed in chapter 3 will be applied to the water supply system of a tenant-owned dwelling. The main purpose is to evaluate the possibility of qualitatively establishing the causes of undesirable indoor events caused by environmental impacts to the water supply system, and to quantitatively compare the undesirable indoor events with the occurrence of specific human health effects and dose-response relationships.

The primary failure/success criteria to be used are, if available, threshold values in the Swedish Building Regulations, or guiding values found from authoritative advices or published research.

6.2 System definition

The dwelling is a tenant-owned flat situated in the municipality of Luleå, Sweden. The tenant-owner society consists of 48 two-storey houses with 424 dwellings of different sizes. The houses were built in 1976 and 6 buildings are founded with a basement, while the remaining are founded with concrete slab on the ground. The buildings are equipped with exhaust air ventilation systems and the heating of both spaces and domestic hot water is based on district heating. Three district heating substations are in the area and the substation supporting the actual dwelling is situated approximately 100 meters from the dwelling. The distribution network for hot tap water is not equipped with a hot water circulation system.

The dwelling is situated on the bottom floor comprising two rooms and a kitchen with a living area of 64 m^2. The building is founded on a concrete slab on the ground. According to Figure 6.1, the incoming water piping is located in the installation shaft in the bathroom and also supports the top floor flat. Piping is drawn from the shaft to the toilet, the washstand and the bath, as well as a connection from the piping to the kitchen sink. The length of the pipes from the connection in the installation shaft to the shower in the bath is approximately 2,5 meters. The shower hose is made of plastic material and the pipes of copper.

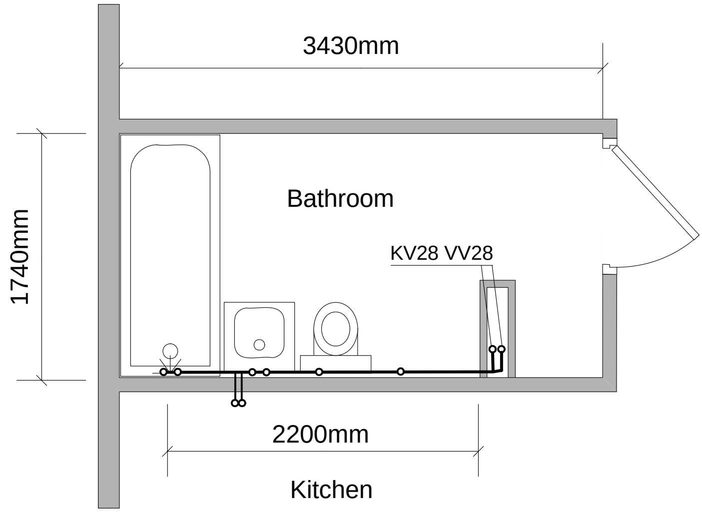


Figure 6.1 *Principal drawing of dwelling bathroom and water piping location.*

Potable water to the houses is distributed from the Luleå drinking water treatment plant. Water used in the water treatment plant is pumped up from Lule älv (the nearby river) and filtered through the ground and two infiltration ponds down to the groundwater, i.e. the water plant is defined as an artificial groundwater recharge plant.

6.3 Hazard identification and initial consequence evaluation

6.3.1 Undesirable indoor events, random variable Y_{env}

In the hazard identification in chapter 4, environmental impacts were identified with the potential to cause undesirable indoor events. In section 4.5, microbial growth in the water supply system was accounted for and more specifically the growth of *Legionella* bacteria. A chain of events was identified before the transmission of the organisms through aerosols to humans was possible. The main transmission source in a dwelling is the shower head in the bathroom.

6.3.2 Dose-response relationships, random variable X_{env}

Legionnaires' disease occurs when water droplets containing *Legionella* bacteria are inhaled deeply into the lungs where infection can occur. The dose-response relationship is unknown, though Storey et al (2004b) used the single-hit model, accounted for in chapter 4, to estimate the risk of infection.

Swedish threshold values or guiding values are unavailable, but guiding values from the US EPA and EWGLI were accounted for in chapter 4, suggesting:

- "a low but increased level of concern" > 100 cfu/100 ml
- "disinfection should be considered" 100 – 1000 cfu/100 ml
- "immediate disinfection of equipment" > 10 000 cfu/100 ml

6.4 Construction of the fault tree

In section 4.2, a sub-top event to the undesirable indoor top event was identified as "Microorganisms or substances from microorganisms in indoor air". In the hazard identification in chapter 4 one environmental impact, *Legionella* contaminated aerosols, was identified with the potential to cause undesirable indoor events from the water supply system. In the fault tree in Figure 6.2, the input event "*Legionella* contaminated aerosols in indoor air" passes through an OR-gate, since other microorganisms or products from microorganisms can be the cause of an unhealthy indoor environment. The event is further developed as the reason for an unhealthy indoor environment caused by the domestic water system.

According to section 4.5.3, there are two ways for *Legionella* contaminated aerosols to enter a building. They may be either transmitted to the indoor air through aerosol producing indoor equipment, e.g. shower heads, whirlpool baths, etc., or they may be transmitted from aerosol producing equipment outdoors, e.g. from cooling towers entering indoor air through the ventilation system. Both events are able to cause the output event, separately or combined, and therefore pass through an OR-gate according to Figure 6.2. The event of interest is the transmission of *Legionella* contaminated aerosols from aerosol producing indoor equipment, and especially shower heads, since this is the most common way of transmitting aerosols within dwellings.

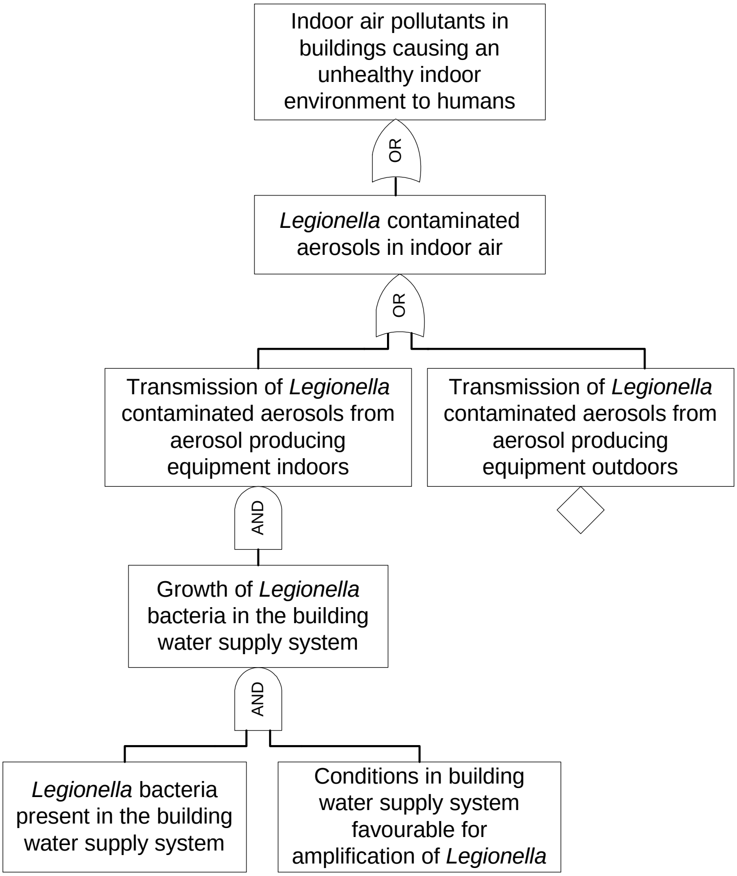


Figure 6.2 Partly developed fault tree with causes to indoor air pollutants from Legionella bacteria.

The transmission of bacteria can only occur if there is growth of *Legionella* bacteria in the building water supply system. Therefore, the event passes through an AND-gate in the fault tree. Two conditions have to be fulfilled for *Legionella* bacteria to grow in the water pipes. The bacteria have to be present in the building water supply system, and the conditions in the system have to be favourable for the growth and multiplication of the bacteria, i.e. an environmental impact together with some conditions in the system partly depending on human involvement. These two conditions have to be combined and therefore also pass through an AND-gate in Figure 6.2.

The fault tree is further developed in Figure 6.3 with the event "*Legionella* bacteria present in the water supply system". The event is caused by either the incoming water to the building water supply system containing bacteria, or by bacteria already accumulated in the system depending, e.g. on the age of the system. The accumulation of bacteria can be tested in the dwelling and is therefore considered a basic event. Incoming water could also constitute a basic event, since the event can be controlled through testing the water quality. However, the event may be developed further according to the chain of legionella events that have to be fulfilled before humans suffer from Legionnaires' disease. For the incoming water to contain bacteria, the distribution network must contain bacteria and support its survival from the waterworks to the building water supply system, Figure 6.3. This event is not further developed here and is therefore marked with a diamond.

According to chapter 4, there has to be an environmental source containing *Legionella*; in the waterworks in Luleå this environmental source is the river where the water is pumped up to undergo artificial infiltration. Usually, the level of *Legionella* bacteria is unaffected by the disinfection procedures at the water treatment plant and the input event is therefore defined as "Outgoing water from waterworks to distribution network contains *Legionella* bacteria". This event is defined as a basic event, since the level of bacteria may be measured in the outgoing water. Szewzyk and Stenström (1993) found that this type of water plant has a lower frequency of positive *Legionella* tests than water plants using surface water. According to the manager of the plant in Luleå, the outgoing water has not been tested for *Legionella* recently, since the water temperature in the distribution network is too cold for growth. However, bacteria may also have accumulated in the distribution network, and Storey et al (2004a) showed that *Legionella* might accumulate and detach from the distribution pipe biofilm. The detachment was favoured by turbulent water conditions and concentrated numbers of *Legionella*, ranging from a few cells in small clusters to approximately 100 cells in large clusters, could be found in the bulk water. The event is not further developed and marked as a basic event.

The output event "Conditions in building water supply system favourable for amplification of *Legionella*" needs four combined input events to be fulfilled. From the hazard identification in chapter 4, these four events were the presence of protozoa for protection and nutrients, the presence of biofilm on the inner surface of the water pipes, water temperature between 25°C and 42°C with an optimal growth temperature of 35°C, and finally, sufficient time in stagnant or slow flowing water. These events are here defined as basic events, though they are possible to develop further.

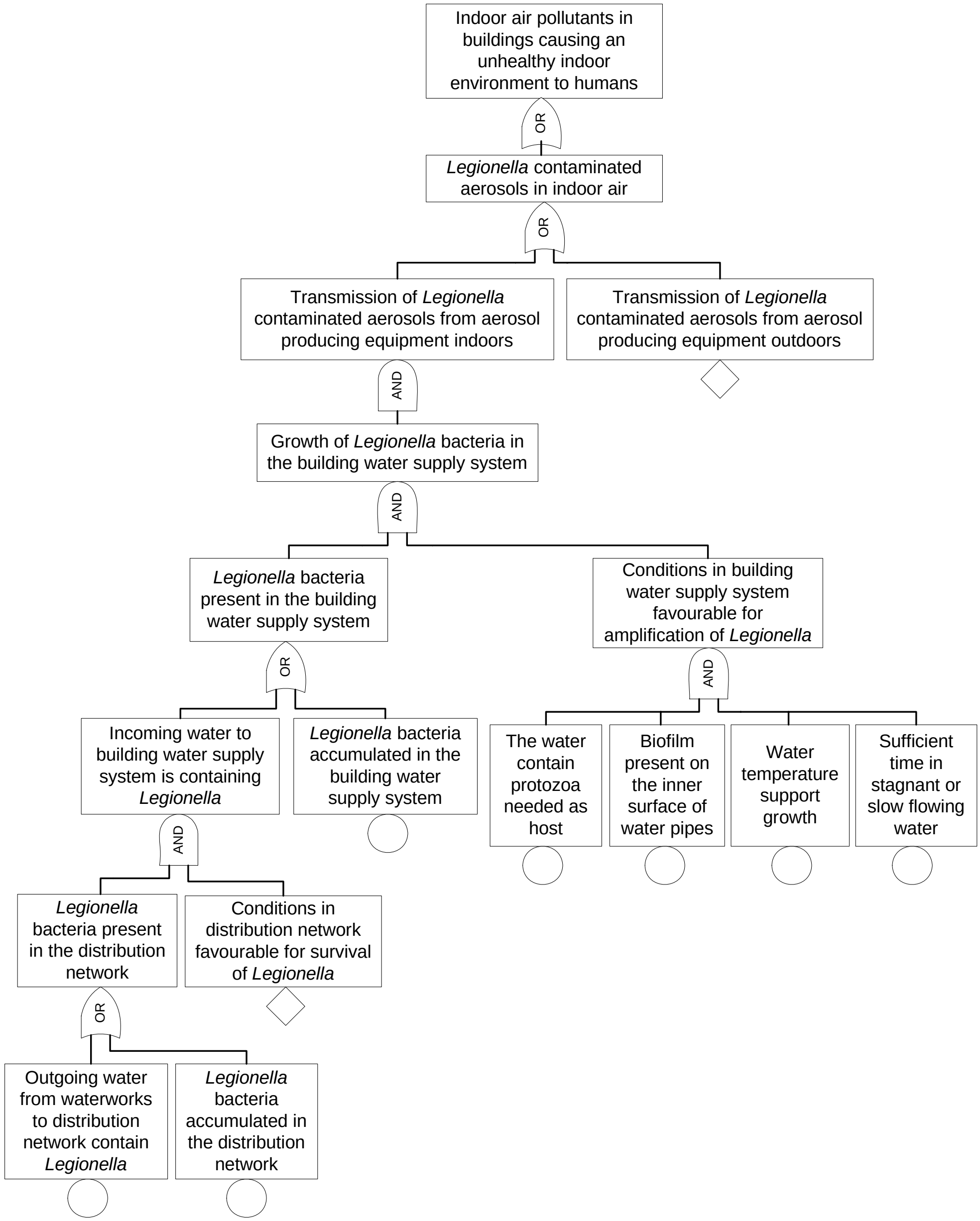


Figure 6.3 Fully developed fault tree from the event "Legionella contaminated aerosols in indoor air".

The risk of common-cause failures when using undeveloped events can be discussed, since some of the probable input events to "Conditions in distribution network…" are in principle the same as for the event "Conditions in building water supply system…", e.g. the event "Biofilm present on the inner surface of water pipes". However, biofilm is present in two different systems and supports its survival in one case and its amplification in the other. The contents of microorganisms in the biofilm may also be different. Therefore, the eventual similarity between the input events to the two different output events is not considered common-causes.

6.5 Qualitative examination of the fault tree

The fault tree has been developed down to levels where experimental data can be difficult to find, and the tree structure is reduced according to the shaded events in Figure 6.4 to evaluate the top event. One event has been disregarded from the original fault tree, i.e. "Transmission…from aerosol producing equipment outdoors" is not of interest in the dwelling analysis, and the probability of occurrence of the event $p_f = 0$. The event "Incoming water…containing *Legionella*" has been reduced to a basic event, since the amount of bacteria leaving the waterworks or the survival potential in the distribution network are unknown, whereas the amount of bacteria in the incoming water is possible to measure. The uncertainty incorporated in the reduction can be handled using structural reliability analysis since several random variables can be taken into account in a single basic event.

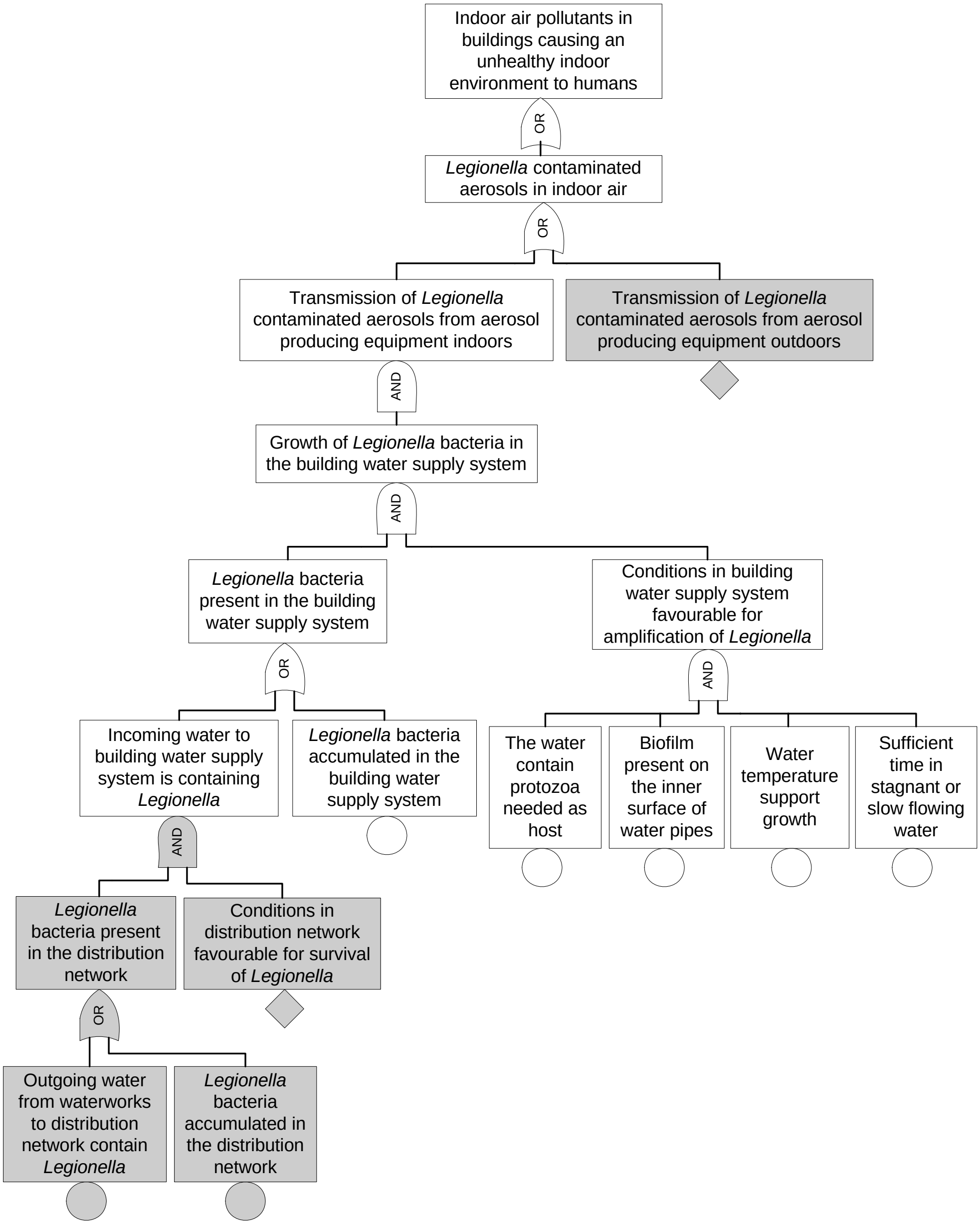


Figure 6.4 *Events (marked with shaded colour) in the original fault tree which are to be reduced or changed in properties.*

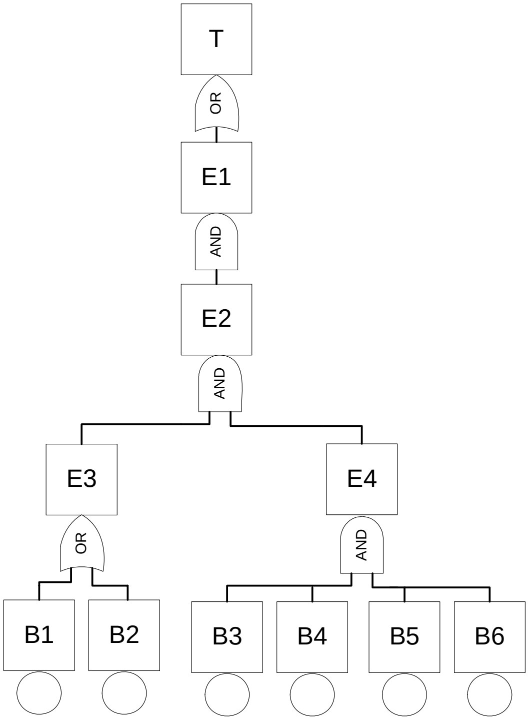


Figure 6.5 *Reduced tree of the event ”Legionella contaminated aerosols in indoor air”.*

The fault tree in Figure 6.5 is reorganised in accordance with Figure 6.4, where the fault tree events are characterised with capital letters and numbers when looking for minimal cut sets. The basic events (symbolised with circles) are characterised with B, fault events (symbolised with rectangles) with E, and the top event is symbolised with T. To determine the minimal cut sets of the fault tree, the events are first translated into its equivalent Boolean equations from the top of the tree down to the bottom and the basic events.

$$\begin{aligned} &T=E1=E2=E3\cap E4 \\ &E3=B1\cup B2 \\ &E4=B3\cap B4\cap B5\cap B6 \end{aligned} \tag{6.3}$$

The next step is to express each fault event in terms of the basic events, starting from the bottom and up in the tree. To eliminate any mistakes due to the similarity between the union and intersection symbols, union will be marked with + and intersection with $\cdot$.

The top event T is the union of the two minimal cut sets (B1 B3 B4 B5 B6) and (B2 B3 B4 B5 B6), i.e. the top event will occur if B1 and/or B2 occur in combination with the events B3 to B6.

$$\mathrm{T}=(\mathrm{B1}+\mathrm{B2})\cdot\mathrm{B3}\cdot\mathrm{B4}\cdot\mathrm{B5}\cdot\mathrm{B6} \tag{6.4}$$

In chapter 3, the undesirable indoor event, Y_{env}, was defined as a function of the environmental load q_{env} together with the design and construction of the building component, denoted D_{env}. In this case, the environmental load q_{env} includes q_{B1} and q_{B2}, and the variables that are possible to influence during the building process, which include the basic event B5, i.e. the tap water temperature T, and in some ways the basic event B6, i.e. time t of stagnant tap water in the pipes, by reducing tap water pipes used less frequently, and where humans will be exposed to aerosols during usage of the outlet.

$$Y_{\mathrm{env}} = f\left(q_{\mathrm{B1}}, q_{\mathrm{B2}}, T, t\right) \tag{6.5}$$

If measures of probabilities instead of probability density functions are used, the probability of the undesirable indoor event could be calculated without regarding the cause to the unhealthy indoor environment. However, the estimated probability cannot be compared with any threshold value or dose-response relationship.

6.6 Quantitative evaluation of the fault tree

The occurrence of the top event T, concerning the presence of *Legionella* contaminated aerosols in indoor air, depends on the occurrence of the basic events B1 to B6, i.e. the fault event E1. However, since the fault tree was reduced, each basic event may depend on several random variables and by using structural reliability analysis (SRA), functions can be used to express the event space and the relationship between the set of random variables.

6.6.1 Definition of the fault event E1

The fault event E1 “Transmission of *Legionella* contaminated aerosols from aerosol producing equipment indoors” is dependent on the occurrence of fault event E2 “Growth of *Legionella* bacteria in the building water supply system”. According to chapter 4, the exponential growth rate of microorganisms can be expressed as (Brundrett, 1992; Thougaard et al, 2001):

$$\frac{dN}{dt} = \mu \cdot N \tag{6.6}$$

where

N	number of cells
t	time
μ	constant of specific growth rate

Integration of (6.6) between the time t_1 and t_2 gives:

$$\int_{N_1}^{N_2} \frac{dN}{N} = \int_{t_1}^{t_2} dt \cdot \mu \qquad \Rightarrow \qquad \ln\left(\frac{N_2}{N_1}\right) = \mu \cdot (t_2 - t_1) \tag{6.7}$$

$$\Rightarrow \quad N_2 = N_1 \cdot e^{\mu \cdot (t_2 - t_1)} \tag{6.8}$$

The function of the vector $\mathbf{Y}_{\mathrm{E1}}$ expressing the relationship between the random variables can then be given by:

$$G(\mathbf{Y}_{\mathrm{E1}}) = N_1 \cdot e^{\mu \cdot (t_2 - t_1)} \tag{6.9}$$

The random variables of interest in the analysis are the initial amount of *Legionella* bacteria, N_1, the specific growth rate, μ, and the time of stagnant water in the pipes, Δt.

6.6.2 Estimation of the constant of specific growth rate, μ

A random variable of interest in the analysis from equation (6.9) is the constant of specific growth rate, μ, which depends on i.a. the presence of biofilm, quantity of nutrient, and the water temperature. The constant of specific growth rate is then given by the basic events B3, B4, and B5.

In the laboratory environment, *Legionella pneumophila* have a mean generation time of 2 hours, i.e. time to double the number of cells. Multiplication in tap water is much slower because of the limited quantity of nutrient presence. To calculate the constant of specific growth rate and the mean generation time, tests of *Legionella* concentration were made in the shower in the tenant-owned dwelling, defined in the system definition in section 6.2. ALcontrol Laboratories in Karlstad was hired to analyse the water samples. The water samples were collected in 500 ml plastic bottles containing sodium tiosulphate. Three different tests were planned and performed at different occasions accounted for in Table 6.1. The tests performed were:

Test A — The water temperature in the shower was set to 38°C by running the water. The water was then left stagnant during the night with the same adjustments of the thermostat and the tap.

The water sample (A1) was collected in the morning from the first water coming out of the shower. After 5 minutes of running the water, another water sample (A2) was collected. The temperature of the samples was measured.

Test B — The water was left stagnant for 19 days with the same adjustments of the thermostat and the tap.

The water sample (B1) was collected in the morning from the first water coming out of the shower. After 5 minutes of running the water, another water sample (B2) was collected. The temperature of the samples was measured.

Test C — The water was left stagnant for 39 days with the same adjustments of the thermostat and the tap.

The water sample (C1) was collected in the morning from the first water coming out of the shower. After 5 minutes of running water, another water sample (C2) was collected. The temperature of the samples was measured.

Sample 1 shows the amount of *Legionella* bacteria present in the stagnant tap water. Sample 2 shows the amount of bacteria in the piping network. After each test the minimum and maximum temperatures that can be achieved in the shower and in the nearby washstand were controlled. The water samples were placed in a special bag with ice packs and sent by mail to ALcontrol Laboratories for analysis.

Table 6.1 Data from Legionella tests in dwelling shower.

	Sample 1			Sample 2								
Date	Time	Temp	cfu/ 100 ml	Time	Temp	cfu/ 100 ml	Shower temp Min.	Shower temp Max.	Wash temp Min.	Wash temp Max.	Test	Days
2005-02-28	07.11	18	500	07.16	36	17	15	41	9	51	A	0,4
2005-03-29	07.21	19	3900	07.26	36	150	16	41	7	53	B	19
2005-04-25	07.15	20	240	07.20	36	1	15	41	4	53	A	0,4
2005-05-31	08.07	21	0	08.12	36	0	15	42	6	52	A	0,4
2005-08-01	07.29	21	100000	07.34	36	50	16	41	11	51	C	39

Time — time of collection of sample
Temp — temperature of sample taken
cfu/100 ml — colony forming units per 100 millilitre water
Days — time of stagnant water in days

The results of Sample 1 show an increasing amount of *Legionella spp* depending on time of stagnant water, cf. Figure 6.6.

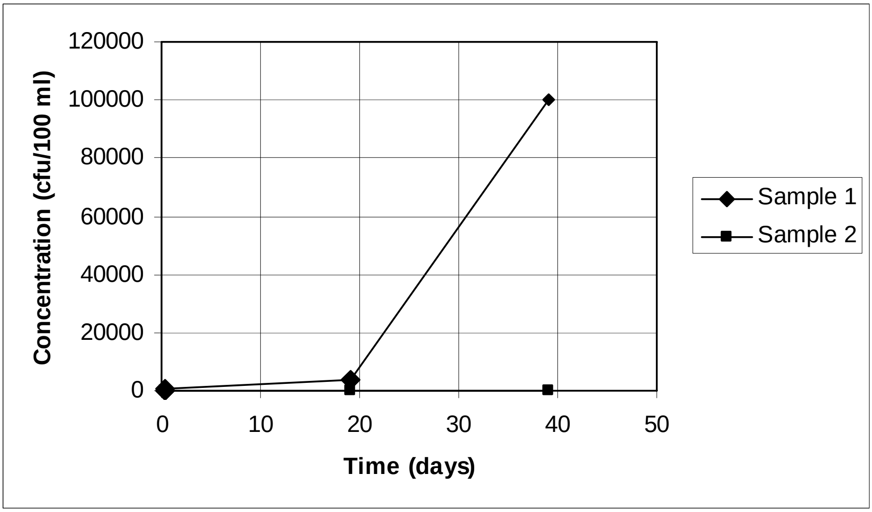


Figure 6.6 Diagram of Legionella concentration in shower.

The results from Sample 2 do not show the same relationship between the time of stagnant water and the concentration of *Legionella spp*. The reason to the different concentrations in the second sample could be because the contaminated biofilm in the shower hose or in the pipes is detached during the water flushing. In all tests except one, *Legionella spp* were found in different concentrations. The two samples taken 2005-04-25 were typed by ALcontrol Laboratories and identified as *Legionella pneumophila* serogroup 2-14, i.e. not *Legionella pneumophila* serogroup 1, which is the serogroup predominantly connected with Legionnaires' disease.

From the equation (6.8) the constant of specific growth rate, μ, and the generation time can be calculated using data from the water samples in the dwelling shower. The equation can be changed to 10-logarithm:

$$\log N_2 - \log N_1 = \frac{\mu(t_2 - t_1)}{2{,}303} \tag{6.10}$$

or:

$$\log N_2 = \frac{\mu}{2{,}303} \cdot (t_2 - t_1) + \log N_1 \tag{6.11}$$

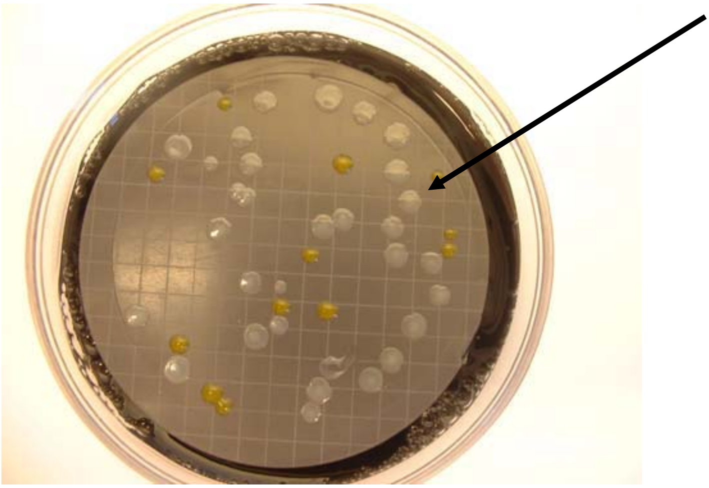


Figure 6.7 *Photo of Legionella pneumophila serogroup 2-14 found in the dwelling shower (Photo: ALcontrol Laboratories).*

Equation (6.11) describes a straight line in a coordinate system with the time on the x-axis and the logarithm of the concentration of microorganisms on the y-axis. A mean value of the three 'Test A'-samples is used giving 246 cfu/100 ml, and plotting the logarithm of the concentrations from the shower against the time in hours gives the straight line shown in Figure 6.8.

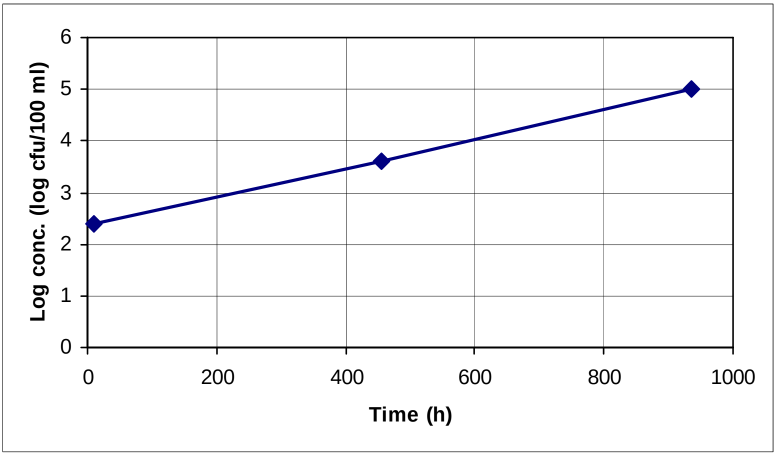


Figure 6.8 *Diagram of logarithmic concentration versus time of Legionella pneumophila serogroup 2-14 found in the dwelling shower.*

Calculating the constant of specific growth rate μ between the three points in the plot gives:

$$\mu = \frac{\log 100000 - \log 3900}{24 \cdot (39 - 19)} \cdot 2{,}303 = 0{,}0068 \text{ h}^{-1} \tag{6.12}$$

$$\mu = \frac{\log 3900 - \log 246}{24 \cdot (19 - 0.4)} \cdot 2{,}303 = 0{,}0062 \text{ h}^{-1} \tag{6.13}$$

and the generation time g:

$$g = \frac{\ln 2}{\mu} \quad \rightarrow \quad g = \frac{0{,}693}{0{,}006} = 115{,}5 \text{ h} \tag{6.14}$$

The amount of colony forming units of *Legionella pneumophila* in the shower hose is doubled approximately every fifth day, compared with Figure 4.6 in chapter 4 showing the estimated mean generation time in tap water for different temperatures. The temperature in the tap water changed from approximately 38°C during usage to between 18-21°C when the samples were taken. According to Figure 4.6, a temperature of 18-21°C would give a mean generation time of more than five days, though the growth in the analysed dwelling shower was initiated during higher temperatures.

Now, the growth of *Legionella pneumophila* sg 2-14 in the analysed dwelling shower can be expressed using equation (6.8) which gives:

$$N_2 = N_1 \cdot e^{0{,}006 \cdot \Delta t} \tag{6.15}$$

The specific growth rate is considered to be a deterministic value in this analysis.

6.6.3 Estimation of the time of stagnant water, Δt

The basic event B6 is defined as “Sufficient time in stagnant or slow flowing water”. The time of stagnant water Δt in the shower and pipes is a random variable that has to be estimated. A study of showering habits has not been possible to find. Therefore, the showering habits in a single-person dwelling during one year are estimated, c.f. Table 6.2.

Table 6.2 Estimation of showering habits during a year in a dwelling.

Time of stagnant water, Δt	Frequency, x_i
12	8
24	28
48	102
72	26
96	3
144	1
168	1
504	1

The dwelling shower is not used during a three-week summer vacation and during six occasions comprising longer weekends or business trips between 4 and 7 days. The remaining days during the year are split up in time of stagnant water between half days to three days, depending on activities, e.g. days training at the local gym include the use of the gym shower and not in the dwelling. The estimated data is plotted in the diagram in Figure 6.9.

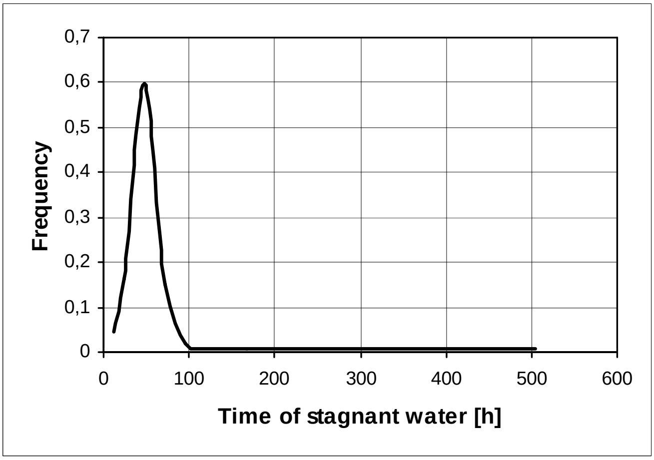


Figure 6.9 Estimated time of stagnant water in a dwelling during a year.

A rough assumption is that the data of showering habits is lognormal distributed LN(66; 119) (h).

6.6.4 Estimation of the initial amount of Legionella bacteria, N_1

The fault event E3 depends on the union of the basic events B1 and B2, and is defined as "*Legionella* bacteria present in the building water supply system", i.e. the variable N_1 in equation (6.9). The variable N_1 is a random variable depending on the amount of *Legionella* bacteria present in the incoming water to the building and the accumulated amount of bacteria already present in the water supply system.

The amount of *Legionella* bacteria in the incoming tap water to the building, i.e. the basic event B1, was not tested, and an assumption has to be made. Storey et al (2004b) assumed that *Legionella* were present everywhere and uniformly distributed both in the biofilm in the distribution network and in the bulk water, and according to the hazard identification in chapter 4, the concentration of *Legionella* bacteria in outgoing water from the waterworks is generally very low with only a few organisms per litre. It is assumed that the concentration of *Legionella* bacteria in the incoming tap water to the building varies between a minimum level of 0,1 cfu/100 ml and a maximum level of 1 cfu/100 ml uniformly distributed described by the probability density function U(0,1; 1).

The results from Sample 2 from the *Legionella* tests in the dwelling, i.e. the basic event B2, show the concentration of *Legionella* bacteria accumulated in the dwelling pipes and in the shower hose. It is also assumed that the accumulated bacteria in the pipes are uniformly distributed as described by the probability density function U(0; 500) (cfu/100 ml), which was the minimum and maximum values found in the tests.

6.6.5 Estimating the undesirable indoor event Y_{env}

The top event "*Legionella* contaminated aerosols in indoor air" occurs if the event E1 occurs. The relationship is described by equation (6.9):

$$G(\mathbf{Y}_{\mathrm{E1}}) = N_1 \cdot e^{\mu \cdot \Delta t}$$

and the top event is equal to the undesirable event Y_{env}. However, the function is not possible to simulate probably because of the fast increase of the exponential distribution. Therefore, equation (6.11) is used:

$$G(\mathbf{Y}_{\mathrm{env}}) = \log N_2 = \frac{\mu}{2{,}303} \cdot (t_2 - t_1) + \log N_1$$

The undesirable indoor event is estimated using the random variables N_1, i.e. the union of U(0,1; 1,0) and U(0; 500) (cfu/100 ml), and Δt, LN(66; 119) (h). The constant of specific growth rate μ is assumed to be deterministic in this analysis, though it depends on several random variables like the amount of nutrients, biofilm and temperature, suggesting a variation in the parameter. However, the water temperature in the shower hose and pipes indoors is quickly the same as the indoor temperature, and during longer periods of stagnant water the water temperature becomes equal to the temperature indoors. In chapter 5, the temperature indoors was considered constant over the year with T_i = 20,9°C, collected from the ELIB-report as a mean value in single-family dwellings (Norlén and Andersson, 1993). This can be compared with the indoor temperature during the tests of 18-21°C. Therefore, the constant of specific growth will be considered deterministic with μ = 0,006 h^{-1}.

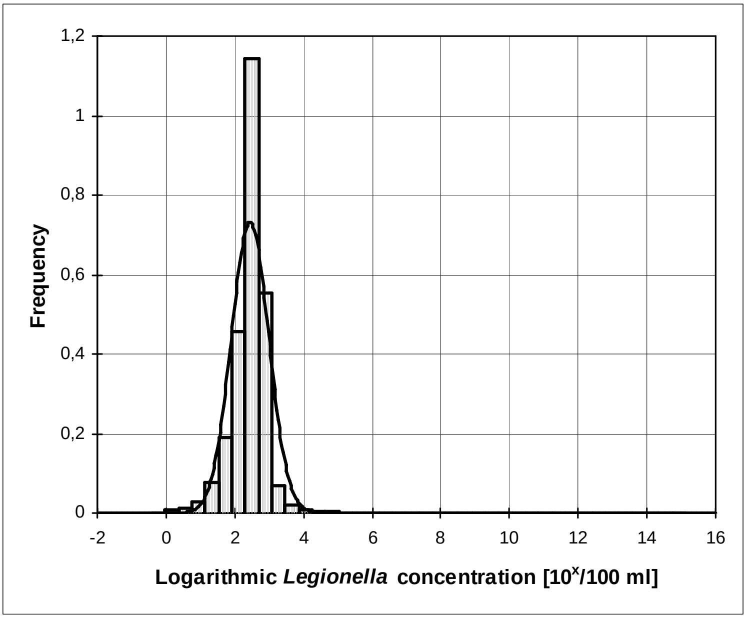


Figure 6.10 Histogram and proposed distribution of the simulated undesirable indoor event Y_{env} "Legionella contaminated aerosols in indoor air".

The Monte Carlo simulation (@Risk) is performed using 10 000 iterations to estimate the undesirable indoor event Y_{env}, Figure 6.10. The estimated distribution actually expresses the growth of *Legionella* bacteria in the shower hose, i.e. the fault event E2. It is assumed that this is also the concentration in the outgoing water, i.e. the fault event E1. The distribution fit in @Risk illustrates that the simulated data for *Legionella* contaminated aerosols in indoor air can be explained by a normal distribution N(2,4; 0,5), transformed from 10-base gives a lognormal distribution LN(251; 3,2) (cfu/100 ml).

6.7 Risk estimation

The risk estimation is made under the assumption of living in the analysed tenant-owned flat defined in section 6.2. The hot water is heated with district heating and the distribution network is not equipped with a hot water circulation system. The undesirable indoor event, Y_{env}, is supposed to be compared with the dose-response relationship, X_{env}. From chapter 3, risk is defined as violating the limit state function given by Eq. 3.8:

$$M_{\text{env}} = G(X_{\text{env}}, Y_{\text{env}}) = X_{\text{env}} - Y_{\text{env}} < 0$$

The undesirable indoor event Y_{env} is described by the lognormal distributed probability density function N(251; 3,2) (cfu/100 ml) estimated in the previous section. The probability density function of the random variable Y_{env} is given by:

$$f_{\text{Y}_{\text{env}}}(x) = \frac{1}{\sqrt{2\pi} \cdot x \cdot \varepsilon} \cdot e^{-\frac{1}{2}\cdot\left(\frac{\ln x - \lambda}{\varepsilon}\right)^2} \quad , \qquad 0 \le x < \infty \tag{6.16}$$

where

$$\lambda = \ln\left[\frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}}\right] \quad , \qquad \varepsilon = \sqrt{\ln\left[\frac{\sigma^2 + \mu^2}{\mu^2}\right]} \tag{6.17}$$

Legionnaires' disease occurs when water droplets containing *Legionella* bacteria are inhaled deeply into the lungs where infection can occur. However, a dose-response relationship is unavailable and the undesirable indoor event will have to be compared with only the guiding values found in chapter 4. The comparison is made using @Risk, and the probability of exceeding the guiding value in the dwelling is estimated.. The failure/success criteria used are the guiding values suggested by the US EPA and EWGLI:

- "a low but increased level of concern" > 100 cfu/100 ml
- "disinfection should be considered" 100 – 1000 cfu/100 ml
- "immediate disinfection of equipment" > 10 000 cfu/100 ml

The comparison is made for 100, 1000, and 10 000 cfu/100 ml and is shown in Figure 6.11 to Figure 6.13.

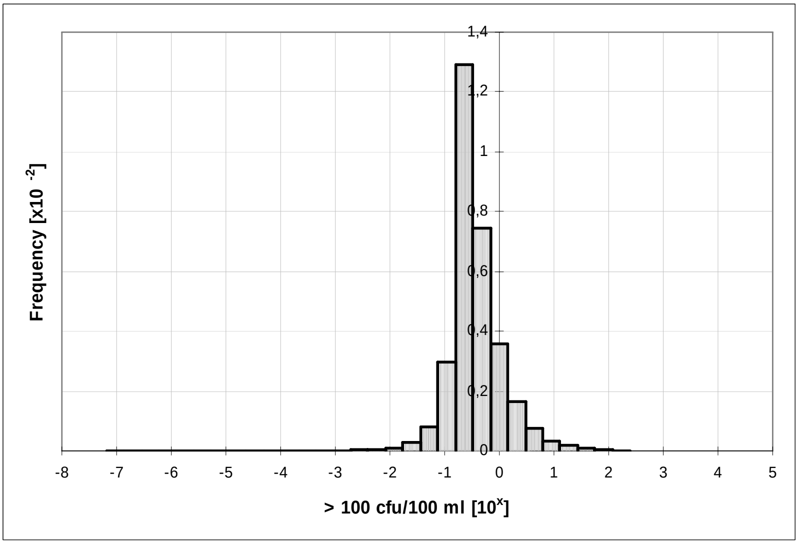


Figure 6.11 *Comparison of the undesirable indoor event and the guiding value 100 cfu/100 ml.*

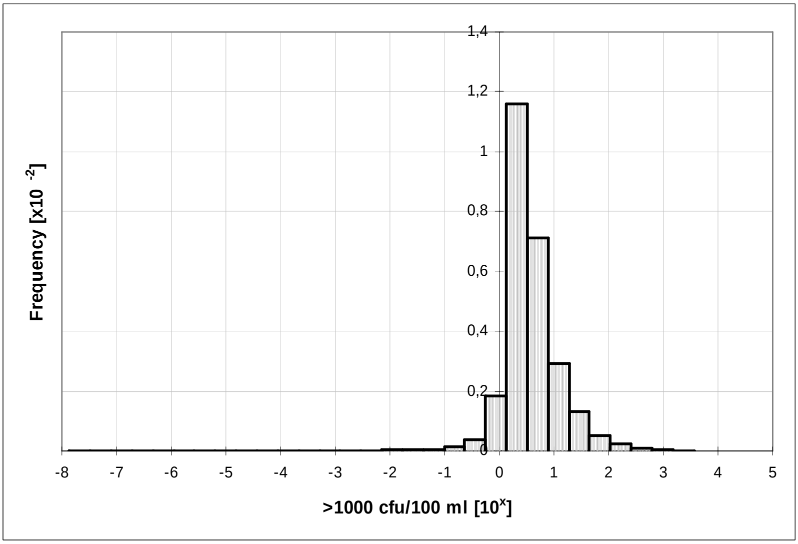


Figure 6.12 *Comparison of the undesirable indoor event and the guiding value 1000 cfu/100 ml.*

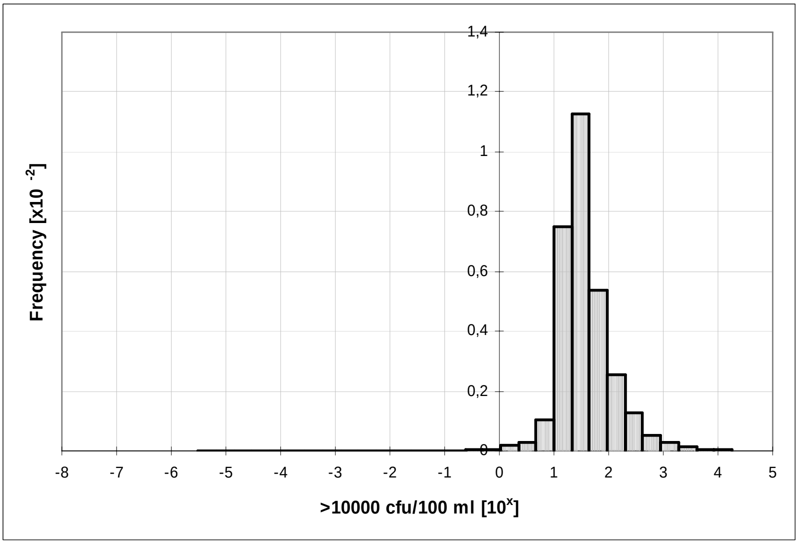


Figure 6.13 Comparison of the undesirable indoor event and the guiding value 10 000 cfu/100 ml.

Calculations in @Risk give the probability of exceeding the guiding value:

100 cfu/100 ml $p_f = 0{,}85$

1000 cfu/100 ml $p_f = 0{,}054$

10 000 cfu/100 ml $p_f = 0{,}0058$

living in the analysed dwelling.

6.8 Summary of chapter 6

The risk analysis process proposed in chapter 3 was applied to a tenant-owned dwelling with the purpose of evaluating the possibility to compare the undesirable indoor event caused by the environmental impact *Legionella* bacteria and the increased risk to humans described by a dose-response relationship, i.e. similar comparison as the load effect and resistance are compared in structural reliability analysis.

The qualitative evaluation to find the basic events contributing to the occurrence of the undesirable indoor event "*Legionella* contaminated aerosols in indoor air" was made using fault tree analysis. The events of interest were the level of *Legionella* bacteria in the incoming water and the already accumulated bacteria in the water pipes, and the conditions to support bacterial growth in the system. The relationship between the random variables describing the undesirable indoor event was expressed by:

$$G(\mathbf{Y}_{\text{env}}) = \log N_2 = \frac{\mu}{2,303} \cdot (t_2 - t_1) + \log N_1 \qquad \text{[cfu/100 ml]}$$

The undesirable indoor event was estimated using the random variables N_1, i.e. the union of U(0,1; 1,0) and U(0; 500) (cfu/100 ml), and Δt, LN(66; 119) (h). The constant of specific growth rate, μ = 0,006 h^{-1}, was estimated through tests performed in the dwelling and assumed to be deterministic in this analysis even though it depends on several random variables, such as the amount of nutrients, biofilm and temperature, suggesting a variation in the parameter. The undesirable indoor event was quantitatively estimated using the Monte Carlo simulation with the computer software @Risk. The distribution fit suggested the event to be normal distributed N(2,4; 0,5), which transformed from 10-base gave a lognormal distribution LN(251; 3,2) (cfu/100 ml).

Risk is defined as the violation of the limit state function, and the dose-response relationship X_{env} and undesirable indoor event Y_{env} are compared according to:

$$M_{\text{env}} = G(X_{\text{env}}, Y_{\text{env}}) = X_{\text{env}} - Y_{\text{env}} < 0$$

However, a dose-response relationship was unavailable and the comparison was made using guiding values found from the US EPA and EWGLI. The comparison using @Risk gave the probability of *Legionella* bacteria above the guiding values living in the analysed tenant-owned dwelling to be:

100 cfu/100 ml	$p_f = 0,85$
1000 cfu/100 ml	$p_f = 0,054$
10 000 cfu/100 ml	$p_f = 0,0058$

The performed analysis includes several uncertainties in both the qualitative evaluation and the quantitative estimation since simplifications have been necessary throughout the work due to a lack of data or scientific knowledge. However, the purpose of the analysis was to evaluate the possibility to compare the undesirable indoor event caused by the environmental impact *Legionella* bacteria and the increased risk to humans. A more thorough discussion about the results and uncertainties will be performed in chapter 7.

7 DISCUSSION AND CONCLUSIONS

7.1 Introduction

The main objective of this work was to develop a probabilistic procedure similar to the one used in modern design codes for building structures. The purpose of the procedure was to estimate the risk of an unhealthy indoor environment to occur caused by the design and construction of buildings. This was meant to be achieved by identifying decisions made in the building process about the future or the existing building with the potential to cause an unhealthy indoor environment to humans. The objectives were also to find a method similar to the probabilistic method used in structural reliability analysis, and to verify the model by implementing it on hazards where sufficient data were available. This chapter will discuss the developed procedure and the application of different environmental impacts to buildings, its possibilities and limitations.

7.2 The proposed risk analysis procedure

Based on the literature review in chapter 2, a procedure for risk analysis was proposed in chapter 3 with the objective to quantitatively estimate the risk of indoor air pollutants to occur and cause an unhealthy indoor environment to humans. The procedure was based on the IEC standard of risk analysis combined with fault tree analysis. The use of structural reliability analysis (SRA) revealed the risk to be defined as the violation of the limit state function:

$$M_{\mathrm{env}} = G(X_{\mathrm{env}}, Y_{\mathrm{env}}) = X_{\mathrm{env}} - Y_{\mathrm{env}} < 0$$

The random variables X_{env} and Y_{env} were defined as:

X_{env} = the dose-response relationship, i.e. the relationship between the exposure to humans of the undesirable indoor event and the proportion of the exposed population suffering from negative health effects.

Y_{env} = the undesirable indoor event, i.e. a function of the environmental impact together with the design and construction of the building.

Fault tree analysis (FTA) has earlier proved to be an efficient tool also in the building process. It is a commonly used deductive method that allows for both qualitative and quantitative evaluation and for which rules and guidelines exist. The tree structure offers a clear and informative picture of causes to fault events and is therefore an excellent communication tool. FTA was used for the qualitative evaluation of the undesirable indoor event Y_{env}, which was described by basic events with a set of random variables logically connected with a function expressing their relationship. However, before using FTA some general constraints must be considered.

- FTA can be a rather time-consuming task.
- The establishment of the undesirable event needs reflection to be possible to develop down to basic events without creating a tree that is too elementary or too detailed, and hence difficult to evaluate.
- Small subsequent steps in the deductive reasoning to find the closest cause to fault events is necessary otherwise important fault events can be overlooked.

For the general case standard fault trees would be possible to establish and use on different standard types of building components for risk estimation, but also as a communication tool and checklist.

Application of observations to the model shows several uncertainties both in the model and in the observations. Starting with the uncertainties of the undesirable indoor event Y_{env} some general conclusions are discussed in the following which have major influence on the accuracy of the risk estimation.

- The expression of basic events with proper random variables, probability density functions and their relationship demand a relatively profound and detailed knowledge about the subject of interest. Help from different scientific areas may be necessary to reduce uncertainties caused by lack of knowledge.
- The definition of the relationship between the basic events is often collected from the literature and may include uncertainties not known to the creator of the fault tree.
- Assigning probability density functions to the random variables can be difficult, since data of the observations may be sparse or difficult to receive.
- Assigning a proper distribution to data may be difficult, since the probabilities of interest almost always are present in the outer tail of the probability density function. A proper distribution of the entire population may not be the proper distribution for the estimation of risk.

Uncertainties are also present in the expression of human sensitivity X_{env} described by a dose-response relationship, a threshold value or guiding value.

- The distribution function of the dose-response relationship is not always S-formed but instead linear with no threshold dose, i.e. even at low dosage exposure humans are at risk. Normal distributions seem more appropriate describing the variation in sensitivity in the population.
- Establishment of guiding values when no dose-response relationship is available opens to questions about the relevance of the values, i.e. how likely is it that humans become unhealthy when exposed to concentrations above the guiding value.

However, the main objective of the work was to investigate the possibility of developing a probabilistic procedure to estimate the risk for an unhealthy indoor environment to occur from air pollutants caused by environmental impacts together with the design and construction of the building, similar to the probabilistic method used in SRA. Though, several uncertainties are present and have to be handled for a more accurate risk estimation, it is concluded that the undesirable indoor event Y_{env}, similar to the load effect S in SRA, and the dose-response relationship X_{env}, similar to the resistance R in SRA, can be compared as in SRA.

7.3 Radon concentrations indoors

The risk for indoor radon concentrations was estimated for a concrete slab on the ground with properties described in section 5.2. The causes to the undesirable indoor event Y_{env} "Radon concentrations in indoor air" were developed down to the basic events using fault tree analysis. The function expressing the relationship was given by:

$$G(\mathbf{Y}_{\text{env}}) = \frac{C_{\max} \cdot \lambda}{(\lambda + n) \cdot V_{\text{build}} \cdot \ell} \cdot \frac{\Delta p \cdot l \cdot w^3}{12\eta \cdot t} \qquad [\text{Bq/m}^3]$$

The random variables of interest in the analysis were the pressure difference, Δp, between the indoor and outdoor air, N(1,53; 0,86) (Pa), and the radon concentration in soil air, C_{max}, N(114 720; 10 370) (Bq/m^3). The width and extension of cracks and narrow openings in the base floor ($l \cdot w^3$) were considered using a random variable of concrete compressive strength f_{cm}, LN(40; 2,4) (MPa), and deterministic values for settlements and other openings.

The undesirable indoor event Y_{env} for the analysed single-family dwelling was estimated using Monte Carlo simulation and the computer software @Risk, and the distribution proposed was lognormal corresponding with the Swedish epidemiological study by Pershagen et al (1993). The undesirable indoor event Y_{env} for the single-family dwelling could be described by LN(64; 31) (Bq/m^3)

concerning indoor radon concentrations. The dose-response relationship X_{env} was collected from the epidemiological study, where the increased risk to suffer from lung cancer caused by indoor radon concentrations was estimated to 3,4 % per 1000 Bq/m^3 during one year of exposure (Pershagen et al, 1993).

The probability of violating the limit state function living in the analysed single-family dwelling was estimated, i.e. the undesirable indoor event Y_{env} was compared with the dose-response relationship X_{env}. The probability of limit state violation was:

$p_f = 0{,}002$ per year.

i.e. the probability that humans living in the analysed single-family dwelling would suffer from lung cancer. Data was collected from measurements in Hudiksvall to verify the model with real-world observations. However, the indoor radon concentration in buildings founded on the normal and high risk areas were approximately the same. One group founded on normal risk area and equipped with exhaust air- air supply ventilation contained enough observations to estimate an accurate distribution proposed to be lognormal LN(81; 101) (Bq/m^3). The risk of suffering from lung cancer was estimated to:

$p_f = 0{,}003$ per year.

The undesirable indoor event Y_{env} was also compared with the failure/success criterion 200 Bq/m^3 which is the threshold value stipulated in the Swedish Building Regulations (BFS 2002:19) to not be exceeded. The comparison gave the probability:

$p_f = 0{,}0001$

to have a higher level of indoor radon concentration compared with the threshold value living in the analysed single-family dwelling. The same comparison was made for the observations from Hudiksvall giving:

$p_f = 0{,}04$ for the observations and,

$p_f = 0{,}07$ for the proposed lognormal distribution.

It is obvious that the proposed lognormal distribution for the observations in Hudiksvall does not fit the input values properly in the area of interest, i.e. the outer tail. It is also noted that the observed radon concentrations have a wider spread than the modelled concentrations, giving a higher probability exceeding the stipulated threshold value in reality.

Some conclusions about limitations and uncertainties identified which have to be developed further by experts in each field of science to increase the precision of the risk estimation of indoor radon concentrations.

- The pressure difference was only considered using the difference in temperature between indoor and outdoor air which is a rough assumption, since i.a. wind characteristics influence the pressure difference. A more proper model of the pressure difference would improve the accuracy of the risk estimate.
- Estimating the cracks and narrow openings was a difficult task, where several assumptions had to be made, e.g. the development of cracks caused by shrinkage, cracks caused by settlements, and narrow openings between different building components and pipes passing the base floor. The use of concrete compressive strength as a random variable does not give the proper sensitivity to the importance of crack width. Research is performed regarding crack propagation in advanced concrete structures. More research is needed concerning less advanced structures like single-family dwelling concrete slabs, since the effect of cracks concern a great deal of the population.
- The distribution function of the dose-response relationship suffering from lung cancer caused by radon indoors is linear with no threshold dose, i.e. humans are at risk even at low dosage exposure. In the risk estimation, a uniform distribution was assumed as a probability density function, though a normal distribution seems more appropriate to describe the variation in sensitivity of the population. A normal distribution would also give a lower estimate of the risk suffering from radon related lung cancer.

7.4 *Legionella* contaminated aerosols indoors

The risk for *Legionella* contaminated aerosols indoors was estimated for the tenant-owned dwelling with properties described in section 6.2. The causes of the undesirable indoor event Y_{env} "*Legionella* contaminated aerosols in indoor air" was developed down to basic events using fault tree analysis. The function expressing this relationship was given by:

$$G(\mathbf{Y}_{env}) = \log N_2 = \frac{\mu}{2,303} \cdot (t_2 - t_1) + \log N_1 \qquad \text{[cfu/100 ml]}$$

The random variables of interest in the analysis were the initiating amount of bacteria, N_1, which was the union between the incoming amount from the distribution network, U(0,1; 1,0) (cfu/100 ml), and the accumulated amount in the dwelling pipes, U(0; 500) (cfu/100 ml), together with the time of stagnant water Δt, LN(66; 119) (h). The constant of specific growth rate, μ = 0,006 h^{-1}, was considered to be deterministic, though it depends on several variables, such as the amount of nutrients, biofilm and water temperature.

The undesirable indoor event Y_{env} was quantitatively estimated using the Monte Carlo simulation with the computer software @Risk. The distribution proposed was normal N(2,4; 0,5), that transformed from 10-base give a lognormal distribution LN(251; 3,2) (cfu/100 ml). No dose-response relationship X_{env} was available describing the sensitivity to *Legionella* bacteria in the population. Instead guiding values found in the literature had to be used.

In the risk estimation the probability of violating the limit state function was estimated, i.e. the undesirable indoor event Y_{env} was compared with the variable X_{env} expressed with guiding values. The probabilities of *Legionella* bacteria in the shower above the guiding values living in the tenant-owned dwelling were:

100 cfu/100 ml	$p_f = 0,8$
1000 cfu/100 ml	$p_f = 0,05$
10 000 cfu/100 ml	$p_f = 0,006$

An inventory has been performed by the Swedish Institute for Infectious Disease Control (SMI) and VVS Installatörerna, where buildings associated with Legionnaire's disease have been investigated (Det Norske Veritas, 2004). Data on measurements of *Legionella* concentrations in building water supply systems have not been possible to receive in this work depending on patient secrecy. However, the inventory may perhaps answer some questions about the relationship between infection of humans and the amount of *Legionella* bacteria in the building water supply system.

Some conclusions about limitations and uncertainties identified which have to be developed further by experts in each field of science to increase the precision of the method.

- The constant of specific growth rate is estimated using test results from only one dwelling and is considered to be deterministic. The amount of nutrients, variation in temperature, etc, are factors known to be important to the growth and multiplication, though not considered.
- Time of stagnant water in the building water supply system is an important input in the model and has influence on the risk estimation. A better knowledge of water usage habits in the population would improve the accuracy of the risk estimate.
- Estimating the initial amount of bacteria in the water supply system includes i.a. the amount of bacteria present in the incoming water to the building that is approximated and not tested. Bacteria have also accumulated in the pipes for a long time, which is an uncertainty considered using the results from the second sample taken during the tests.
- The uncertainty with the guiding values to express the variable X_{env} includes the fact that no dose-response relationship is available. Some people may suffer from Legionnaire's disease inhaling aerosols from water with "only" 100 cfu/100 ml, whereas the author of this thesis had 100 000 cfu/100 ml in the shower after returning from the summer vacation and still feels healthy! The sensitivity in the population depends on several parameters like age, smoking habits, other infections etc.

7.5 Comparison of risk criteria

It was stated in the introduction to this thesis that there is much to suggest that the creation of good indoor environments is an important factor to health and well-being to humans, and, that risks not taken on voluntary demand higher quality and safety requirements to be regarded as acceptable. One such case is the occurrence of indoor air pollutants causing an unhealthy environment to humans in buildings where people stay more than occasionally, i.e. at home or at work.

The Swedish Design Regulations (BFS 2003:6) stipulates that structures have to be designed considering different safety classes. The safety index β and the corresponding probability of failure are defined in ISO 2394-1998, *General principles on the reliability for structures*.

Safety class 1: $\beta = 3{,}7 \rightarrow \quad P = \Phi(-\beta) = 0{,}11 \times 10^{-3}$

Safety class 2: $\beta = 4{,}3 \rightarrow \quad P = \Phi(-\beta) = 0{,}85 \times 10^{-5}$

Safety class 1: $\beta = 4{,}8 \rightarrow \quad P = \Phi(-\beta) = 0{,}79 \times 10^{-6}$

Structures are to be designed according to a chosen safety class for which the maximum allowable probability of failure of the structure is the conditional probability of a person being killed or injured. A comparison with structural design safety is interesting. In the case of *Legionella* bacteria in the water supply system failure is difficult to discuss, since the dose-response relationship is unknown. However, the safety index β and the probability exceeding the threshold value 200 Bq/m^3 stipulated by the Swedish Building Regulations for new buildings were estimated for the undesirable indoor event Y_{env} concerning indoor radon concentrations giving:

$$\beta = 3{,}62 \quad \rightarrow \quad P(X_{env}-Y_{env}<0) = 0{,}14 \times 10^{-3}$$

The observations from Hudiksvall, where the buildings were built on normal risk area founded with a concrete slab on the ground and ventilated with exhaust air – air supply, had the probability $p_f = 40 \times 10^{-3}$ of exceeding the threshold value. The estimated safety index β is in approximate accordance with safety class 1, which is valid for the design of structures where the risk of serious injuries or death to humans as a failure consequence is minimal.

The WHO Air Quality Guidelines (WHO, 2000) states that lifetime lung cancers risk below 1×10^{-4} cannot be expected to be achievable because of the natural concentration of radon in ambient outdoor air. However, in Sweden with approximately 9 million people with a life expectancy of 80 years, this would result in 12 people suffering from radon related lung cancer each year. SSI has estimated the number of deaths in lung cancer connected to radon indoors to approximately 500 cases per year. A comparison can be made with the number of people in Sweden killed in the traffic. In 2004, 480 people were killed in traffic related accidents. The threshold value stipulated by the Swedish Building Regulations for new buildings is 200 Bq/m^3. WHO recommend remedial measurements to be considered for buildings with radon concentrations above 100 Bq/m^3, and in the Swedish Radiation Protection Institute's (SSI) comments on the Radon Commission; they suggest the threshold value to be reduced to 50 Bq/m^3, which would be in accordance with the stipulated environmental quality objectives.

The foundation of a single-family dwelling is not associated to high loading, which probably influences the efforts put on the design and construction where cracks in the concrete slab are regarded as something natural and unavoidable. To increase the safety and reliability towards indoor radon concentrations, more effort has to be put on the design and construction of the foundation, especially since it has been shown that high indoor radon concentrations are possible even on ground not associated to high risk. A single-family dwelling will probably always be exposed to movements and therefore to cracks. A solution to the problem with incoming radon gas could be to place a membrane above or below the concrete slab as a standard procedure independent of risk area. In addition, the membrane would act as moisture protection, though different precautions have to be taken depending on where the membrane is placed. A radon protection membrane can be bought at a cost of less than 50 SEK/m^2. Adding labour expenses, the additional cost to the construction of the analysed single-family dwelling of 110 m^2 would be approximately 10 000 SEK, tax excluded.

7.6 Summing-up

A lot of scientific knowledge exists about several causes to an unhealthy indoor environment although knowledge of the relationship between causes and illness sometimes is unknown.

Figure 7.1 Framed wall unprotected from rain and melting snow and with visible signs of soaked up water.

However, the scientific knowledge seems to have difficulties to find its way down to levels in the building process where decisions about the future or existing building are taken. The author have been able to follow the work with the extension of the university premises at a close range and seen, for example, the framed wall standing unprotected in both melting snow and rain, Figure 7.1.

One objective of the work was to identify decisions made in the building process during design and construction which had influence on the future indoor environment. Summing-up the more detailed description made earlier gives that:

- the risk of high levels of radon concentrations indoors has to be considered independent of the assumed or measured radon concentration in soil air which includes precautions like air-tight foundations and proper ventilation,
- the risk of microbial growth has to be considered independent of material and the material should be considered contaminated already when arriving from the manufacturer. All material has to be protected from moisture in all phases of the building process, and
- *Legionella* bacteria are not only a problem in large complex buildings like hospitals, hotels and public baths. It can be a problem also in dwellings and especially in equipment where the water temperature is controlled to avoid scalding, e.g. in the shower.

The author wish that this work will lead to increased awareness that decisions during the design and construction of buildings have high influence, not only in human well-being, but to our well-being.

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APPENDIX A

Rules of Boolean algebra

Table A.1 Rules of Boolean algebra (Vesely et al, 1981).

Designation	Mathematical symbols
Commutative law	$E_1 \cap E_2 = E_2 \cap E_1$ $E_1 \cup E_2 = E_2 \cup E_1$
Associative law	$E_1 \cap (E_2 \cap E_3) = (E_1 \cap E_2) \cap E_3$ $E_1 \cup (E_2 \cup E_3) = (E_1 \cup E_2) \cup E_3$
Distributive law	$E_1 \cap (E_2 \cup E_3) = (E_1 \cap E_2) \cup (E_1 \cap E_3)$ $E_1 \cup (E_2 \cap E_3) = (E_1 \cup E_2) \cap (E_1 \cup E_3)$
Idempotent law	$E \cap E = E$ $E \cup E = E$
Law of absorption	$E_1 \cap (E_1 \cup E_2) = E_1$ $E_1 \cup (E_1 \cap E_2) = E_1$
Complementation	$E \cap \overline{E} = \varnothing$ $E \cup \overline{E} = \Omega = 1$ $\overline{(\overline{E})} = E$
de Morgan's theorem	$\overline{(E_1 \cap E_2)} = \overline{E_1} \cup \overline{E_2}$ $\overline{(E_1 \cup E_2)} = \overline{E_1} \cap \overline{E_2}$
Unnamed relationships but frequently used in the reduction process	$E_1 \cup (\overline{E_1} \cap E_2) = E_1 \cup E_2$ $\overline{E_1} \cap (E_1 \cup \overline{E_2}) = \overline{E_1} \cap \overline{E_2} = \overline{(E_1 \cup E_2)}$

APPENDIX B

Insulation thickness

The necessary insulation thickness under the concrete slab in chapter 5.2 is calculated using the method shown in Harderup (1993, 2000). The single-family dwelling has an area of 110 m^2 (b=8,00 m, l=13,75m) and the foundation is made on undisturbed soil of glaciofluvial sand. The annual mean temperature is T_0=6,6°C, and the indoor temperature is T_i=20,9°C. Sand has a thermal conductivity (λ_j) of 2,0 W/m°C and a thermal capacity (C) of 2,0x10^6 J/m^3°C to be used for calculation of insulation thickness under the concrete slab. The insulation to be used is ground stone wool with the thermal conductivity (λ_i) of 0,036 W/m°C.

$$\frac{L}{B} = \frac{13,75}{8} = 1,72 \tag{B.1}$$

$$u_{\text{mitt}} = \frac{T_1 - \Delta T - \overline{T_0}}{T_1 - \overline{T_0}} = \frac{20,9 - 3 - 6,6}{20,9 - 6,6} = 0,79 \tag{B.2}$$

From the calculated values in equation (B.1) and (B.2) the value of *d/B* can be established using Figure 13 in Harderup (2000).

$$d / B \approx 0,15 \tag{B.3}$$

This gives

$$d = \frac{d_{\text{i}} \cdot \lambda_{\text{j}}}{\lambda_{\text{i}}} \Rightarrow \frac{d}{B} = \frac{d_{\text{i}} \cdot \lambda_{\text{j}}}{B \cdot \lambda_{\text{i}}} \Rightarrow 0,15 = \frac{d_{\text{i}} \cdot 2,0}{8,0 \cdot 0,036} \Rightarrow d_{\text{i}} = \frac{0,15 \cdot 8,0 \cdot 0,036}{2,0} = 0,022$$

The necessary insulation thickness is 22 mm.

C RADON CONCENTRATION DATA

C.1 Radon data (daily mean value)

1994-12-01	110,9565
1994-12-02	112,8636
1994-12-03	115,6364
1994-12-04	118,9545
1994-12-05	119,9091
1994-12-06	117,6364
1994-12-07	114,7273
1994-12-08	116,4091
1994-12-09	117,1667
1994-12-10	116,6364
1994-12-11	118,7826
1994-12-12	118,3636
1994-12-13	116,9091
1994-12-14	114,4545
1994-12-15	111,8182
1994-12-16	116,5454
1994-12-17	113,7273
1994-12-18	114,4545
1994-12-19	115,6522
1994-12-20	115,913
1994-12-21	116,2727
1994-12-22	112,3182
1994-12-23	113,5909
1994-12-24	115,6364
1994-12-25	116,8182
1994-12-26	119,6522
1994-12-27	125,2273

1994-12-28 -
- *1994-12-31*
4 days of data missing

1995-01-01	120,7986
1995-01-02	112,6041
1995-01-03	104
1995-01-04	106,3828
1995-01-05	110,5395
1995-01-06	114,7281
1995-01-07	113,9677
1995-01-08	115,7137
1995-01-09	121,5251
1995-01-10	125,5268
1995-01-11	119,6262
1995-01-12	109,8895
1995-01-13	105,2706
1995-01-14	111,3806
1995-01-15	112,6189
1995-01-16	113,4197
1995-01-17	118,4962
1995-01-18	120,0319
1995-01-19	117,7358
1995-01-20	116,4868
1995-01-21	119,0979
1995-01-22	126,4252
1995-01-23	129,8301
1995-01-24	126,3084
1995-01-25	120,8602
1995-01-26	118,3411
1995-01-27	118,9592
1995-01-28	118,1585
1995-01-29	120,206
1995-01-30	117,2833
1995-01-31	110,5993
1995-02-01	120,833
1995-02-02	118,0268
1995-02-03	115,9452
1995-02-04	126,7948

1995-02-05	130,5968
1995-02-06	137,0816
1995-02-07	143,288
1995-02-08	142,4254
1995-02-09	139,8152
1995-02-10	137,7039
1995-02-11	135,2782
1995-02-12	139,7239
1995-02-13	138,8742
1995-02-14	138,2179
1995-02-15	143,5663
1995-02-16	149,1789
1995-02-17	150,425
1995-02-18	149,644
1995-02-19	143,9295
1995-02-20	141,4872
1995-02-21	138,1202
1995-02-22	137,3067
1995-02-23	134,8258
1995-02-24	135,0573
1995-02-25	128,4664
1995-02-26	124,246
1995-02-27	120,4545
1995-02-28	126,3262
1995-03-01	123,3241
1995-03-02	123,0926
1995-03-03	124,9177
1995-03-04	125,6882
1995-03-05	125,0255
1995-03-06	126,7523
1995-03-07	123,5222
1995-03-08	117,8207
1995-03-09	119,1243
1995-03-10	117,7204
1995-03-11	117,8683

1995-03-12	119,1525
1995-03-13	119,1567
1995-03-14	123,1053
1995-03-15	127,2154
1995-03-16	126,438
1995-03-17	124,9533
1995-03-18	127,8271
1995-03-19	121,096
1995-03-20	116,9817
1995-03-21	109,155
1995-03-22	110,376
1995-03-23	115,1317
1995-03-24	120,7562
1995-03-25	122,6274
1995-03-26	118,2812
1995-03-27	121,2532
1995-03-28	118,4006
1995-03-29	114,7578
1995-03-30	108,1436
1995-03-31	112,1028
1995-04-01	118,7464
1995-04-02	121,2595
1995-04-03	119,3182
1995-04-04	117,6104
1995-04-05	112,859
1995-04-06	117,7549
1995-04-07	119,3097
1995-04-08	117,156
1995-04-09	116,627
1995-04-10	117,9906
1995-04-11	118,0352
1995-04-12	117,3088
1995-04-13	116,6674
1995-04-14	118,6487
1995-04-15	122,8313
1995-04-16	126,2574
1995-04-17	125,7392
1995-04-18	124,5454
1995-04-19	122,1177
1995-04-20	115,3972

1995-04-21	114,5476
1995-04-22	115,8985
1995-04-23	121,5034
1995-04-24	123,4728
1995-04-25	128,494
1995-04-26	130,6584
1995-04-27	128,2052
1995-04-28	125,3122
1995-04-29	123,7769
1995-04-30	121,4656
1995-05-01	120,4354
1995-05-02	122,6636
1995-05-03	122,6933
1995-05-04	125,8326
1995-05-05	124,7302
1995-05-06	125,2591
1995-05-07	120,9792
1995-05-08	119,5497
1995-05-09	117,8972
1995-05-10	115,9537
1995-05-11	114,874
1995-05-12	112,9338
1995-05-13	112,0561
1995-05-14	114,8577
1995-05-15	114,6389
1995-05-16	114,3373
1995-05-17	113,1075
1995-05-18	118,1287
1995-05-19	113,7149
1995-05-20	113,802
1995-05-21	116,3882
1995-05-22	117,859
1995-05-23	122,5403
1995-05-24	119,7338
1995-05-25	119,8768

1995-05-26
1 day of data missing

1995-05-27	112,2247
1995-05-28	113,5603
1995-05-29	113,9567
1995-05-30	111,634
1995-05-31	108,7885

1995-06-01 -
- 1995-06-26
26 days of data missing

1995-06-27	113,6168	1995-08-06	102,3669	1995-09-15	107,984
1995-06-28	115,4779	1995-08-07	102,8866	1995-09-16	110,4545
1995-06-29	117,2175	1995-08-08	99,2971	1995-09-17	108,785
1995-06-30	112,0195	1995-08-09	99,932	1995-09-18	109,898
1995-07-01	110,3894	1995-08-10	99,4031	1995-09-19	111,8246
1995-07-02	110,051	1995-08-11	96,9796	1995-09-20	113,0352
1995-07-03	111,4167	1995-08-12	99,5386	1995-09-21	112,1516
1995-07-04	109,5624	1995-08-13	99,9681	1995-09-22	109,5242
1995-07-05	104,5541	1995-08-14	100,2485	1995-09-23	109,4223
1995-07-06	103,0586	1995-08-15	96,9626	1995-09-24	110,1503
1995-07-07	102,8186	1995-08-16	96,5357	1995-09-25	109,9512
1995-07-08	102,7315	1995-08-17	95,9891	1995-09-26	109,1228
1995-07-09	101,8373	1995-08-18	96,3218	1995-09-27	107,5552
1995-07-10	103,2496	1995-08-19	96,8476	1995-09-28	110,3335
1995-07-11	104,9491	1995-08-20	95,8454	1995-09-29	107,8887
1995-07-12	104,4053	1995-08-21	96,1195	1995-09-30	109,0739
1995-07-13	104,8555	1995-08-22	96,3148	1995-10-01	111,8732
1995-07-14	101,986	1995-08-23	98,5471	1995-10-02	115,5201
1995-07-15	101,5635	1995-08-24	97,4979	1995-10-03	113,4303
1995-07-16	105,7052	1995-08-25	96,6608	1995-10-04	116,9881
1995-07-17	114,692	1995-08-26	96,4804	1995-10-05	117,706
1995-07-18	117,3194	1995-08-27	94,4605	1995-10-06	117,0476
1995-07-19	116,6249	1995-08-28	93,9189	1995-10-07	118,3029
1995-07-20	115,4737	1995-08-29	93,0413	1995-10-08	119,9883
1995-07-21	119,3458	1995-08-30	94,4116	1995-10-09	117,8261
1995-07-22	119,0994	1995-08-31	93,0501	1995-10-10	119,7621
1995-07-23	113,1457	1995-09-01	92,7503	1995-10-11	118,2477
1995-07-24	112,6737	1995-09-02	93,6741	1995-10-12	118,2646
1995-07-25	114,0824	1995-09-03	97,5519	1995-10-13	118,3751
1995-07-26	111,6044	1995-09-04	99,3417	1995-10-14	116,8989
1995-07-27	111,4677	1995-09-05	98,9613	1995-10-15	117,2557
1995-07-28	111,0089	1995-09-06	99,5872	1995-10-16	117,1984
1995-07-29	109,9724	1995-09-07	99,0506	1995-10-17	117,158
1995-07-30	110,0828	1995-09-08	100,4248	1995-10-18	113,6172
1995-07-31	107,859	1995-09-09	100,5161	1995-10-19	108,0756
1995-08-01	108,6024	1995-09-10	99,1525	1995-10-20	108,7723
1995-08-02	107,2839	1995-09-11	100,3096	1995-10-21	107,3209
1995-08-03	107,5191	1995-09-12	100,6223	1995-10-22	108,4579
1995-08-04	105,5714	1995-09-13	101,1032	1995-10-23	110,1763
1995-08-05	102,3619	1995-09-14	104,4605	1995-10-24	110,6415

1995-10-25	112,6402
1995-10-26	110,6648
1995-10-27	112,6696
1995-10-28	110,7436
1995-10-29	106,4242
1995-10-30	108,0565
1995-10-31	108,4834
1995-11-01	111,605
1995-11-02	111,8564
1995-11-03	111,1087
1995-11-04	103,7256
1995-11-05	104,3068
1995-11-06	108,2385
1995-11-07	108,0289
1995-11-08	108,9146
1995-11-09	111,2723
1995-11-10	109,3139
1995-11-11	106,6164
1995-11-12	106,9626
1995-11-13	108,2816
1995-11-14	109,3331
1995-11-15	112,2218
1995-11-16	111,4082
1995-11-17	111,5683
1995-11-18	107,3267
1995-11-19	110,102
1995-11-20	105,907
1995-11-21	107,5297
1995-11-22	109,0845
1995-11-23	113,2094
1995-11-24	116,559
1995-11-25	120,4896
1995-11-26	122,3088
1995-11-27	121,8946
1995-11-28	116,8041
1995-11-29	117,9524
1995-11-30	115,4397

C.2 Iterative calculation of safety index β

alfa dp	alfa C	alfa f	beta	dg/ /dZdp	dg/ /dZC	dg/ /dZf	norm. length	dg/ /dbeta	g(beta)	g(beta)/ /delta
High risk area										
0,5	0,5	0,5	3							
0,9638	0,26658	-0,0086	5,872	-39,237	-10,85	0,3486	40,712	-24,87	71,437	-2,8724
0,8471	0,5312	-0,0178	3,76	-39,632	-24,85	0,8338	46,787	-44,828	-94,703	2,1126
0,9275	0,3737	-0,013	3,673	-41,082	-16,55	0,5767	44,295	-43,602	-3,7768	0,0866
0,914	0,40552	-0,0134	3,624	-38,985	-17,3	0,5717	42,653	-42,628	-2,0806	0,0488
0,9179	0,39652	-0,0132	3,623	-39,31	-16,98	0,566	42,825	-42,823	-0,0617	0,0014
0,9171	0,39833	-0,0132	3,623	-39,199	-17,02	0,5658	42,74	-42,74	-0,006	0,0001

Abbreviations:

alfa dp	sensitivity factor for difference in air pressure, $\alpha_{\Delta p}$
alfa C	sensitivity factor for radon concentration in soil air, α_{Cmax}
alfa f	sensitivity factor for concrete compression strength, α_{fcm}
beta	safety index β
dg/dZdp	differentiating g(Z) with respect to $Z_{\Delta p}$
dg/Dzc	differentiating g(Z) with respect to Z_{Cmax}
dg/dZf	differentiating g(Z) with respect to Z_{fcm}
norm.length	distance from design point to origin
dg/dbeta	differentiating g(Z) with respect to safety index β
g(beta)	limit state surface in the normalised z-coordinate system
g(beta)/delta	second term in Newton-Raphson method