Comparative study of risk analysis methods from a fire safety perspective

-Case study of new underground facilities at CERN

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Abstract
This report has investigated which type of risk analysis methods that can be used in an early design phase in a unique facility from a time and quality perspective. Two planned underground facilities for the HL-LHC at CERN have been used as a case study. The methodology is an action research study with information gathered from a literature study and survey. Six different risk analysis methods have been chosen to represent different types of methods. The chosen methods are event tree analysis, preliminary hazard analysis, What-if, Gretener method, ROGA and NFPA 101. The results from the comparison of the methods were that the more complex risk analysis method needed detailed information of the final design of the facility and equipment. In an early design phase, this was hard to find which lead to a result with many uncertainties and assumptions. One conclusion of this report is that a more simple methodology is to prefer in an early design phase when comparing different design options. Another conclusion is that there is a need to develop a tool to create design fires for electrical cabinets and to develop a specific risk analysis method for this type of facility that can be used in an early phase.

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Preface

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"Just as hunters can identify animals from tracks in mud or snow, physicists identify subatomic particles from the traces they leave in detectors" (CERN, 2015a)

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Summary

Risk exists everywhere, but depending on the situation, the way to manage risk might differ. Two aggravating circumstances are if the probability is low or if the analysed facility is unique. CERN houses unique equipment, which have limited or no statistical data regarding consequences or probability for the risks. Due to CERN's upgrade of the Large Hadron Collider (LHC) to the High-Luminosity LHC, two new underground facilities will be built. These facilities are a subject to these aggravating circumstances. The facilities are still in the design phase and several civil engineering options are being evaluated. However, there are some questions from the occupational health & safety and environmental protection unit (HSE), regarding if the baseline configuration meets the safety criteria. One alternative option is therefore instead recommended by the project safety officer, in agreement with the HSE unit. It should be noticed that the planned facilities will be located 80 meters below surface and the alternative option demands a more extensive excavation, which render in a higher cost. The special circumstances at CERN lead to high demands on the performed risk analysis.

The division of fire safety engineering at Lund University participates in this project with one master thesis and two bachelor theses. These reports include one qualitative analysis of the fire and evacuation safety based on design fires and fire and evacuation simulations, a risk analysis and one analysis of the fire safety of the rescue chambers. The different analyses were done for both the baseline configuration and the alternative option.

This is the master thesis, which includes design fires and the risk analysis of the project. To get a scientific aspect in the thesis, an action research study was done. The purpose of this research was to compare different risk analysis methods in order to investigate what type of risk analysis method is to prefer in an early design phase of a unique facility, where many details are unknown. A literature study was done where risk analysis methods, which could be used for fire risks and were not developed for a specific industry, were chosen for further analysis.

The result from this thesis can be divided into two parts, results regarding the use of the risk analysis methods in an early phase and the results regarding the analysis of CERN's facilities. The lack of information lead to problems when using the more complex method (Event tree analysis) where many details have to be known or otherwise based on assumptions. In this thesis, the limited information regarding the final design lead to that several assumptions had to be made, which rendered in uncertainties in the analysis. Complex methods are also time and resource demanding, which can be a problem in an early design phase if different options needs to be evaluated. Simplified methods (What-if and Preliminary hazard analysis) and index methods (NFPA 101) are easier and quicker to use. These methods are not as sensitive to changes in the design as the complex method. All the assumptions and the uncertainties introduced in the complex method render in a result that is no more accurate than the simplified methods.

The use of the different risk analysis methods shows that the alternative option is to prefer. Most of the methods highlight the problematics with the evacuation in the baseline configuration, which the alternative option solves. The thesis also shows that a simpler risk analysis method is to prefer in an early design phase, when different options shall be evaluated.

Another result from this thesis is that there is a need to develop tools to design fires for cabinets and to develop specific risk analysis methods for this type of facility.

Sammanfattning

Risker finns överallt men beroende på situationen kan dessa vara olika svåra att hantera. Två försvårande omständigheter är om sannolikheten för en risk är låg eller om den aktuella anläggningen är unik av sitt slag. CERN huserar utrustning som är världsunik, vilket ger begränsad statistisk bakgrund angående konsekvens eller sannolikhet för riskerna i deras anläggningar. I samband med att CERN ska uppgradera Large Hadron Collider (LHC) till High-Luminosity LHC ska två nya anläggningar byggas. Anläggningarna är fortfarande i planeringsstadiet och ett antal olika förslag har tagits fram för analys. Dock finns det vissa frågetecken från säkerhetsavdelningen på CERN om huvudförslaget uppfyller förväntade säkerhetskrav. Ett av de alternativa förslagen har därför rekommenderats från avdelningen. Det bör tilläggas att de tänkta anläggningarna ska befinna sig ca 80 meter under marknivå och den alternativa lösningen kräver att en större volym grävs ut vilket leder till ökade kostnader. De speciella förhållandena som råder på CERN leder till höga krav på genomförda riskanalyser.
På grund av detta genomförs ett projekt där avdelningen för brandteknik på Lunds tekniska högskola har bidragit med tre arbeten, en masteruppsats, två kandidatuppsatser. Dessa arbeten omfattar en kvalitativ analys av brand- och utrymningssäkerhet i form av designbränder samt brandförlopps- och utrymningssimuleringar, riskanalys och en analys av brandsäkerheten hos räddningskammare. Detta genomfördes för både huvudförslaget samt det alternativa förslaget som rekommenderats av säkerhetsavdelningen på CERN.

Detta är masteruppsatsen och omfattar designbränder och riskanalysen i projektet. För att även få in en vetenskaplig aspekt i uppsatsen gjordes även en aktionsforskning. Syftet med aktionsforskningen var att jämföra olika typer av riskanalysmetoder och därigenom undersöka vilken sorts riskanalys som lämpar sig bäst vid en analys i ett tidigt skede av en unik anläggning, där många detaljer är okända. En litteraturstudie genomfördes där urval av riskanalyser skedde utifrån att de ska gå att använda för brandrisker samt att de inte ska vara gjorda för en specifik verksamhetstyp.

Resultatet från uppsatsen kan delas upp i två delar, resultat kring användandet av riskanalyser i ett tidigt skede samt resultat kring analysen av anläggningarnas utformning. För de förstnämnda resultaten märktes det tydligt att bristen på information ledde till problem för mer komplexa metoder där många detaljer antingen måste vara kända eller att många antaganden måste göras. I denna uppsats ledde graden av okända detaljer om slutkonstruktionen till att flera antaganden behövde göras, vilket också ökade osäkerheterna i analysen. Komplexa metoder (Event tree analysis) är även tids- och resurskrävande vilket kan vara ett problem i ett tidigt skede om olika förslag ska analyseras. Förenklade metoder (Preliminary hazard analysis och What-if) och indexmetoder (NFPA101) är enklare och snabbare att använda och dessutom inte lika beroende av detaljer angående den slutgiltiga konstruktionen. Resultatet visar att på grund av osäkerheterna kring detaljer i utformningen av anläggningarna ger inte en mer avancerad metod ett mer pålitligt slutresultat.

Genom användandet av de olika riskanalysmetoderna framgår det att det alternativa förslaget är att föredra. Det som de flesta metoderna belyser är problematiken med utrymning i huvudförslaget, vilket löses med alternativet. Vidare så framgår det av uppsatsen att en enklare riskanalysmetod är att föredra då flera olika lösningar ska jämföras i ett tidigt skede av projekten.

Övriga resultat i denna uppsats är att det behöver utvecklas verktyg för att skapa designbränder för elskåp och att även utveckla en specifik riskanalysmetod för den här typen av anläggningar.

Table of contents

Abbreviations

ATLAS	A large Toroidal LHC ApparatuS, one of two general-purpose detectors at the Large Hadron Collider (LHC).
CAFS	Compressed air foam system
CERN	The European Organization for Nuclear Research
CFD	Computational Fluid Dynamics
CFRS	CERN Fire and Rescue Service
CMS	The Compact Muon Solenoid (CMS) is a general-purpose detector at the Large Hadron Collider (LHC).
ETA	Event Tree Analysis
EVAC	Evacuation (software)
FDS	Fire Dynamics Simulator (software)
HL-LHC	High Luminosity Large Hadron Collider
HRR	Heat Release Rate
HSE	Occupational health & safety and environmental protection unit
LHC	Large Hadron Collider
NFPA	National Fire Protection Association
PHA	Preliminary Hazard Analysis, risk analysis method
PM	Access shaft
ROGA	Risk-Oriented Hazard Analysis
UV	Ultra Violet
UA	Two connecting galleries between the UR tunnel and the LHC tunnel.
UL	Same as UA galleries but smaller and only cryonic ducts, no technical equipment.
UR	Wide equipment tunnel running parallel to the LHC tunnel. The equipment tunnel is housing transformers and power converters.
US	Cavern for cryogenic equipment
UW	Cavern for ventilation and water pumps
VUV	Vacuum Ultra Violet

Nomenclature

α	[kW·min^{-1}]	Slope coefficient during growth phase
ΔH_c	[MJ·kg^{-1}]	Heat of combustion
ρ_∞	[kg·m^{-3}]	Ambient air density
ρ_{cable}	[kg·m^{-3}]	Density of cables
τ	[s]	Decay time constant
φ_{air}	[-]	Fraction air in cables
$\varphi_{plastic}$	[-]	Fraction plastic in cable trays
A	[-]	The probability of ignition (Gretener method)
A_{cable}	[m^2]	Surface area of the cable
B	[-]	Degree of danger (Gretener method)
D_c	[m]	Characteristic diameter
C_a	[-]	Area adjustment coefficient
c_{eff}	[-]	Combustion efficiency
$c_{p,air}$	[kJ·kg^{-1}·K^{-1}]	Specific heat capacity for air
$c_{p,cable}$	[kJ·kg^{-1}·K^{-1}]	Specific heat capacity for cables
E'_{tray}	[MJ·m^{-1}]	Fire load per meter cable tray
F	[-]	Fire resistance of the building (Gretener method)
f_c	[-]	Convection factor
g	[m·s^{-2}]	Gravitational acceleration
H_{tray}	[m]	Height of cable tray/cables
h	[W·m^{-2}·K^{-1}]	Convective heat transfer coefficient
$l_{initial}$	[m]	Length of ignited area at ignition
N	[-]	Standard measures (Gretener method)
P	[-]	Possible dangers (Gretener method)
$\dot{Q}$	[kW]	HRR
$\dot{Q}''$	[kW·m^{-2}]	HRR per unit area
$\dot{Q}_0$	[kW]	HRR used for dimension in growth phase
$\dot{Q}_{initial}$	[kW]	HRR at ignition
$\dot{Q}_{max}$	[kW]	Max HRR
$\dot{Q}_{t_d}$	[kW]	HRR at start of decay
R	[-]	Fire risk (Gretener method)
S	[-]	Special measures (Gretener method)
T_∞	[K]	Ambient temperature
T_{cable}	[°C]	Temperature in cable
$T_{g,z}$	[K]	Temperature in plume at height z
t	[s]	Time
t_d	[s]	Time at start of decay
t_g	[s]	Time to reach $\dot{Q}_0$
$t_{\dot{Q}_{max}}$	[s]	Time to max HRR
V_{cable}	[m^3]	Volume of cable
v_p	[m·min^{-1}]	Flame propagation speed

W_{tray}	[m]	Width of cable tray
w_f	[m]	Width of flame front
z	[m]	Height
z_0	[m]	Dimension height

Definitions

Scenario	A chain of events.
Simulation	Refers to a scenario calculated with computers.
Event	Refers to something that happens on the time line with a positive or negative outcome.
Risk analysis	In the risk analysis the normal state is defined and hazards are identified and quantified as a level of risk usually consisting of a consequence and a probability. The risk analysis is a part of the broader term risk assessment.
Risk assessment	In the risk assessment the risk is presented and evaluated in addition to the risk analysis.
Point 1	Located at the ATLAS detector in CERN main site, Meyrin, near the CFRS. Point 1 is one of the two locations for the new facilities.
Point 5	Located at the CMS detector in CERN site de Cessy. Point 5 is one of the two locations for the new facilities.

1. Introduction

During the next upgrade of the European organisation for nuclear research's (CERN) Large Hadron Collider (LHC) apparatus to High-Luminosity LHC (HL-LHC), two new underground facilities will be constructed. The demands on the fire and evacuation safety on these new facilities are high and therefore needs to be analysed and investigated.

This master thesis will be part of a larger project that involves the fire safety of the constructions and the possibility to evacuate. The overall objective of the larger project is to find a solution that takes the restrictions in space, accessibility and ventilation into account. Unique equipment and surroundings, e.g. radioactivity, contributes to aggravating circumstances.

Lund University and the Division of Fire Safety Engineering participate with three theses within the larger project. This thesis (report 5511), report 5513 and report 5512 will together cover design fires, scenarios, risk assessment, fire simulation and evacuation. Due to the design of the facilities are still in an early phase many changes can be expected. This thesis will be made so that these changes can easily be adapted to the changes afterwards.

The scope of the whole project is to assess two different civil engineering solutions, prepared for two different points of the LHC in the framework of the HL-LHC project, from a fire safety perspective. The two different civil engineering solutions are the baseline configuration and one alternative option.

This thesis also includes a literature study to see if there are other risk analysis methods, which could contribute to the risk assessment at CERN, or other facilities of the same type, in the future. In the thesis it will also be investigated how other similar facilities are using risk analysis methods.

The different theses involved in the project are presented in table 1.

Table 1. Description of the three theses involved in the collaboration between CERN and Lund University.

Report number	**Author/authors**	**Description**
5511	Erik Isaksson and Frida Olin	Risk analysis methods
5512	Johannes Corbee	Evacuation and reliability of rescue chambers
5513	Gustav Wallgren	Fire simulations

1.1 Purpose

The purpose of this thesis is to compare different risk analysis methods regarding evacuation in case of fire. If possible, the methods will also be analysed from a fire safety perspective regarding operating and asset protection. This is done to investigate if one method is to recommend in an early design phase from a time and quality aspect.

1.2 Overall objective

The overall objective of this thesis is to do a comparative study to identify a suitable risk analysis method that can be used to evaluate different fire safety solutions within a unique facility of this type in an early design phase. The CERN facility will be used as a case study object.

The sub objectives of this thesis are:

- Determine design fires that will challenge the fire safety measures in the tunnel at CERN.
- Make an event tree and from this make a priority list of scenarios that will be simulated in report 5513.
- Compare and evaluate different risk analysis methods and identify the most suitable method for the case study.
- Investigate how risk analyses are used at other particle accelerator facilities.

1.3 Methodology

Since the purpose and the overall objective of this thesis have a problem solving characteristic, it is chosen to use an action research methodology. The used methodology is based on a combination of survey and case study for information gathering (Höst, Regnell & Runeson, 2011). The collected information is then used to solve the problems of how to use risk analysis methods in an early design phase regarding quality and resource aspects. A literature study is used to identify different risk analysis methods that could be applicable at CERN's facility. The result from the chosen risk analysis method will be compared to see if one method provides better result. The literature study is complemented by interviews with fire engineers at two particle accelerator facilities, ESS and MAX IV.

Since this thesis is a collaboration between the Division of Fire Safety Engineering at Lund University and CERN it was decided that the work should begin with a visit at CERN. The visit resulted in additional information about the large project that the thesis is a part of. During the visit, it became clear what CERN was expecting from this collaboration and it also became clear what a possible scientific part for this thesis could be.

The work started at CERN by defining design fires and choosing different scenarios based on a simplified early event tree analysis (ETA). The following literature study aimed to investigate what other methods could be used.

The search engines that were used in the literature study were Google, Google scholar, LUBsearch and Scopus. The search was limited to articles in the engineering area and the primary keywords that were used were technical risk analysis methods. The search was then extended from this first search to get more information about the found methods.

1.3.1 Choice of strategy

This master thesis runs parallel with two bachelor theses (report 5512 and 5513). A certain amount of collaboration and overlap between the theses is necessary. To some extent, this master thesis relies on some of the results from the other theses, and vice versa.

From a practical standpoint, the work was divided into several phases. In the beginning, input data of the design fires was provided to report 5512 and 5513 in order to proceed with the evacuation modelling and the computational fluid dynamics modelling, respectively.

An overview of the methodology is presented in figure 1. In the first phase, design fires were identified by simplified methods taking fire ignition, fire spread and evacuation issues into account. With the information from the literature, different heat release rate (HRR) curves were created. To give a more realistic HRR curve, calculations was made to see when the fire propagated at different distances to cable trays and cabinets. These calculations could then be used quickly to create a design fire for a specific point in the tunnel. Fires were designed for a number of locations in the underground facilities.

In the second phase, an event tree for each of the chosen locations was made to present an overview of the different scenarios that affected the possibility to evacuate. From this event tree, a priority list of scenarios was made. The priority depended on the extent of the HRR curves and evacuation problems for the different scenarios.

The majority of the thesis was a literature study, and it was carried out in phase three. The study aimed to investigate which risk analysis methods that could be used for this kind of facility. Another objective with the literature study was to investigate what risk analysis methods other facilities of the same type used and what they thought about the methods. To complement the literature study, interviews was done with fire engineers at similar facilities to CERN. These facilities were MAX IV and ESS. The interviews were semi-structured in that way that it was based on a few questions prepared on beforehand but mostly the interviewed engineers were allowed to share their thoughts freely about what types and how risk analysis methods are used in their facility and what they think of risk analysis methods in general.

In phase four, the methods were applied to the CERN facilities to evaluate if CERN would benefit from using another approach according to quality and time efficiency. CERN had requested that the ETA should be used. Since all methods had their advantages and disadvantages and CERN houses unique types of facilities, it was interesting to evaluate different risk analysis methods and compare the results from them.

In the last phase, the methodology was refined and evaluated. In this phase calculations, interpretation and evaluation of the results was made. In this phase, the thesis was also completed. The method is shown in figure 1.

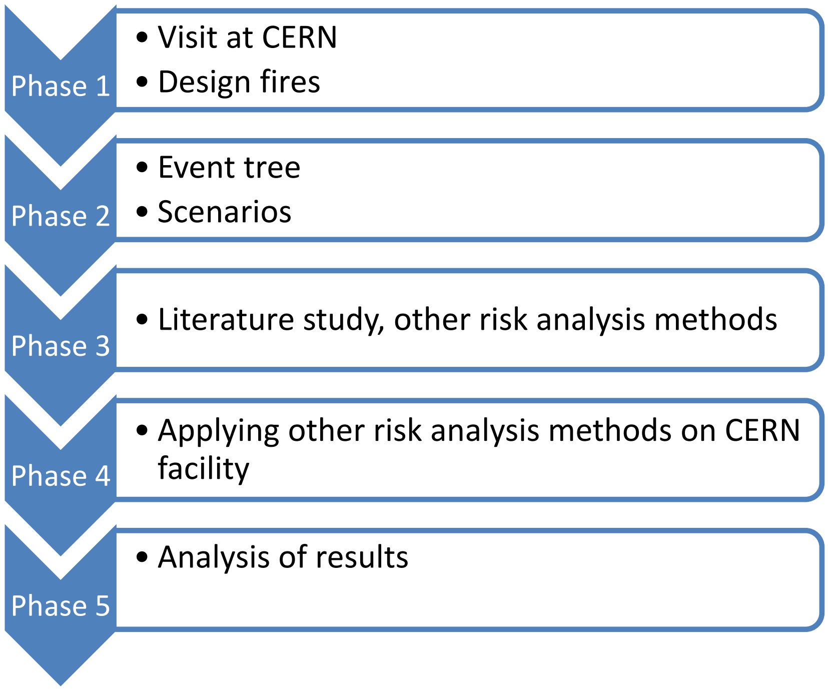

Figure 1. Overview of the methodology structure used in this thesis.

1.4 Disposition

Chapter 1 Introduction: The purpose, objectives, methodology are presented. In addition, the boundaries and limitations of this thesis are presented.

Chapter 2 Background: The context of this thesis is presented. The different areas, phases and other important details of the background for this thesis are described.

Chapter 3 Design fires: The method of creating design fires is described. The design fires specifically developed for CERN facilities are presented.

Chapter 4 Description of Risk analysis methods: The method for selecting risk analysis methods is described. In addition, each risk analysis method that is chosen is presented.

Chapter 5 Analysis: In this chapter, the different risk analysis methods are applied on CERN. A short discussion of the use of the method follows the analysis of each method.

Chapter 6 Summary of risk analysis at other facilities: MAX IV and ESS are shortly described. This chapter also contains interviews with fire engineers at the two facilities.

Chapter 7 Discussion: The result of the whole thesis is discussed. The risk analysis methods are compared to each other. Assumptions are discussed and reflected on.

Chapter 8 Conclusions: The conclusions of this thesis are presented.

Chapter 9 Future research: Suggestions for future research are presented.

1.5 Boundaries

The boundaries for this master thesis are set to include only risks regarding fire safety and evacuation considering personal safety, asset protection and operation safety. The new underground facilities connected to the HL-LHC project, used as case study in this thesis, will be subjected to several different phases during its lifetime:

- Construction
- Installation
- Commissioning
- Operation
- Technical shut down

Due to the limitations in time for this master thesis, the focus will be on short stops in the operational phase (short technical stop). Where no CFD simulations have to be done, also the technical shut down (long technical stop) will be analysed.

If the characteristics of the two facilities at point 1 and 5 differ, the data from point 5 will be used. This is due to a longer travel time for the fire brigade to point 5. For clarification of point 1 and 5, see definitions or chapter 2.1.1.

The thesis is based on the assumption that a fire has occurred. Therefore, the thesis focuses on the possibility to reduce the effect of consequences and not the probability of ignition.

When working in this project, the following parameters will be considered where it is necessary:

- Geometry of the premises (including access and ventilation doors) and characteristics of materials.
- Ventilation systems and their behaviour in case of fire.
- Presence of pressurized zones.
- Smoke extraction systems and their behaviour in case of fire.
- Smoke curtains.
- Fire detection and alarm systems.
- Presence (type, number, distribution, etcetera) of combustible materials.
- Number, distribution and characteristics of occupants in different design/operation phases.
- Intervention of Fire and Rescue Services.
- The administrative procedure for fire permit used at CERN, Safety Code E, (CERN, 1995).

The achievement of the fire safety objectives shall be proved thanks to simulations in report 5512 and 5513.

The thesis will have focus on worst credible case scenarios. It will not investigate interaction from occupants, like attempts to extinguish the fire, since it will result in less severe cases.

1.6 Limitations

Since the HL-LHC project is still in progress and many details are still not decided, it is important to keep in mind that the suggested designs are preliminary and they might be updated. A number of assumptions are made and this paper will follow the updated documents from CERN as far as possible.

2. Background

The following text is a citation from CERN and is their official summary of the organisation.

"*CERN, the European Organization for Nuclear Research, is an intergovernmental organisation with 21 Member States*[1]*. Its seat is in Geneva but its premises are located on both sides of the French-Swiss border. CERN's mission is to enable international collaboration in the field of high-energy particle physics research and to this end it designs, builds and operates particle accelerators and the associated experimental areas. At present more than 11 000 scientific users from research institutes all over the world are using CERN's installations for their experiments. The accelerator complex at CERN is a succession of machines with increasingly higher energies. Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy, and so on. The flagship of this complex is the Large Hadron Collider (LHC) as presented in* figure 2*"* (CERN, 2015b).

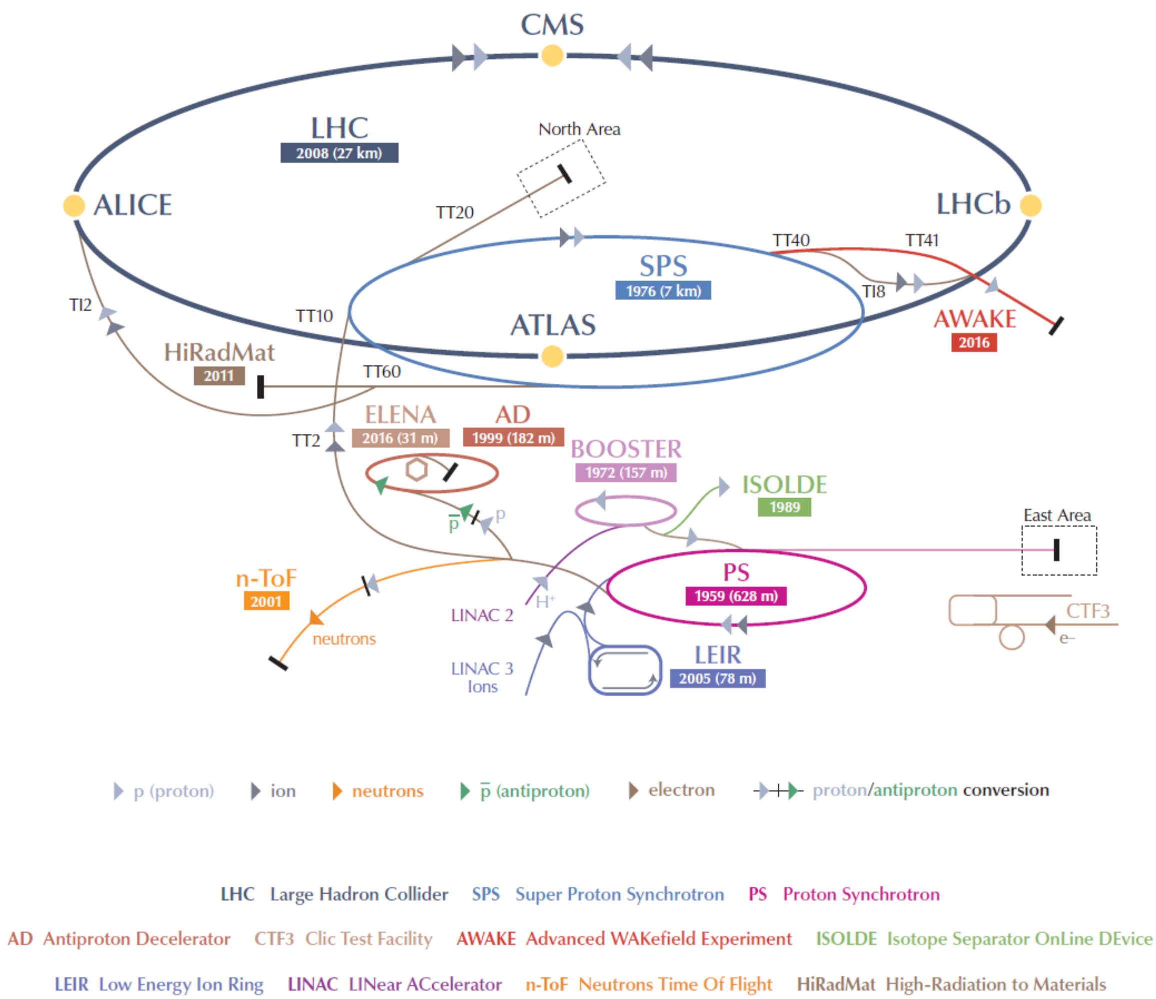

Figure 2. CERN Accelerator Complex, used with permission from CERN.

[1] The CERN Member States are currently Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and United Kingdom. In addition: Serbia and Turkey are Associate Member States and Romania is Candidate for Accession.

The next phase of the LHC is to improve the effectiveness to even higher levels by upgrading to HL-LHC, which is supposed to be in service from 2025 and forward. The HL-LHC project is a collaboration between CERN and many European, American and Japanese laboratories. The aim with HL-LHC is to increase the amount of useful collisions in the detectors by a factor 5 to 10. Most of the replacements will be at point 1 and point 5, see figure 4, and in total 1.2 km of the existing accelerator will be affected (CERN, 2015c).

2.1 New underground facilities

The two new facilities will be located at opposite side, point 1 and 5, of the LHC ring approximately 80-100 meters below ground level but a few meters above the LHC. Both facilities can be considered identical except for the distance to the rescue service. The main purpose of the facilities is to move the transformation from alternative current to direct current closer to the LHC. Therefore, both high power transformers and cables will be present in the facilities. Other equipment will be different types of electrical and computer cabinets, different types of cables and a cryogenic chamber and equipment. In the analysed designs the facilities will be consist of seven major parts; access shaft (PM57), cavern (US57), main tunnel (UR57), four transversal tunnels (UA53/57 and UL53/57).

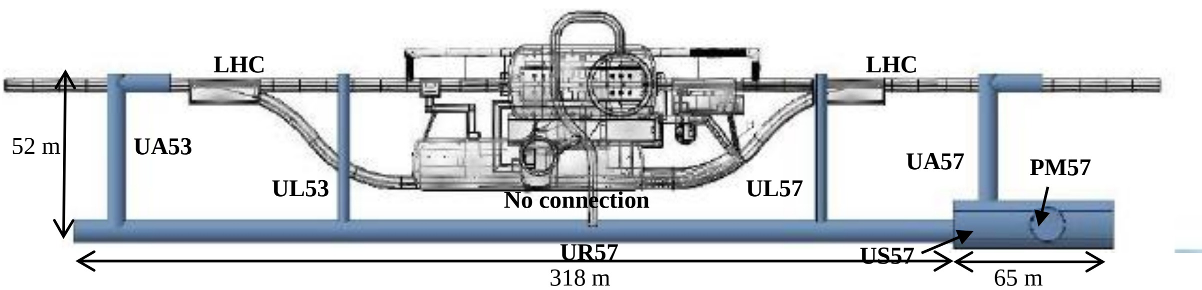

Figure 3. Proposed design of the facilities seen from above. Used with permition from CERN.

2.1.1 Point 1 and 5

The new underground facilities will be built at access point 1 and point 5 of the LHC. The construction of the facilities will begin within a few years. The location of the different points can be seen in figure 4.

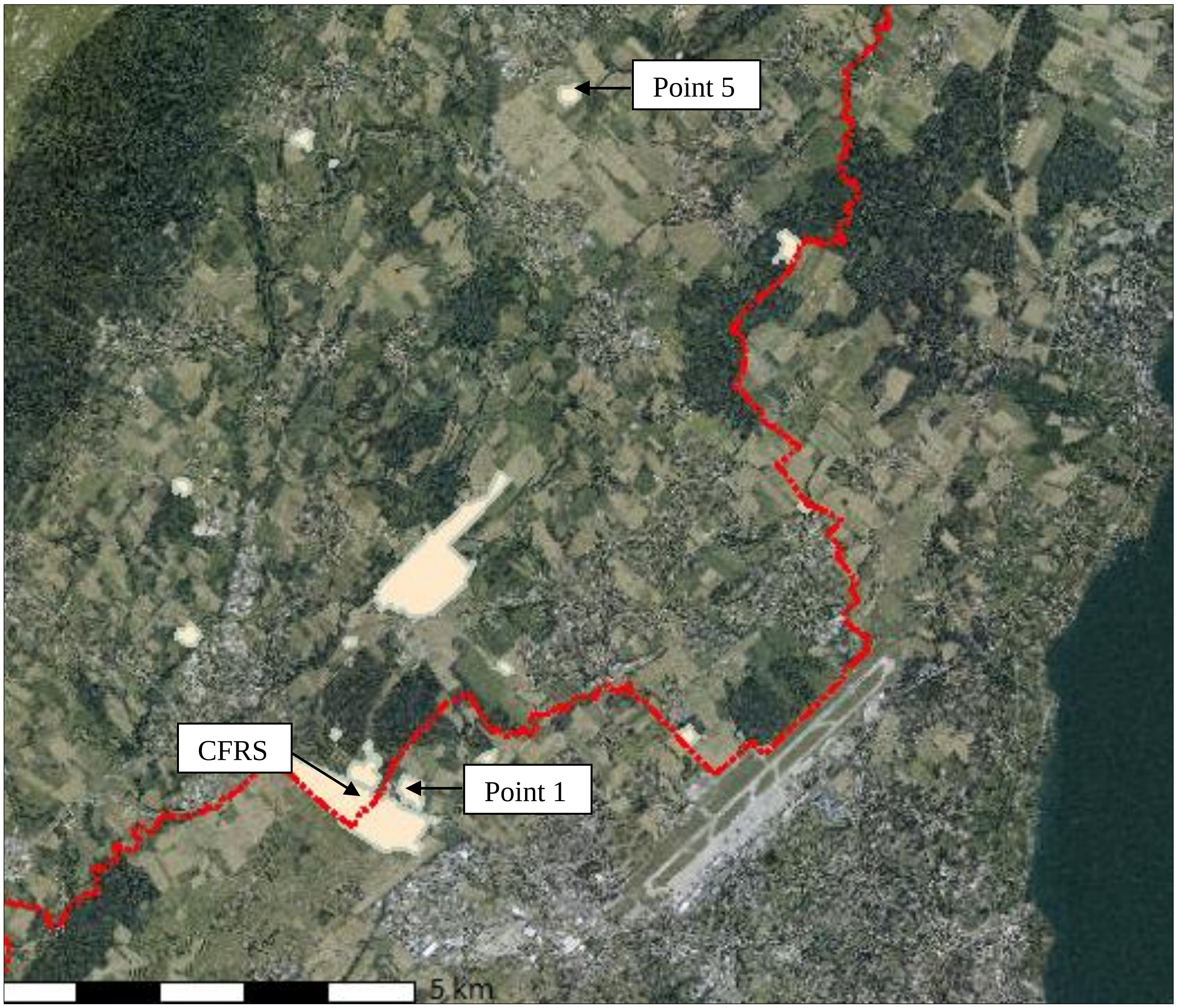

Figure 4. Overview of the location of CFRS, point 1 and point 5. The different CERN sites in the area are marked by a brighter colour with a green outline. The red line is the Swiss-French border (CERN, 2015d). Used with permission from CERN.

Point 1 is located near the main, Meyrin, site of CERN. This makes the response time for CERN Fire and Rescue Service (CFRS) relatively short. Figure 5 shows the short distance from CFRS and point 1. For point 1, they need 4 minutes to analyse the alarm, print access plans and follow other procedures. Then they need additionally 3 minutes of travel time. When CFRS arrives at point 1, the preparation time is estimated to be 10 minutes. To summarize, the travel time and preparation time is approximately 10 minutes each. This results in 20 minutes from fire alarm to actual start of the fire extinguishing operation at point 1 (Galofré Vilá, 2012).

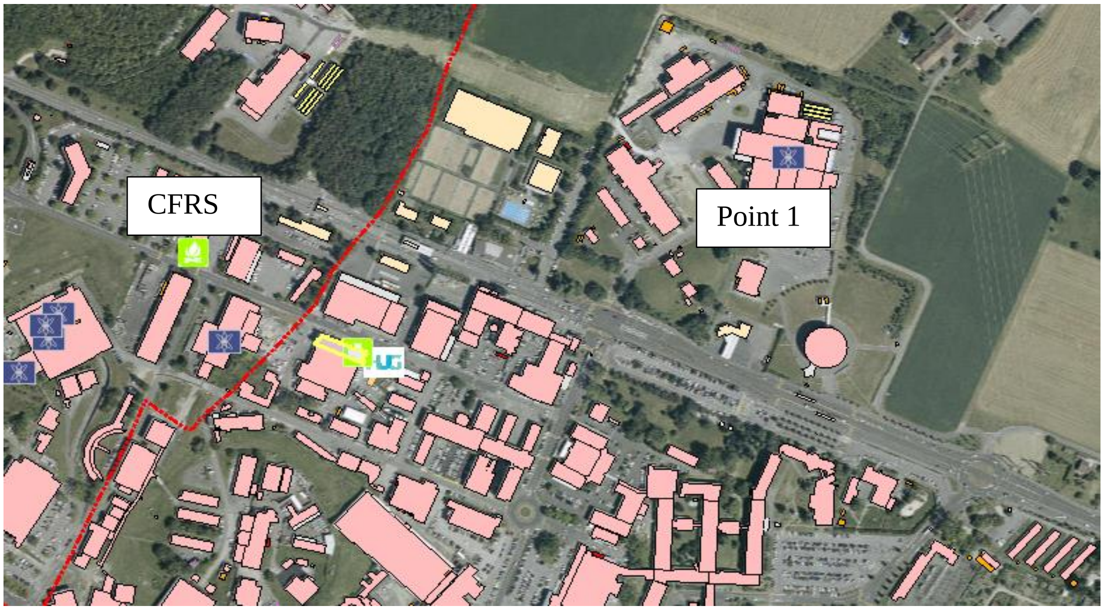

Figure 5. Detailed overview of CFRS location compared to point 1 (CERN, 2015d). Used with permission from CERN.

Point 5 is located further away from CFRS who instead have 20 minutes travel time. For point 5 the time for analyse the alarm, print access plans and follow other procedures as well as preparation on site are the same as for point 1. From point 5, this results in approximately 40 minutes from fire alarm to actual start of the fire extinguishing process (Galofré Vilá, 2012).

Since point 5 is more critical due to the longer response time, the focus in this master thesis will be to investigate the conditions in the facilities in point 5. Due to the similarities between point 1 and point 5, it is assumed that conditions that are accepted in point 5 also will be accepted in point 1.

2.1.2 Preliminary safety measures

There is an ongoing discussion in the HL-LHC project regarding the design of some of the fire safety measures. One suggestion is to make some functions automatic in point 5, like smoke extraction, and keep the same measures manual in point 1. This has been taken into consideration throughout the thesis.

The fire safety measures under consideration are:

- Smoke detection
- Smoke curtains
- Fire doors
- Smoke extraction with redundant fans
- Shut down of normal ventilation
- Rescue chambers
- Control room that monitors the equipment
- Emergency plaque with emergency stop/phones/lighting and manual evacuation alarm

2.1.3 Baseline configuration

Two different designs for the new underground facilities will be evaluated in this master thesis. The first one is called the baseline configuration and consists of a tunnel about 300 m long (UR57) and 2 couples of transversal galleries, UA53/57 & UL53/57. These transversal galleries are dead-ends, which means that there is only one escape direction in the galleries. Rescue chambers are proposed in order to provide occupants with a safe zone where they can wait to be rescued by CFRS. The dead-end configuration and the use of rescue chambers (first case ever at CERN) raise a number of safety issues especially for the evacuation of occupants and intervention of CFRS. In the baseline configuration, there are no connections between the LHC and the new facilities (Otto, 2015).

For the proposed baseline configuration, the fire compartmentalisation scheme with fire doors (green), fire curtains (yellow) and rescue chambers (red) are shown in figure 6.The different compartments are evaluated regarding the consequences and probability of ignition in Appendix I.

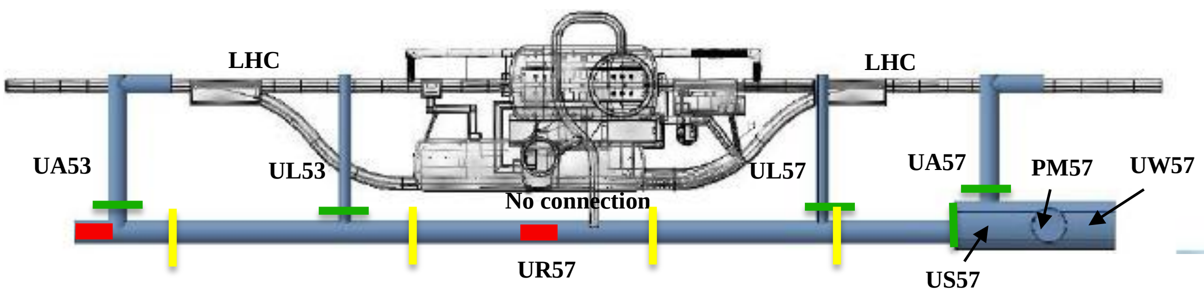

Figure 6. Baseline configuration in access point 5, seen from above, with compartments, fire doors (green), smoke curtains (yellow) and rescue chambers (red).The design will be similar in access point 1. Used with permission from CERN.

Evacuation

The strategy for evacuation is that personnel between the smoke curtains and the PM access shaft will evacuate directly to the access shaft. They will wait for the lift in the over pressurized safe area and then emerge by the lifts. Personnel on the far side of a smoke curtain as seen from the PM access shaft will be able to find shelter in one of the two rescue chambers, from where they would be evacuated by the CFRS as soon as possible. One rescue chamber is located in the UR tunnel just outside UA53 gallery and the other is located in the middle of the UR tunnel (Otto, 2015). These chambers can withstand smoke and could work as a safe place for occupants until the circumstances are good enough to evacuate. One problem with the rescue chambers is that there are uncertainties whether they can withstand a fire. This is discussed further in report 5512. The preliminary size and appearance of rescue chamber are shown in figure 7.

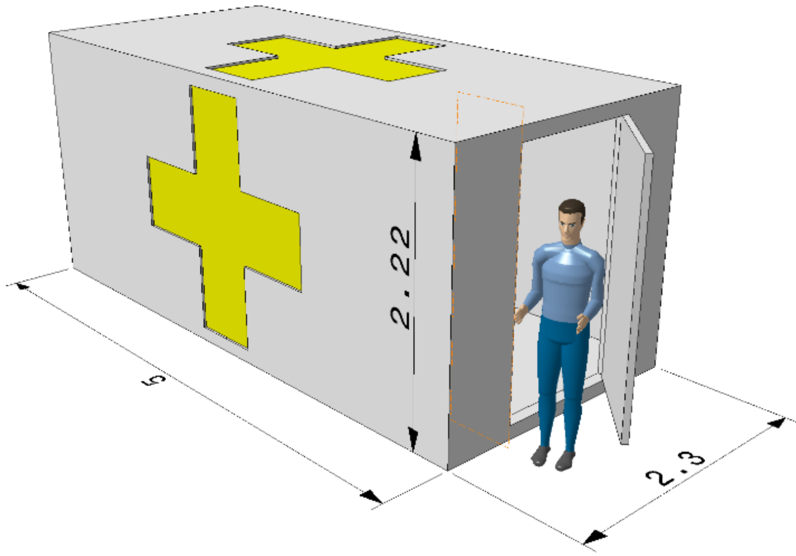

Figure 7. Preliminary size and appearance of rescue chamber. Used with permission from CERN.

2.1.4 Alternative option

The other design that will be evaluated in this master thesis is an option where the UL and UA galleries are connected to the LHC by emergency pathways. This option gives the occupants and the CFRS additional access/egress points and allows them to use the access shaft of the ATLAS or CMS experiments. The connections will consist of staircases connecting to the UA galleries and short tunnels connecting to the transport side of the LHC tunnel. The connection from the UL galleries will be a vertical shaft with a ladder down to LHC. Like in the baseline configuration there will be an access shaft to the surface from the UR tunnel (Otto, 2015). The alternative option with connections to LHC is shown in figure 8. A possible problem with this design is the increased level of radiation in the new facilities.

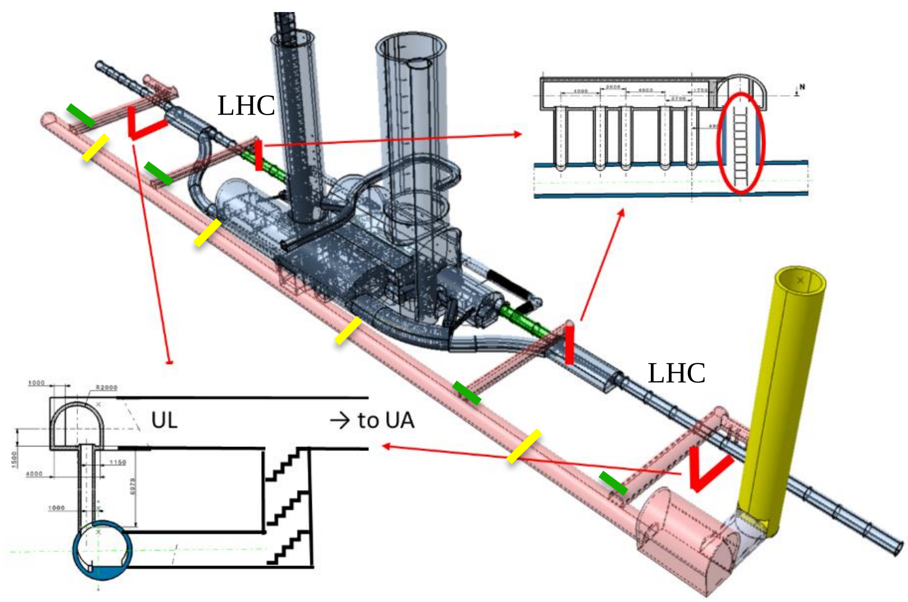

Figure 8. Alternative option with connection to the LHC with fire doors (green) and smoke curtains (yellow). Used with permission from CERN.

The alternative option with connections to the LHC will have the same fire compartmentalisation as the baseline configuration. The additional connections to the LHC will be protected with blast-doors to resist pressure waves, smoke and fire doors.

2.2 Different critical operational modes

There are five different phases that the facilities can have during their lifetime. The facilities are built during construction phase and the equipment is installed in the installation phase. The commissioning phase that then follows is when the equipment is tested and the final adjustments are done. The real experiments are performed during the operation phase. When the equipment needs to be updated, readjusted, replaced or if the machine simply will not be used any more it will come to a technical shut down.

Due to limitations in time, this thesis cannot analyse all these phases. Therefore, most of the analysis will be on operational phase with a focus on short technical stop. Some discussion and analysis will also be done on technical shut down.

2.2.1 Operation phase – short technical stop

This is the phase in which the particle accelerator is operating and in normal condition the machine will be on full power and preferably, no occupants will have access to the tunnel. However, if the machine comes to a short technical stop during operation phase, a few occupants will get the opportunity to investigate and solve the problem. At most five teams of two persons each will have access to the tunnel. There will be no beam during short technical stops but all the equipment will still be powered. The fire ignition is primarily associated to electrical equipment during the operation phase.

2.2.2 Technical shut down – long technical stop

A planned stop is called technical shut down. The number of occupants in the long technical stop could be approximated to the same as for short technical stop, i.e. 10 persons. In this phase, there will be no power to the machines. During this phase, a certain amount of maintenance is possible and this is why increased fire ignition probability is considered compared to operation phase. The fire risks associated to the technical shut down are related to the different kinds of work that will be done. It could be for instance hot work (welding) or the presence of different types of transient fire load (wooden pallets, cable drums, plastic for transport protection etcetera). The consequences of a fire increase if different fire safety measures are turned off during this phase. For example, the fire detection might be turned off when hot work needs to be done in some location of the tunnel. CERN has produced a document, Safety Code E, for safety procedures during hot work in their premises (CERN, 1995).

2.3 CERN Fire and Rescue Service

CFRS is divided in three teams of two persons each. This means that there can be up to six persons available the first and most important 30 minutes. For events that CFRS cannot handle by themselves, they depend on local rescue services from either the French or the Swiss side. CFRS is located on CERN premises close to point 1, see figure 5.

CFRS prefer to use a strategy underground where they have two attack and retreat points. This is to ensure the possibilities to evacuate personnel and to increase the extinguishing capacity.

The CFRS underground strategy is to deploy from a safe point with at least two fire rated doors between the safe point and the fire. The safe point is an area where the firefighters have access to fresh air and can prepare for the extinguishing process without being affected by the fire.

Evaluations have been done by CFRS to ensure the capacity of different strategies. The limitations and strategies are summarised below.

Offensive:

- Fire attack. Extinguishers, < 25kg fuel load.
- Fire attack. Portable CAFS, HRR < 5MW + direct attack possible.
- Fire attack. Water dry riser, HRR < 20MW + direct attack possible.

Defensive:

- Door protection. Water dry riser, HRR > 20MW or direct attack not possible.

3. Design fires

Since it is not possible to calculate all fires that can occur in the tunnel, design fires that represent the worst credible cases will be used. By studying the drawings of the proposed designs for the tunnel, it can be seen that there will be a significant amount of cable trays and high voltage cabinets present. Harrison (2007) points out that according to Advanced Incident Reporting System (AIRS) database (1997) the three most common technical errors that result in a fire ignition are short circuit, arcing and overheating. She also argues that because the unknown failures represent over 30% of the events unfortunately makes the reported statistics uncertain. Harrison (2007) also points out that a fire often occurs due to a chain of faults and not only because of a single fault. However, the fires at CERN with most severe consequences have been caused by internal failure of the electrical equipment (Harrison, 2007). Because of the high amount of technical equipment in the new underground area, it is therefore decided that the most likely fire source will be a technical error.

The design fire that is chosen consists of a fire that occurs in an electrical cabinet where there are several cable connections and circuit boards. The fire can then propagate to nearby cabinets and/or cable trays.

3.1 Theory design fires

The burning of an object can be divided into four phases; ignition, growth, steady state and decay phase. The ignition phase is in the beginning, before the fire is self-sustaining. The fire needs energy from an external source to create pyrolysis gases. In this thesis, the assumption is that the ignition has occurred. Therefore, there will be no calculations for the ignition phase. This is because the time can vary from hours, due to overheating, to just a fraction of a second when ignition is caused by arcing (EPRI/NRC-RES, 2005). Another reason is that it is hard to create a CFD-model for FDS that support very low HRR (McGrattan, McDermott, Hostikka & Floyd, 2010).

The growth phase starts after the ignition, when the fire is self-sustaining, and continues until the maximum HRR is reached. The growth phase can usually be adapted as αt^2 parabolic curve but it can also be calculated in other ways. An example is cable trays where the growth phase can be seen as a linear relationship. In ISO/TR 13387-2 the growth speed is divided into different grades from slow to very fast. In this thesis, the growth phase will be calculated according to equation 1. The rewritten form in equation 2 is used to calculate the time to the maximum HRR (USNRC, 2012).

$$\dot{Q} = \dot{Q}_0 \cdot \left(\frac{t}{t_g}\right)^2 \qquad \text{(Equation 1)}$$

$$t_{\dot{Q}_{max}} = t_g \cdot \sqrt{\frac{\dot{Q}_{max}}{\dot{Q}_0}} \qquad \text{(Equation 2)}$$

$\dot{Q}$	[kW]	HRR
$\dot{Q}_0$	[kW]	HRR used for dimension in growth phase
$\dot{Q}_{max}$	[kW]	Max HRR
t	[s]	Time
t_g	[s]	Time to reach $\dot{Q}_0$
$t_{\dot{Q}_{max}}$	[s]	Time to max HRR

The steady state phase starts when the fire has reached the maximum HRR and ends when the HRR starts to decay. During the steady state phase, the fire has a limited supply of either oxygen or fuel. This prevents the fire from increasing in HRR and keeps it in a steady state. During the steady state phase, the HRR of the fire is the same as the maximum HRR.

The decay phase starts when the oxygen or fuel supply drops to a level where the max HRR cannot be sustained. When the decay phase is reached, the HRR can be calculated with equation 3 (Mangs, 2004). In equation 4 the HRR calculations for the whole fire scenario of one cabinet, with a max HRR of 1000 kW, is presented and result in a curve similar to figure 9.

$$\dot{Q} = \dot{Q}_{t_d} \cdot \exp\left[-\left(\frac{t-t_d}{\tau}\right)\right] \qquad \text{(Equation 3)}$$

$$\dot{Q} = \begin{cases} t \leq t_{\dot{Q}_{max}} & ; \quad \dot{Q}_0 \cdot \left(\frac{t}{t_g}\right)^2 & \textit{Growth phase} \\ t_{\dot{Q}_{max}} < t \leq t_d & ; \quad \dot{Q}_{max} & \textit{Steady state} \\ t > t_d & ; \quad \dot{Q}_{t_d} \cdot \exp\left[-\left(\frac{t-t_d}{\tau}\right)\right] & \textit{Decay Phase} \end{cases} \qquad \text{(Equation 4)}$$

τ	[s]	Decay time constant
$\dot{Q}$	[kW]	HRR
$\dot{Q}_0$	[kW]	HRR used for dimension in growth phase
$\dot{Q}_{max}$	[kW]	Max HRR
$\dot{Q}_{t_d}$	[kW]	HRR at start of decay
t	[s]	Time
t_d	[s]	Time at start of decay
$t_{\dot{Q}_{max}}$	[s]	Time to max HRR
t_g	[s]	Time to reach $\dot{Q}_0$

Figure 9. Schematic figure of the HRR curve.

Due to the presence of high-energy equipment there is a risk of a high energy arcing fault occurring. The phenomenon arcing is an intense discharge of electrons creating an arc between two electrodes. The arc occurs when the electrodes reach temperatures high enough to cause a rapid vaporization of the conductive materials (EPRI/NRC-RES, 2005).

3.2 Design fire in electric cabinet

When designing the correct HRR curves for electrical cabinets, a very detailed description of the actual cabinet is needed to get a good approximation. For the cabinets that will be used in the tunnel only the exterior measurements have been provided. Because of this, a design cabinet with conservative assumptions, based on earlier experiments, will be used in the calculations.

There has been some testing through the last 25 years, mostly on cabinets used at nuclear power plants, but the results have had some variations due to different experimental set-ups, type of cables and type of cabinets. Because of this, the U.S. Nuclear Regulation Commission (NRC) and the Electric Power Research Institute (EPRI) have created a guide on how to design a fire for different types of cabinets (EPRI/NRC-RES, 2005). This guide uses earlier experiments and thereafter makes a probabilistic distribution for the peak HRR for different types of electrical cabinets. In this report the 98th percentile value for vertical cabinets with closed and open doors will be used which results in a peak HRR for the two cases at 450 kW and 1000 kW respectively (EPRI/NRC-RES, 2005).

The experiments performed by Mangs (2004) shows that the growth rate is not enough to reach the maximum HRR of 1 MW within 10 minutes. The fastest growth rate value in the experiments would result in 1 MW after 12.5 minutes. This corresponds to a “slow” growth grade according to the ISO/TR 13387-2. The time to reach a steady state burning will be approximated to 20 min (Mangs, 2004) for a 450 kW fire and 8 min (EPRI/NRC-RES, 2005) for a 1000 kW fire.

For the decay phase, the experiment data from Mangs (2004) will be used as background information. In the test, the decay time constant varied from 13 to 23 minutes where a high decay time constant results in a slow decay time. The value placed in the middle of the interval, 18 minutes, will be used for the decay time constant due to the lack of information.

An assumption made by Mangs (2004) is that the propagation to adjoining cabinets will occur after approximately 11 minutes based on the air temperature in the cabinet. Since the HRR used in the simulations exceed the HRR in Mangs (2004) experiments and the uncertainties around his assumption it is decided to use 10 minutes instead. The HRR curve for cabinets used in most simulations is presented in figure 10 and is represented by seven cabinets, which are located next to each other. The fire starts in an open cabinet and then spreads in two directions to the adjoining cabinets every 10th minute. All HRR curves in this report are simplified versions of reality. Generally, a real fire shows a smoother HRR curve.

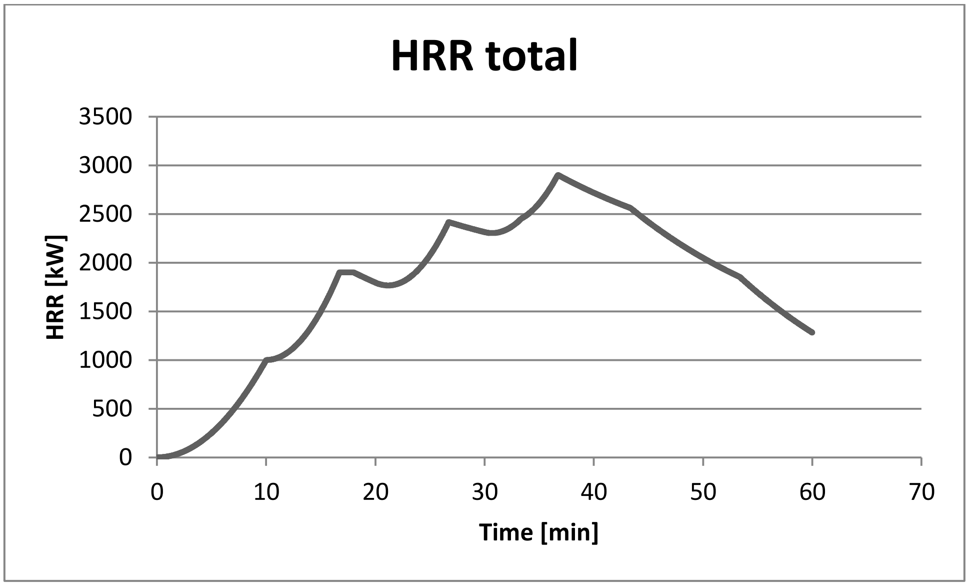

Figure 10.Example of HRR curve for cabinets.

Propagation to cables will be assumed to happen at a temperature of 250 °C that Mangs (2004) found to correlate both with his experiments and with Troitzsch (1990). For the propagation, the Heskestad plume model and lumped mass heat will be used (Karlsson & Quintiere, 2000 and Holmstedt & Nilsson, 2008). The Heskestad plume model calculations are presented in equation 7 and 8 (Karlsson & Quintiere, 2000). When calculating heat transfer to a lumped mass the assumption is made that the temperature is the same in the whole object instead of having a heat gradient with a lower temperature in the centre. The cable temperature calculations are made with equation 9 (Holmstedt & Nilsson, 2008).

The calculations give a propagation time of 10 minutes with open cabinet and 13 minutes with closed cabinet. In both cases, a cable tray is placed 3 meters above the ground. The values used in the calculations for propagation to cables are presented in Appendix V.

$$z_0 = 0{,}083 \cdot \dot{Q}^{2/5} - 1{,}02 \cdot D_c \qquad \text{(Equation 7)}$$

$$T_{g,z} = 9{,}1 \cdot \left(\frac{T_\infty}{g \cdot c_{p,air}^2 \cdot \rho_\infty^2}\right)^{1/3} \cdot \left(\dot{Q} \cdot f_c\right)^{2/3} \cdot (z - z_0)^{-5/3} + T_\infty \qquad \text{(Equation 8)}$$

$$T_{cable} = \frac{h \cdot A(T_{g,z} - T_\infty)}{c_{p,cable} \cdot \rho_{cable} \cdot V} + T_\infty \qquad \text{(Equation 9)}$$

ρ_∞	[kg·m^{-3}]	Ambient air density
ρ_{cable}	[kg·m^{-3}]	Density of cables
A_{cable}	[m^2]	Surface area of the cable
$c_{p,air}$	[kJ·kg^{-1}·K^{-1}]	Specific heat capacity for air
$c_{p,cable}$	[kJ·kg^{-1}·K^{-1}]	Specific heat capacity for cables
D_c	[m]	Characteristic diameter
f_c	[-]	Convection factor
g	[m·s^{-2}]	Gravitational acceleration
h	[W·m^{-2}·K^{-1}]	Convective heat transfer coefficient
$\dot{Q}$	[kW]	HRR
T_∞	[K]	Ambient temperature
T_{cable}	[°C]	Temperature in cable
$T_{g,z}$	[K]	Temperature in plume at height z
V_{cable}	[m^3]	Volume of cable
z	[m]	Height
z_0	[m]	Dimension height

3.3 Design fire in cable trays

To calculate the fire propagation in cable trays some simplifications will be done. Firstly the fire load will be calculated by a simplified method used at CERN and can be seen in equation 10 (Corsanego, EDMS 1405658, 2014). The method used at CERN is based on experiments performed by U.S.NRC in the CHRISTIFIRE project (USNRC, 2012). In the CHRISTIFIRE projects several different type of cables were tested with respect to fire spread. In addition, different combinations of cable types and amount of cables were tested. The method used by CERN (Corsanego, EDMS 1405658, 2014) scales down the amount of parameters to density of cables and the amount of plastic in the cables, amount of air in the cable tray and the cables trays cross sectional area. The method gives a fire load per meter cable tray in the unit J·m^{-1}. All the used input data for the cable tray calculations are presented in Appendix VI.

$$E'_{tray} = H_{tray} \cdot W_{tray} \cdot \rho_{cable} \cdot (1 - \varphi_{air}) \cdot \varphi_{plastic} \cdot \Delta H_c \qquad \text{(Equation 10)}$$

ΔH_c	[MJ·kg^{-1}]	Heat of combustion
ρ_{cable}	[kg·m^{-3}]	Density of cables
φ_{air}	[-]	Fraction air in cables
$\varphi_{plastic}$	[-]	Fraction plastic in cable trays
E'_{tray}	[MJ·m^{-1}]	Fire load per meter cable tray
H_{tray}	[m]	Height of cable tray/cables
W_{tray}	[m]	Width of cable tray

The methods for fire propagation and HRR calculations have also been used at CERN earlier (Corsanego, EDMS 1414267, 2014) but they were developed from experiments made for evaluation of fire safety in nuclear power plants (EPRI/NRC-RES, 2005). The propagation speed for both horizontal and vertical cable trays were obtained from experiments using different kinds of cables. The propagation speed in horizontal cables varies between 1,1 - 32 m/h depending on the cable type and if the tray is influenced by hot smoke layer. For vertical cable trays, the same speed varies between 15 – 50 m/h. The HRR per unit area is 150 or 250 kW/m^2 depending on the type of cable (Corsanego, EDMS 1414267, 2014). There are two main types of cables; thermoplastic and thermosetting. Thermosetting cables have the lower HRR and slower flame propagation speed than thermoplastics (Corsanego, EDMS 1414267, 2014). Another differnce between the cable types is that thermosetting cables, due to their chemical characteristics, do not melt during fire and do therefore not produce drops like thermoplastics. Thermosetting cables have higher fire rating and are recommended by CERNs own safety standards. Even though the details of equipment and cables are still to be decided, it is chosen to use the highest fire rated thermosetting cables in the calculations, due to CERNs own demands.

Another assumption is that they are affected by hot smoke and this result in a horizontal flame spread of 11 m/h. The HRR will be 150 kW/m^2. At ignition of the lowest tray, it is assumed that one meter cable tray is ignited. The initial HRR can then be calculated with equation 11. The area adjustment coefficient is a constant depending on the type of cable tray for example if it is a wired tray or open top with closed bottom (Corsanego, EDMS 1414267, 2014).

$$\dot{Q}_{initial} = l_{initial} \cdot W_{tray} \cdot \dot{Q}" \cdot C_a \qquad \text{(Equation 11)}$$

C_a	[-]	Area adjustment coefficient
$l_{initial}$	[m]	Length of ignited area at ignition
$\dot{Q}"$	[kW·m^{-2}]	HRR per unit area
$\dot{Q}_{initial}$	[kW]	HRR at ignition
W_{tray}	[m]	Width of cable tray

To calculate the maximum HRR the time to run out of fire load in a cable tray section needs to be calculated. This is done by dividing the fire load for a section with the corresponding HRR for the burning area of the section as seen in equation 12. During the growth phase equation 13 is used to calculate the HRR, where α is calculated with equation 14. The maximum HRR is calculated with equation 15. The whole fire scenario is described with equation 16 and visualised in figure 11. In figure 11 the cable tray is divided into three different areas; unburnt, burning and decayed area. In the figure, it can be seen that the flame propagation speed is equal to the decay speed resulting in a steady HRR once initial ignited area has decayed. The equations used for the propagation in cables are based on the information given in USNRC (2012) and Corsanego (2014).

$$t_{\dot{Q}_{max}} = \frac{E'_{tray} \cdot l_{initial} \cdot c_{eff}}{60 \cdot \dot{Q}_{initial}} \quad \text{(Equation 12)}$$

$$\dot{Q} = \dot{Q}_{initial} + \alpha \cdot t \quad \text{(Equation 13)}$$

$$\alpha = w_f \cdot \dot{Q}" \cdot v_p \quad \text{(Equation 14)}$$

$$\dot{Q}_{max} = \alpha \cdot t_{\dot{Q}_{max}} \quad \text{(Equation 15)}$$

$$\dot{Q} = \begin{cases} t < t_{\dot{Q}_{max}} & ; \quad \dot{Q}_{initial} + \alpha \cdot t \qquad \mathit{Growth\ phase} \\ t > t_{\dot{Q}_{max}} & ; \quad \alpha \cdot t_{\dot{Q}_{max}} \qquad \mathit{Steady\ state} \end{cases} \quad \text{(Equation 16)}$$

α	[kW·min^{-1}]	Slope coefficient during growth phase
c_{eff}	[-]	Combustion efficiency
E'_{tray}	[MJ·m^{-1}]	Fire load per meter cable tray
$l_{initial}$	[m]	Length of ignited area at ignition
$\dot{Q}$	[kW]	HRR
$\dot{Q}"$	[kW·m^{-2}]	HRR per unit area
$\dot{Q}_{initial}$	[kW]	HRR at ignition
t	[min]	Time
$t_{\dot{Q}_{max}}$	[min]	Time to max HRR
v_p	[m·min^{-1}]	Flame propagation speed
w_f	[m]	Width of flame front

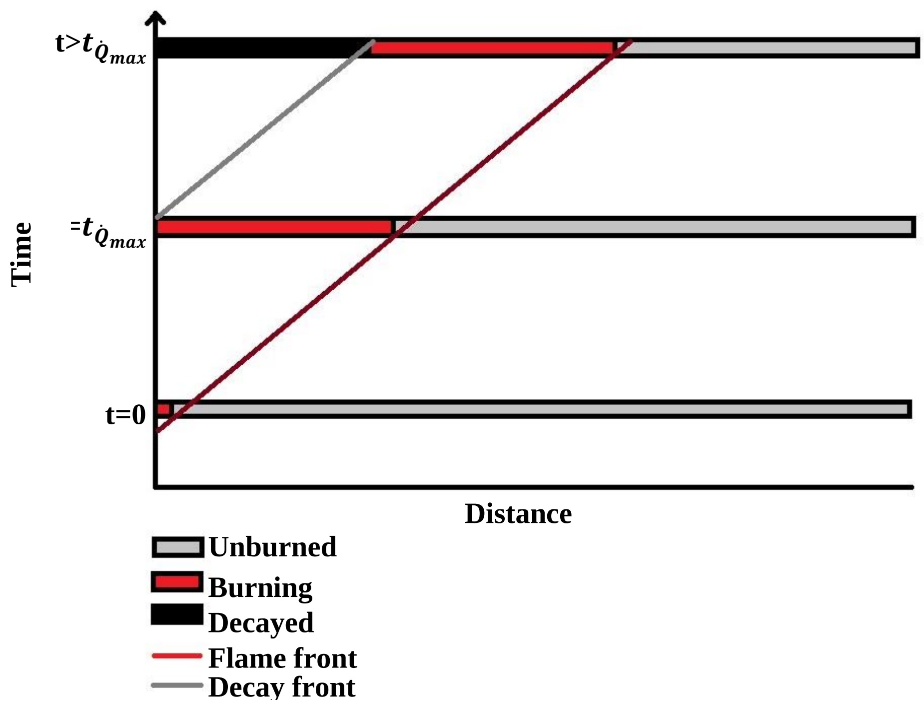

Figure 11. Schematic view of fire propagation in cable trays.

For the propagation between trays in vertical direction, a method called the 5-4-3-2-1 method will be used (EPRI/NRC-RES, 2005). In an experiment on horizontal cable trays, it was found that the time until the ignition of the first tray was five minutes when using a burner. After four minutes the fire spread vertically to the second tray, then three more minutes for the third and so on (EPRI/NRC-RES, 2005). Since there will be no burner that will ignite the cables at CERN, instead the temperature from the hot gases from a burning cabinet will be used to calculate the time to ignition of the first cable tray. Thereafter the 5-4-3-2-1 method will be used. In addition to the 5-4-3-2-1 method, experiments have shown that the fire propagates upwards with an estimated angle of 35° between the cable trays.

USNRC (2012) shows that the fire spread between the cable trays were affected by how the cables are packed. The 5-4-3-2-1 method is a good approximation for loosely packed cables but it is not equally applicable for tightly packed cables. However, in EPRI/NRC-RES (2005), which is the standard for PRA in for nuclear power plants in the United States, the 5-4-3-2-1 method is used without any further regards to these limitations. Therefore, the method is also assumed applicable in this thesis.

A Microsoft Excel spreadsheet will be used to make templates for the calculations of HRR curves and therefore make it easy to adapt to changes made in the design of the facility. An example of the used HRR curve for cable trays is presented in figure 12. The example is for five fully filled cable trays and after 60 minutes, approximately 477 kg of cables would have burned. This number can be compared with that each fully filled cable tray contains almost 40 kg of cables per meter. This is a reasonable amount of weight for large cable trays.

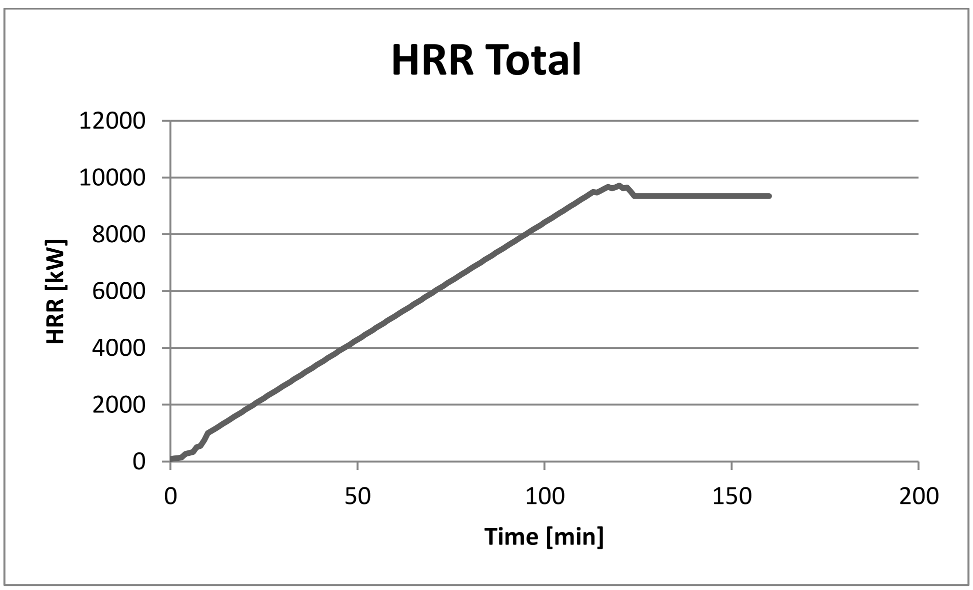

Figure 12. Example of the HRR curve for cable trays.

3.4 Fire load configuration

For the different scenarios, a fire load configuration is made based on the cross section drawings from CERN.

The different locations for the scenarios in the new underground facilities can be seen in figure 13.

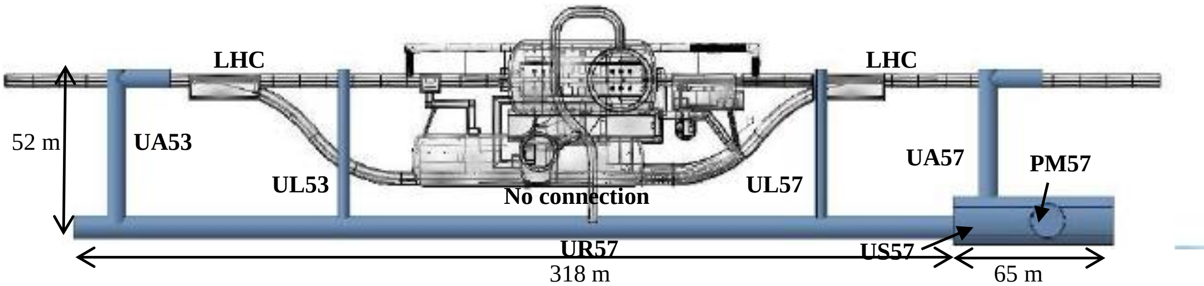

Figure 13. Proposed design of the facilities seen from above. Used with permition from CERN.

3.4.1 Setup of cabinets and cable trays

The setup when both cabinets and cable trays are present is shown in figure 14. The numbering of the cabinets is the order for when the fire propagates to them. The fire starts in cabinet 1 and then propagates to the two adjacent cabinets after 10 minutes and to the next two adjacent cabinets 20 minutes after the beginning of the fire. For the cable trays, the fire propagates to the lowest one after 10 minutes and then propagates upwards with the 5-4-3-2-1 method.

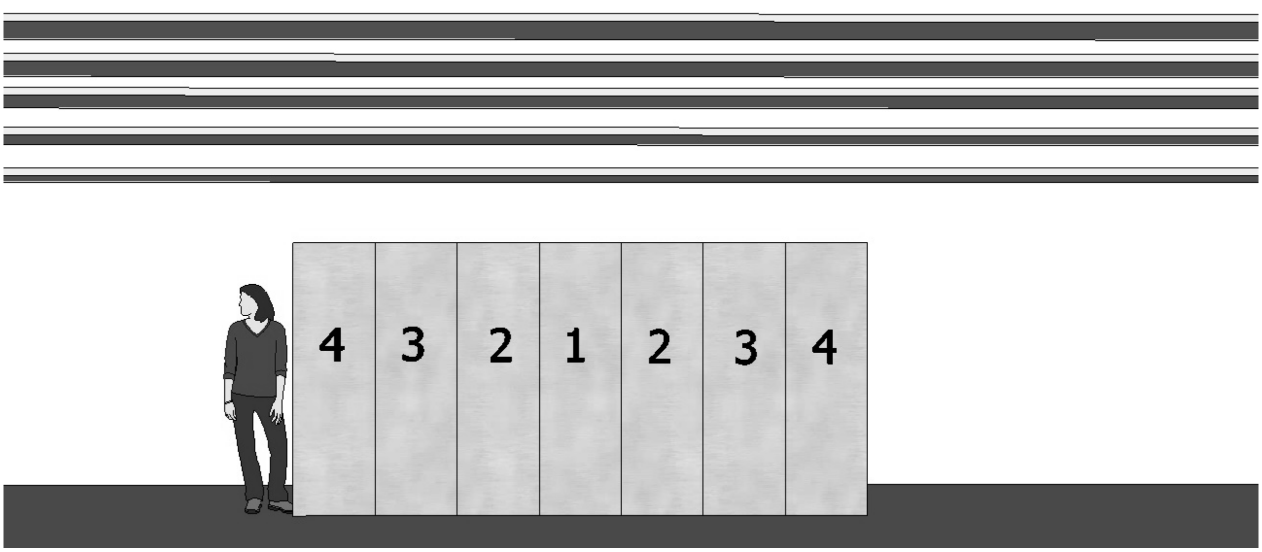

Figure 14. The setup of cabinets and cable trays used in the scenarios.

3.4.2 Fire in the middle of the UR tunnel

For the fire in the middle of the UR tunnel, the assumption is that the fire starts in one cabinet and then propagates to two adjacent cabinets every 10th minute based on testing done by Mangs (2004). Five cable trays will be present with the lowest one approximately 3 m above the ground. Smoke plume calculations will be used to calculate when the lowest tray will ignite. Thereafter the 5-4-3-2-1 method is used for propagation to the other trays. The HRR curve for the first hour is presented in figure 15.

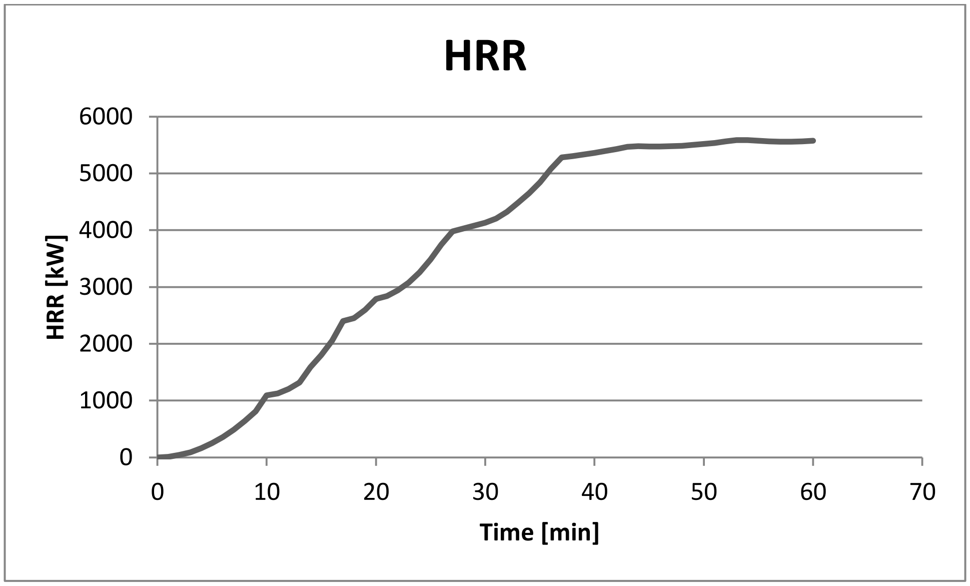

Figure 15. HRR for the first 60 minutes for fire in the centre of UR.

3.4.3 Fire in the far end of the UR tunnel

When there is a fire in the far end of the UR tunnel, the set up will be almost the same as for a fire in the middle of the UR tunnel. The exception is that the cable trays are assumed to be filled only with 10 % of their maximum capacity. This is because most of the cables are connected to cabinets closer to the exit of the tunnel and therefore never reach this part of the tunnel. The fire is assumed to start in a cabinet and propagate to two other cabinets every 10^{th} minute. The propagation to the cable trays follows the same pattern as for the fire in the middle of the UR tunnel. The HRR curve for the first hour is presented in figure 16.

Figure 16. HRR for the first 60 minutes for fire in the far end of UR.

3.4.4 Fire in the UA gallery

For a fire starting in the UA gallery, there will be eight cabinets and five cable trays filled to 10 % of the max capacity. Just as in the UR, the fire is assumed to start in a cabinet. Instead of standing in lines, as in the UR, the cabinets are placed in groups where eight cabinets are placed in two lines standing back to back. This leads to that the fire can spread in three directions. In the simulations, the fire will therefore start in one cabinet and spread to another three after 10 minutes and then three more 20 minutes from the fire start and the last cabinet ignites after a total of 30 minutes. The HRR curve is presented in figure 17.

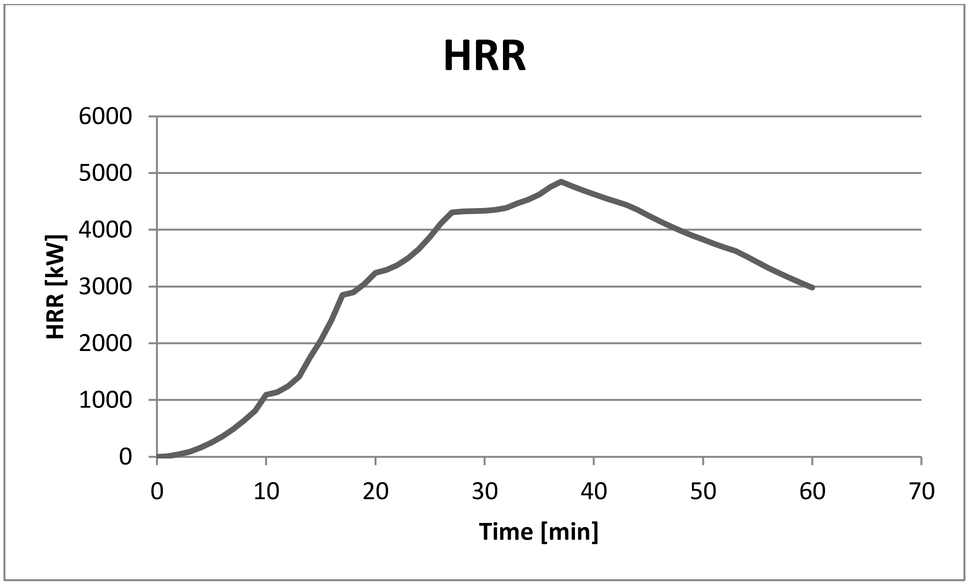

Figure 17. HRR for the first 60 minutes for fire in the UA.

3.4.5 Fire in the US cavern

When the fire starts in the US cavern, it starts in cabinets on the mezzanine where a total of twelve cabinets can be involved. In addition, here the fire will propagate every 10th minute to two other cabinets. However, there are some problems with the calculations of the fire propagation in the US cavern. This is because the cable trays to the tunnel run in the false floor of the mezzanine and in the ceiling in the rest of the tunnel. The problem is because the cables are located below the cabinets and that the there are no specific information about how the cable trays are placed related to the cabinets. It is therefore hard to know if and how the fire will propagate. This results in that no cable trays are involved in the HRR calculations for the fire in the US cavern. The HRR curve for the first hour is presented in figure 18.

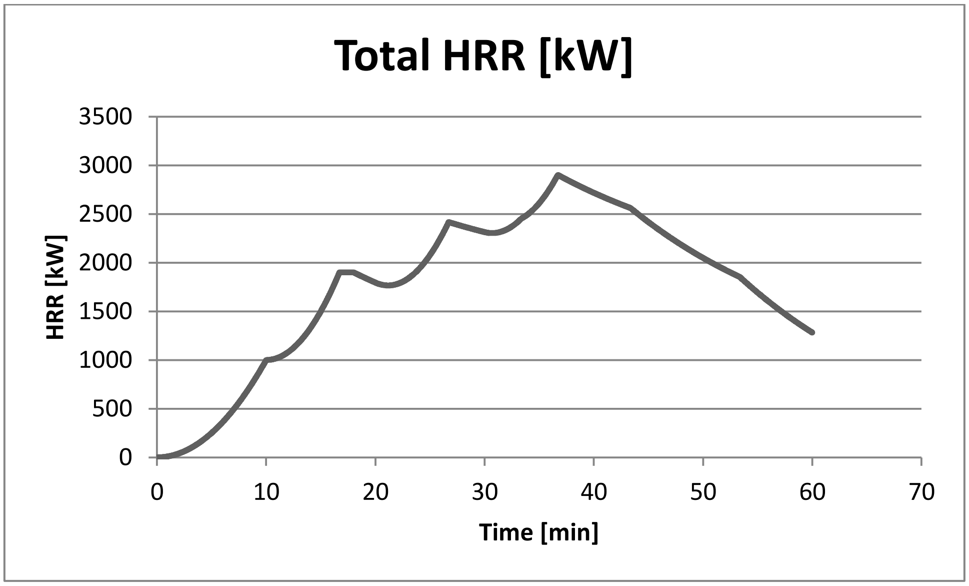

Figure 18. HRR for the first 60 minutes for fire in the US.

4. Description of risk analysis methods

The whole risk assessment process is presented in figure 19. In this thesis, the focus will be on the methods to perform the risk analysis, which consists of the first four steps. Step 1-2 has already been implicitly described in chapter 1 and 2. Step 5-6 is not covered in this thesis.

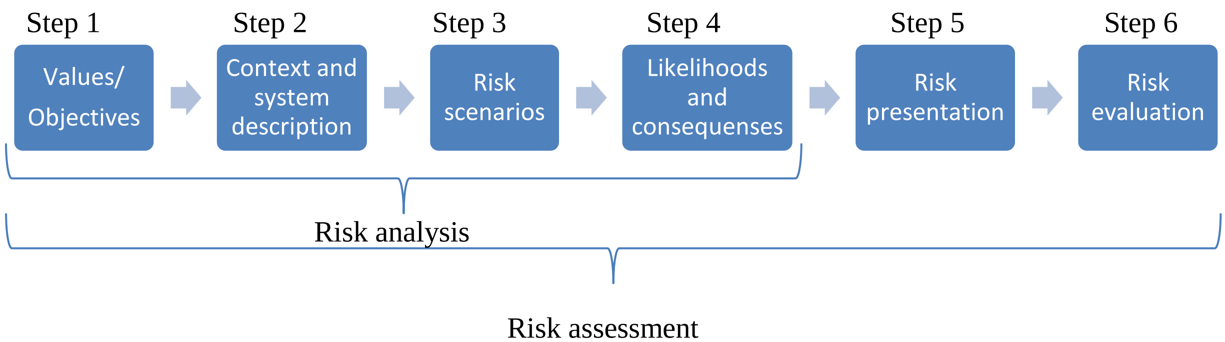

Figure 19. Description of the risk assessment process. Created by inspiration of Räddningsverket (2003).

There are several different types of risk analysis methods and they can be performed on different levels in society, both nationally and locally on a specific system in a facility. According to ISO 23932:2009 *Fire safety engineering- General principles*, it is important to choose an engineering method that has acceptable accuracy and efficiency when it comes to prove if the performance criteria are fulfilled. This could be done by using deterministic or probabilistic calculation methods. It could also be done by analyse data from tests or surveys. If it is not possible to use data from full-scale tests, it is possible to use reference fires instead. If there are no available data, it could be possible to use engineering judgement instead. This would preferably be a team of experts with relevant experience in the area.

ISO 23932:2009 also highlights the need to be observant of the uncertainties that are associated to several of the parts in the risk analysis. They mention for instance that uncertainties associated to the choice of scenarios, the function of the fire protection measure, the choice of engineering method and all of the assumptions that are made along the process. This high level of uncertainty makes if even more important to be very clear and transparent of what values and assumptions that are being used.

Risk analysis methods can be divided into different groups or level s depending on their characteristics. Paté-Cornell (1996) is doing this depending on how the risk analysis methods handle uncertainties and she divides them into the six following levels:

Level 0 does not try to quantify the risk in any way but simply identifies a potential hazard. This level is suitable when the costs are low and the decision is clear. It is harder to use when the hazards have low probability and in those cases it could be complemented with for example FMEA. However, the probability is still not considered in level 0.

Level 1 also does not consider any probability but focuses on the worst case assumptions which leads to the maximal loss.

In *level 2* the focus lays on the worst credible case. Most of the times it does not consider any probabilities but it depend on the case. This level does not quantify the uncertainties and the upper bounds that are chosen might be mistaken for mean values. Level 2 might be too conservative and might not provide the maximum risk reduction in a cost effective way.

Level 3 focuses on mean and median values instead. The advantage with mean values is that it is often cost effective but the disadvantage is that it is sensitive to extreme values. The median is less sensitive to extreme values but has instead less accuracy when it comes to the economic comparisons. Level 3 does not present the effect of the uncertainties.

Level 4 is based on a probabilistic risk analysis method and the risk is presented in a risk curve instead of a point estimation. Level 4 includes different types of uncertainties but since they are included in the same risk curve, it is not possible to extract specific information on the uncertainties.

Level 5 could also be based on a probabilistic risk analysis method. It presents the risks by a group of curves, making it possible to actually see where uncertainties belong.

As stated by Räddningsverket (2003), the former Swedish Rescue Services Agency, the level of detail of the risk analysis is decided by in which design phase of a project the risk analysis is used. An early phase is more in need of a quick and preliminary analysis and a more specified design needs a more detailed analysis. It is common that the analysis gets more detailed when more information of the system is known. Räddningsverket (2003) also argues that the risk analysis should be decided depending on the purpose and the available type of resources. The risk analysis methods could also be divided into several different groups. The technical methods investigate the technical components and their reliability. The Human reliability analysis methods focus on the reliability of humans acting correctly. There are also specific risk analysis methods developed for analysing fire hazards.

4.1 Selection of methods

For the first screening in this thesis, only technical risk analysis methods and the specific methods for a fire analysis are selected. This is because of the fire hazards present in the facility are mainly technical. The result from this first screening is presented in table 2**.** For a short analysis of the different methods, see Appendix II.

Table 2. Result of the first screening.

Methods	
What-if	Checklists
FMEA & FMECA	Risk Matrix
HAZOP	Deviation analysis
Reliability Block Diagram	Preliminary hazard analysis
Fault Tree Analysis	NFPA 101A Guide on alternative approaches to life safety.
Event Tree Analysis	Gretener method
Monte Carlo Methods	ROGA
Cause-consequence analysis(CCA)	GO-FLOW
Markov analysis (MA)	Dynamic event logic analytical methodology (DYLAM)
Probabilistic risk assessment (PRA) and Probabilistic safety assessment (PSA)	Dynamic Event Tree Analysis Method (DETAM)

Due to the limitations in time, there is no possibility to evaluate all of these methods within this thesis. It is therefore chosen to narrow it down further. For the second screening, it is decided that the methods should fulfil the following three criteria:

Criteria 1: The method should not be developed for a specific industry unless for mining or nuclear facilities. This is because CERN's facilities are partly comparable to mines and nuclear power plants regarding fire safety.

Criteria 2: The method should be applicable for risks including fires.

Criteria 3: The method should preferably be qualitative and/or semi-quantitative methods due to the lack of statistics in this kind of facility. In this thesis, semi-quantitative means that the method divides several input data or intervals into groups instead of using the exact values. The time aspect is also crucial for the selection of this criterion.

If the result will be that some methods are similar, the one with most agreement with the criterion will be chosen. A summary of all risk analysis methods can be found in Appendix II.

The methods that match the three criteria and that will be used to evaluate risks in the facilities are:

- Event tree
- Preliminary hazard analysis
- What-if
- Gretener
- ROGA
- NFPA 101

4.2 Event tree analysis

An event tree analysis (ETA) could be both quantitative and qualitative according to Kemikontoret (2001), Räddningsverket (2003) and Stamatis (2014). The method can be performed both individually and in group (Stamatis, 2014 and Kemikontoret 2001). An ETA investigates the outcomes of both success and failure of components (Stamatis, 2014 and Kemikontoret 2001). Stamatis (2014) also points out that one of the strengths with an ETA is that it accounts for dependence and domino effects among several factors. Another strength that Stamatis (2014) point out is that an ETA makes is possible to identify system weakness and it is possible to investigate both single and multiple failures. Stamatis (2014) also highlights some of the disadvantages with the ETA. One of them is that there can only be one initiating event in the tree. If there are multiple initiating events, the amount of event trees must be the same. The method starts by identifying an initial event followed by identifying the safety barriers. After this, the event tree is created and if possible, the probabilities are added to get the frequency for the end events (Kemikontoret, 2001, and Stamatis, 2014).

The ETA can be placed in level 2 to 5 in Paté-Cornell's (1996) different levels of uncertainties in risk analysis methods. The level depends on how the used values are chosen and how the uncertainties are treated.

4.3 Preliminary hazard analysis

A preliminary hazard analysis (PHA) is often used to identify hazards in an early phase of a project (Kemikontoret, 2001 and Stamatis, 2014). Both Kemikontoret (2011) and Stamatis (2014) believes that a PHA provides a good help when it comes to investigate which hazards that needs more detailed risk analysis. They also argue that a PHA could be used as a first step in a more detailed risk analysis. If the system is simple, Stamatis (2014) argues that it could be used as the only risk analysis.

A PHA is often performed by an experienced group (Kemikontoret, 2011 and Stamatis, 2014). They argue that this is one of the disadvantages of the method. If a hazard is missed by the group, it is not evaluated. Stamatis (2014) also points out that another disadvantage with the method is that it does not account for interactions of different hazards. Kemikontoret (2011) suggests using a checklist as a help to identify critical events. The risks are then evaluated based on probability from statistics or the knowledge of the expert group. The consequences could be for example personal injury, stop in production and others. The grading of the consequences is chosen to match the system. For the consequences, Stamatis (2014) suggest a qualitative grading scale ranging from negligible to catastrophic. For the probability, Stamatis (2014) proposes a ranking from extremely remote to probable.

According to Stamatis (2014), a PHA is performed by the following 5 steps:

- Identify known hazards.
- Determine their cause.
- Determine their effects.
- Determine the probability that an accident will be caused by a hazard.
- Establish initial design and procedural requirements to eliminate or control hazards.

Since the PHA do not consider any quantitative estimation of the hazards, it is placed in level 0 in Paté-Cornell’s (1996) different levels of uncertainties in risk analysis methods.

4.4 What-if method

According to Stamatis (2014), the What-if method is the least structured hazard analysis technique and requires the least time. However, there must be knowledge about the analysed object and a clear system description. Räddningsverket (2003) states that the method is simple but Stamatis (2014), Räddningsverket (2003) and Kemikontoret (2001) highlight that the success of the analysis is dependent on the experience of the group members. Before the first group meeting, it is important that everyone is very familiar with the system and understands the issues. Kemikontoret (2001) describes the method as flexible and it can be used whenever in a facilities lifecycle. It could also help to use checklists to start the brainstorming process. To structure the work process both Stamatis (2014) and Räddningsverket (2003) suggest that a moderator leads the work and a scribe makes sure every useful discussion is noted.

The purpose with the What-if analysis is, according to Ingvarsson & Roos (2003), Stamatis (2014) and Räddningsverket (2003), to question the function of a system and evaluate what happens if the function deviates from normal procedures. Stamatis (2014) describes two alternative ways to do the What-if analysis. One alternative is to divide the system that is being analysed into nodes and ask “What if?” questions for each node. The question could for example be *What if an instrument error occurs*? The work should be documented and reported (Ingvarsson & Roos, 2003, Räddningsverket, 2003, Kemikontoret

2001), preferably in a table. Suggested recommendations should also be presented in this table. The other alternative that Stamatis (2014) describes is the focus on how the specific equipment dysfunction in different situations.

One problem with the What-if method is as both Stamatis (2014) and Räddningsverket (2003) mention the experience and knowledge of the group members. They also mention fantasy and thinking process as an important presumption for the analysis. According to Räddningsverket (2003), this makes it easy to overlook some issues but this can be handled by using the What-if method as a part of a more comprehensive risk analysis.

Since the What-if method do not consider any quantitative estimation of the hazards, it is placed in level 0 in Paté-Cornell’s (1996) different levels of uncertainties in risk analysis methods.

4.5 Gretener method

The Gretener method is an index method formed around a basic mathematical formula that includes hazards and the risk increasing factors. It also includes the effect of fire suppressing and prevention measurements (Kaiser, 1980). The method was designed in the 1960s by Max Gretener and has since then underwent several updates. The values for different variables are an empirical derived point system to match the Gretener formula (Watts, 2003), is presented below as equation 5. In the equation it can be seen that the dangers of the facility is divided by the safety measures.

$$R = B \cdot A = \frac{P \cdot A}{N \cdot S \cdot F} \quad \text{(Equation 5)}$$

A	The probability of ignition
B	Degree of danger
F	Fire resistance of the building
N	Standard measures
P	Possible dangers
R	Fire risk
S	Special measures

It is difficult to place the Gretener method in one of Paté-Cornell’s (1996) different levels of uncertainties in risk analysis methods. This is because it is not known how uncertainties were treated in the development of the variables and model. The user of the model only looks at the description of the system and does not introduce new uncertainties. Depending on how the model was developed it is possible to place it in level 1 but most likely in level 2-3.

4.6 ROGA

The risk-oriented hazard analysis (ROGA) is a semi-quantitative risk analysis method designed and mostly used in process industry, but can be used in other areas. The method is designed around two concepts, risk class and dependability class. Each identified hazard is given a risk class (RC) depending on a simplified estimation of the consequences and frequency. The estimation is done with four different factors; extent of damage (S), frequency of the top event (W), probability of present people (A) and probability of people avoiding the hazardous event (G). This is done independently of the safety measures and W, A and G is all semi quantitative (Bock, F., & Haferkamp, K., 2014a).

The dependability class (DC) is instead a rating for the measurements. Two different factors affect what dependability class that is given to a measurement; type of measurement (e.g. human action, enclosure etcetera) and failure probability/rate. The prevention of a specific hazard is accepted when risk class is equal to or less than the sum of dependency classes of the measures according to equation 6 (Bock, F., & Haferkamp, K., (2014b).

$$RC(X) \leq \sum_i DC(Y)_i \qquad \text{(Equation 6)}$$

Depending on the user, the method can be placed in any of the six levels of uncertainties in risk analysis methods mentioned by Paté-Cornell (1996). The level depends on how the used values are chosen and how the uncertainties are treated.

4.7 NFPA 101

The NFPA 101A (2012) explains a group of qualitative index risk analysis methods designed for five different types of buildings. These types are:

- Health care
- Correctional
- Board and Care
- Business
- Educational

The method uses a number of factors that are given a value depending on the design of the analysed facility. Examples of factors that affect the result from these methods are floor area, length to exist, dead-ends, number of exits, measurements and many more. The facility is given grades depending on these different factors. A high value means better safety. Then the values for each factor are compared in a matrix existing of three parts; fire control, egress provided and general fire safety provided. The model is designed so that it corrects if one factor should have higher impact on one of the parts of the matrix. An example is that the smoke control has a higher impact on the provided egress possibility compared to general fire safety and therefore gets a higher value in the egress provided.

Even though none of the building types can be directly comparable to the CERN facilities, the result between different designs can be compared and thereby give a hint of if one of the two suggested design solution in this project is to prefer.

It is difficult to place the NFPA 101 method in one of Paté-Cornell's (1996) different levels of uncertainties in risk analysis methods. This is because it is not known how uncertainties were treated in the development of the variables and model. The user of the model only looks at the description of the system and does not introduce new uncertainties. Depending on how the model was developed it is possible to place it in level 1 but most likely in level 2-3.

5. Analysis

In this chapter, the different risk analysis methods are applied on CERN's facilities. After the analysis of each method, the advantages and disadvantages of the method are summarized in a short discussion. The methods are compared to each other in the overall discussion in chapter 7. To quantify the consequence some of the methods will be combined with design fires and CFD simulations.

5.1 Event tree analysis

In the ETA, this thesis interacts with report 5512 and 5513. Report 5513 is used to get results of the conditions in the tunnel. Report 5512 is used to investigate the evacuation possibilities during fires. Evacuation is simulated with both baseline configuration and the alternative option. The results from report 5512 provide this thesis with input data for the consequences.

Design fires, presented in chapter 3 were used to evaluate the fire safety of the new underground facilities at point 1 and 5. By placing these design fires in different critical locations in the tunnel it was possible to draw conclusions whether the proposed configuration is acceptable or not from a fire safety perspective.

Only short technical shutdown was analysed due to the extensive simulations, which was needed to make the event tree analysis in this thesis, and the many uncertainties in the project, especially for the long technical shutdown.

5.1.1 Tenability criteria

When analysing the safety of evacuees during fire in the simulations, three different tenability criteria are used in report 5512. These criteria are toxicity, visibility and temperature and come from ISO/TS13571:2002(E). The acceptable levels can be seen in table 3. A more detailed description on the use of the criteria can be found in report 5512.

Table 3. Tenability criteria for personal safety.

Parameter	**Value**	**Comments**
Toxicity	FED = 0.3	For fractional effective dose (FED) the threshold 0.3 can be used for most general evacuees in most reasonable fire scenarios.
Visibility	15 m	ISO standard set distances between 5 and 15 meters. To have a single value 15 meters were chosen to be conservative.
Temperature	60 °C	This value is the air temperature when convective heat is considerably painful for unprotected skin.

In the CFD simulations performed in report 5513 only tenability criteria for life safety was used. Therefore, no data for damages on assets could be received.

5.1.2 Short technical stop

The scenarios were evaluated with respect to their severity considering the functioning of the fire safety measures. In total, there are four or five different fire measures present in the tunnel depending on the location of the fire. Those fire measures are fire detection system, evacuation alarm, smoke curtains, smoke extraction and fire doors. A combination of events connected to these measures resulted in a comprehensive event tree, which is presented in Appendix III. To make it more manageable a first prioritizing was made. In consultation with Saverio La Mendola (Fire Safety Engineer for the HL-LHC project at CERN), it was decided to focus on fire detection, evacuation alarm and smoke extraction. The fire detection was chosen because it is the most important fire measure and if this fails, no other fire measure will activate. Next crucial measure was the evacuation alarm. It is necessary that the evacuation alarm work in order to get the attention of the occupants so that they begin evacuation as quickly as possible. The last measure that was chosen in this first selection of scenarios was smoke extraction. Smoke extraction is important since it supposes to improve the possibility to evacuate and reduce the impact of soot particles on equipment. This resulted in a more reasonable amount of end scenarios (five) shown in figure 20.

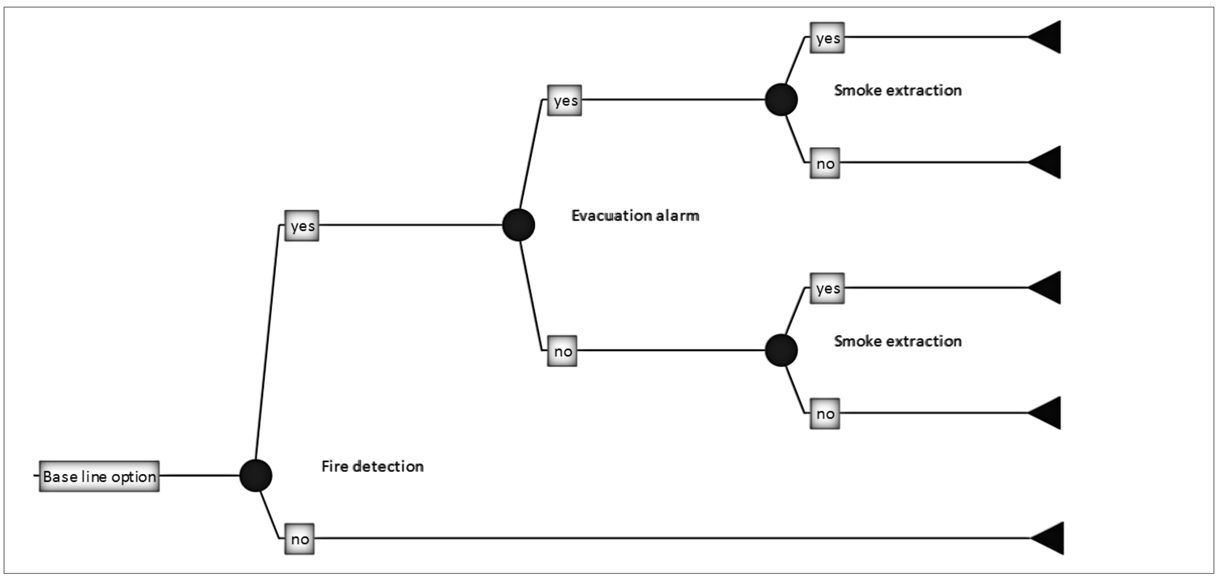

Figure 20. Simplified event tree for scenarios related to design fires.

This event tree is applicable for six different fire locations in the facility; centre of the UR tunnel, far end of the UR tunnel, in the UA gallery, in the UL gallery, in the US cavern and in the PM access shaft. This rendered in a number of 30 scenarios that had to be simulated. Due to the limitations in time and computational capacity for report 5512 and 5513, it was not possible to perform all the necessary simulations. Therefore, this number had to be further reduced.

The first simplification was due to that the only obtained reliability data for evacuation alarms was for fire detection and evacuation alarm combined. Therefore, the two nodes fire detection and evacuation alarm were merged during the calculations. This resulted in only three scenarios for each location. The second simplification was that the fires in the UL galleries were deselected due to lack of combustibles. After this, only 15 scenarios remained. This was still too many and therefore six scenarios were qualitatively chosen to be simulated, due to the expected problems with evacuation. The scenarios were chosen in consultation with Saverio La Mendola (Fire Safety Engineer for the HL-LHC project at CERN). Another three interesting scenarios were selected and might be simulated if time allows. These scenarios are presented in table 4. The chosen scenarios are simulated in report 5512 and 5513. For more details regarding the locations for the chosen scenarios, see Appendix I. Figure 21 shows the locations of the parts of the facility.

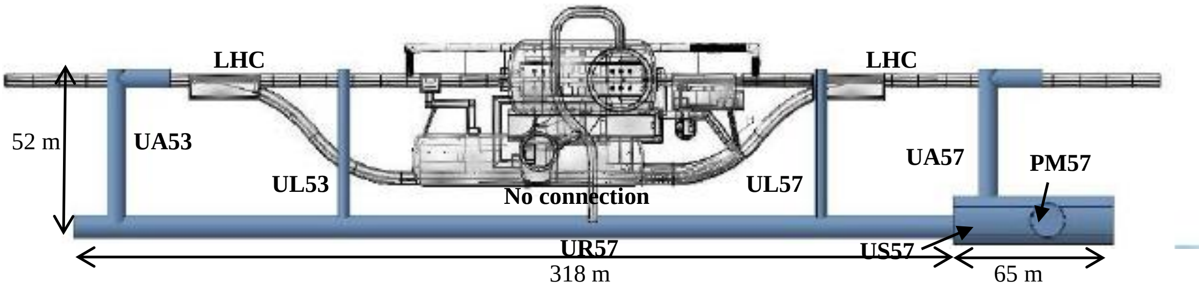

Figure 21. Proposed design of the facilities seen from above. Used with permition from CERN.

Table 4. Scenarios for the short technical stop that will be simulated in FDS.

Number	Description	Comment
1.	Fire in the middle of UR tunnel. All safety measures work as planned. This means that fire detection, evacuation alarm works as intended. The fire doors are closed. The normal ventilation is turned off and the smoke extraction is turned on.	This should be the scenario with least severe consequences.
2.	Fire in the middle of UR tunnel. All safety measures fails. This means that fire detection fails. Due to this the evacuation alarm does not start. The normal ventilation will still be on and the smoke extraction will not activate. The fire doors are closed since this is assumed to be the worst credible case.	This should be the worst credible case. When the doors are closed, the occupants have less possibility to notice a fire in another part of the tunnel.
3.	Fire in the UR tunnel, near the UA53 gallery. Fire doors to UA53 gallery open (fails). Evacuation alarm fails. Fire detection works which means that normal ventilation is turned off and the smoke extraction is turned on.	If the fire doors by some reason are open, the fire gets more oxygen and can propagate and smoke can spread both in the UA gallery and UR tunnel. People in the dead-end of the UA gallery might not notice the fire.
4.	Fire in the UR tunnel, near the UA53 gallery and rescue chamber. Fire doors to UA53 gallery closed. Evacuation alarm fails. Fire detection works, normal ventilation is turned off and the smoke extraction is turned on.	If the fire doors are closed, the occupants will only notice the fire if the door cannot withstand it any more or if the CRFS intervenes.
5.	Fire in the UA53. Fire door between UA and UR closed. Occupants are assumed to be in the far end behind the bend in the UA. All safety measures work as planned.	When occupants are in the far end, they might not notice a fire that starts in the UA. Since they are in the same compartment as the fire, they are directly affected by the fire in an early stage.
6.	Fire in UA53. Detection does not work. Ventilation still on. Evacuation alarm off, fire doors closed. Occupants are assumed to be in the far end behind the bend in the UA.	When occupants are in the far end, they might not notice a fire that starts in the UA. Since they are in the same compartment as the fire, they are directly affected by the fire in an early stage. Late attention to the fire due to no fire alarm.
(7.)	Fire in the US cavern, starts in the cabinets on the mezzanine. All systems work as planned.	Critical point since evacuating personnel must pass through on their way out.
(8.)	Fire in the US cavern, starts in the cabinets on the mezzanine. All systems fail.	Critical point since evacuating personnel must pass through on their way out.
(9.)	Fire in vertical cables in the PM access shaft. All systems work as planned.	Wants to investigate the ventilations impact on the smoke spread in the shaft.

( ) Will be simulated if there is time.

The calculations and the values for the event tree in figure 22 can be seen in Appendix III. The frequency should be used with caution because the values come from a fault instead of a fire in a transformer. It should also be noticed that the frequencies used in the event tree is for only one transformer. In the UR tunnel, there will be multiple transformers present and other equipment where a fire can start, but statistics was only found for transformers.

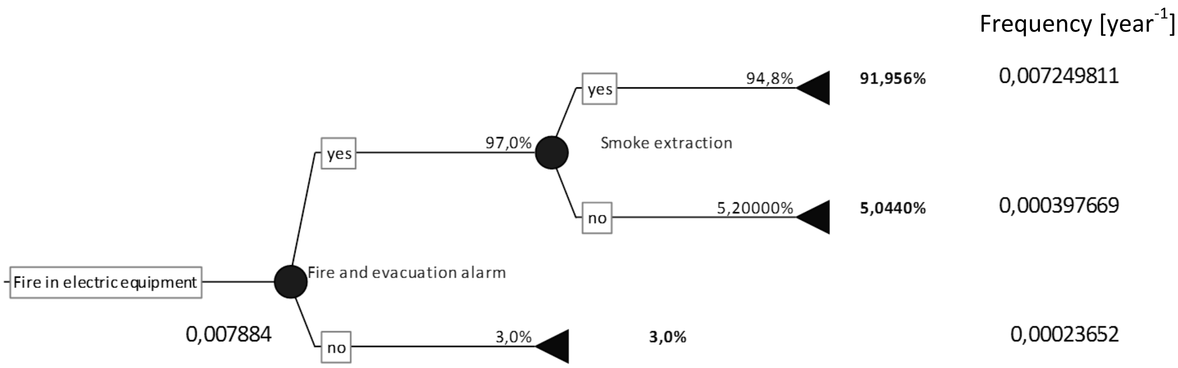

Figure 22. Final event tree used for the scenarios.

In report 5512, the result from the evacuation simulations show that for scenario 5 and 6, for the baseline configuration, the occupants have to evacuate next to the fire in a narrow path or evacuation is not possible at all without exceeding the tenability criteria, mentioned in chapter 5.1.1. For scenario 5 and 6, the baseline configuration is therefore not considered to provide the required safety.

In report 5512, the rest of the scenarios showed no problem with the evacuation for neither of the design options. However, only 15 minutes of the simulation time was acquired which do not provide a complete analysis of the scenarios. For example, several scenarios in the baseline configuration are dependent on the rescue chambers. The temperature and conditions in the tunnel can be assumed to get worse until the CFRS can start their extinguishing process. The simulations can therefore not give an approximation on the exposure on the rescue chambers. At point 5, the CFRS can start to attack the fire after approximately 40 minutes. This results in that the fire could spread in the tunnel for nearly 25 minutes from the end of the simulations until a possible decrease of temperature and HRR in the tunnel. Due to this, no conclusions can be drawn regarding the provided safety by the rescue chambers.

Due to the incomplete analysis of the consequences, it was not possible to complete the ETA in this thesis. The only event tree that could be finished was for a fire in the UA gallery for the baseline configuration. However, this could only be done when assuming that the fire will behave the same as in scenario 5 and 6, when the evacuation alarm activates and the smoke extraction fails. With this assumption, all three scenarios for a fire in the UA gallery rendered in a negative outcome from a personal safety perspective. Therefore, the baseline configuration cannot be considered to fulfil the demanded safety for a fire in the UA gallery.

No data for calculating the damages of the assets were achieved from the simulations. Therefore, the ETA does not consider asset protection in this thesis.

5.1.3 Discussion ETA

The ETA is a good tool to get an overview of the problematics and organise a complex risk analysis with many events and possible scenarios. The calculations are simple and it is also easy to do a sensitivity analysis to find the factors which have the most influence on the result. The tree can be easy to understand and interpret, if the tree is not too complex. If the tree results in a reasonable size, it could be a good tool when presenting a complex problem to decision makers. However, the event tree grows quickly and from this thesis, the conclusion is that the tree should fit on one page in order to be comprehensible and easy to understand. A large event tree makes the consequences hard to handle, especially when analysing one scenario at a time. Instead the method could be simplified either by removing events that are assumed to not have a big impact on the outcome. Another option is to group similar scenarios, with one consequence representing the whole group. A combination of these simplifications has been used in this thesis, which has rendered in a reasonable amount of simulations.

The method depends on other models in order to achieve a complete result. From a fire perspective, as in this thesis, this includes comprehensive fire and evacuation simulations to get the consequences for the ETA. Furthermore, it can be hard to find statistics for probabilities, especially when analysing a unique facility like CERN. It is possible that the input data needs to be taken from similar but not identical equipment. This results in that the analysis is less valid and need to be verified or used with care. The verification, on the other hand, could be done by doing a sensitivity analysis. Since the uncertainties connected to the design fires also affect the ETA, it is of utmost importance to create as accurate design fires as possible. This was difficult in this thesis due to the uncertainties regarding the equipment that would be present. It was also necessary to simplify the event tree in order to get a reasonable amount of scenarios, which might have resulted in loss of information.

When doing a quantitative method, there must also be decided which level of safety that can be considered accepted. This level can be defined for personal safety, asset protection, operational protection, environmental protection, economic and others. The accepted level could be decided either from standards, organisational or insurance agency demands. Although in this thesis, only the safety of people have been analysed due to time and data constrains.

Another downside with the ETA method is that the events always happen at a certain step in the timeline. An alternative method like dynamic event tree, see Appendix II, solves this problem by being more flexible to variations in time. On the other hand, the dynamic tree method gets more complicated and time consuming compared to a standard ETA.

Early in the project, it stood clear that the focus of the ETA was to do computer simulations. In hindsight, it might have been more useful to do hand calculations. This could have been applied to cover more scenarios and it is easier to do a sensitivity analysis with quick hand calculations to compensate the uncertainties in the parameters that the hand calculations introduce. However, the calculations of the consequences and smoke spread were outside the scope of this thesis and the need was noticed to late in the project.

According to chapter 4.2 the uncertainty in the ETA, based on Paté-Cornell's (1996) different levels, can be between level 2 and 5. The way the ETA is used in this thesis, it ends up in level 2. This is because the worst plausible scenarios are chosen.

5.2 Preliminary hazard analysis

Different types of fires were evaluated with the PHA. The fires are presented in table 5. The frequencies and the consequences were divided into three different classes. The grading of the classes does not have strict limits. Instead, it represents how the different events and causes are assumed to relate to each other. Both short and long technical stops are included in Table 5. This is based on the how the method is meant to be used. The intention of the method is to get an early indication of the hazards in the facility and what safety measures that should be present.

Table 5. PHA Brainstorming record for baseline configuration.

Event	Cause	Consequence	Frequency class	Consequence class	Proposed measure
Fire in cabinet	Arcing	Fast initial growth and large damages on asset. Possible loss of human life.	1	2	Detection inside and/or outside cabinets. Compartmentalisation
	Over heating or ground fault	Damages on asset. Possible loss of human life.	2	2	Make sure that cooling and installation of components in cabinets meet the requirements. Compartmentalisation
Fire in cable tray	Overload or Insulation fault	Damages on asset, especially cables. Possible loss of human life.	1	1	High fire rated cables. Tray dividers that prevents further propagation within and between cable trays. Cable detector in cable trays. Compartmentalisation
Detected fire in transient load	Hot work	Minor asset damages.	3	1	Fire extinguisher, Regulated in fire permit
Undetected fire in transient load	Hot work	Quick propagation and large damages on asset. Possible loss of human life.	1	3	Regulated in fire permit, Fire safety steward, Compartmentalisation
Blocked evacuation route during fire	Blocked door or fire between personnel and evacuation door	High possibility of loss of human life.	1	3	Have multiple evacuation routes at every point at the tunnel. Smoke extraction.

When applying the PHA on the baseline configuration it was shown that one of the needed measurements to reach an accepted level of safety was to improve the evacuation possibility. This could be done either by installing rescue chambers as in the suggested baseline configuration, or by provide more evacuation routes from the facility, as in the alternative option. From this conclusion, it can be seen that the alternative option does not need to be evaluated by the PHA since all other measurements will be the same as for the baseline configuration.

5.2.1 Discussion PHA

In the PHA most of the fire safety measures already planned for the facilities are mentioned but also some optional such as local detection inside cabinets and cable trays are suggested. Table 5 shows that one of the worst consequences, for personal safety, derives from the lack of emergency routes. By providing two evacuation routes from every location in the tunnel, the possibility to evacuate is significantly increased. The alternative option solves the evacuation problem by suggesting two evacuation routes from every point of the facility. This is why the alternative option does not have to be evaluated with the PHA. The other case with the highest rated consequences is hot undetected fire during the long technical stop due to hot work. This can be managed with a fire safety steward attending and strictly follow the safety regulations.

For asset protection, the worst consequences can be found in the cases of an undetected fire in transient load and fire in electrical cabinets. The proposed measurement for an undetected fire in transient load is to ensure that the safety regulations are followed and to make sure that a fire safety steward is present during hot works. Regarding the proposed measurement for the undetected fires in cabinets, it is important to make sure that all installations are correctly performed. To ensure that a fire is noticed it might be possible to install detection inside the cabinets.

The limitation of the PHA is that it only gives a harsh overview of the risks. On the other hand, it gives quick and clear results of where the focus should be when doing analyses that are more detailed afterwards. The methodology itself is very easy to use but more experience and knowledge of a certain problem gives a better estimation of the consequence, frequency and measurement options. In this report, there are restricted knowledge and experience in both the facility and in the use of the method, which result in less validity and reliability.

The fact that most of the mentioned measurements are already planned for in the CERN facilities shows that this method reflects what is usually done subconsciously when observing risk in an early stage or new facility.

5.3 What-if method

The technical equipment that was evaluated with the What-if method was those related to fire safety measures. These measures were fire detection, fire alarm, smoke curtains, smoke extraction, shut down of normal ventilation, fire doors and rescue chambers. The results from both baseline configuration and the alternative option are presented. In this method, the focus lies on the equipment. Since the safety measures are the same both for long and short technical shutdown, the method was applied without any reference for the status of the facility. Therefore, it was not necessary to do an analysis on both the short and long technical stop, since the fire safety measures are the same. The grading of the classes does not have strict limits. Instead, it represents how the different events and causes are assumed to relate to each other. The results are presented in table 6.

Table 6. What-if method applied on both designs.

What if?	Cause	Consequence	Existing protection	Probability	Recommendation
Detection off	Technical error	Late or no detection. Large asset damages. Possible loss of human life.	Redundant systems. Control centre monitoring	Low	-
	Turned off	Late or no detection. Large asset damages. Possible loss of human life.	-	Medium	Fire guard. Make sure the fire permit regulations are updated and followed, timer that will activate the detection after a certain amount of time
Fire alarm off	Technical error*	Long notification time. Minor asset damages. Possible loss of human life.	Manual activation possible (not sure it will work if technical failure)	Low	Make sure there are always two separate ways to safe areas. (Outside, rescue chamber, etc.).
	Technical error**	Long notification time. Minor asset damages. Low possibility of loss of human life.	Manual activation possible (not sure it will work if technical failure)	Low	-
Smoke curtains fails	Technical error	Large asset damages. Possible loss of human life.	-	Low	Other type of sectioning
Smoke extraction fails	Technical error	Large asset damages. Possible loss of human life.	Manual activation. Redundant systems	Low	-
Ventilation shut down fails	Technical error	Large asset damages. Low possibility loss of human life.	Manual deactivation	Low	-

Fire doors not closed	Door hold open by blockage	Asset damages. Low possibility of loss of human life.	-	Medium	Controlled daily. Make sure the fire permit regulations are updated and followed. Alarm if open a longer time. When alarm is turned off, use fireguard.
*Rescue chambers fails	Overheating	High possibility loss of human life	-	Medium /High	Alternative evacuation route.

*Only in baseline configuration
**Only in alternative option

With this method, it can be seen that regarding possible loss of human life there are two cases that stands out in the baseline configuration. The first case is if the fire alarm does not activate due to a technical error and this can happen in both short and long technical stop. The result could be that personnel are trapped in either rescue chambers or transversal tunnels. The problem with the rescue chambers is that they might not be able to withstand a fire, which was the second case that stood out. Therefore, the alternative option provides a better solution since there are at least two independent exit routes from each point of the tunnel.

Regarding asset protection, it can be seen that the worst consequences derives from when the fire detection fails or is turned off. For failure in the fire detection, the planned measurement is to have redundant systems. When the fire detection is turned off, the proposed measurement is to have a fire safety steward present during the turned off period. It is also proposed to make sure that the fire permit regulations are updated and followed. The final proposed measurement is to have a timer that will activate the detection after a certain amount of time.

5.3.1 Discussion What-if

The method itself is very uncertain since it is dependent on the user's assumptions, knowledge and experience. The more experienced group the better analysis. It is important to have a group of experienced people with mixed backgrounds and educations to get the whole picture so that noting is overlooked. Another unwanted result could be if there is one very dominant member, who could influence the rest of the group. A solution to this could be to start the analysis in smaller groups with mixed backgrounds and then proceed with the discussion in the whole group. The moderator has a very important role since he is supposed to make sure that everyone gets their voice heard. A downside with the method is the need of many participants in the groups. This makes the method highly demanding on the resources even though it is simple to use. Every participant needs to schedule time for the meetings and in the end the total time consumption for all the participants might end up high. It is also hard to find time for a large group where everyone can attend. However, as the theory chapter 4.4 mentions the method is fast and gives a good overview of the problems that can occur.

With a What-if analysis, it is hard to capture dependencies between objects. If this is done, the result will be similar to an event tree.

In this thesis, the What-if method is limited by the fact that the expert group doing this analysis consists of only two persons with limited knowledge and experience of the method and facility. This could result in important outcomes being overlooked in the analysis and that it therefore result in a low validity and reliability.

5.4 Gretener

Even though the Gretener method looked as a good option at a first glance, a more thoroughly control of the method showed the opposite. The method considers many good aspects such as fire load and size of the facility. On the other hand, it does not take into account the distance to emergency doors. Because of this, both civil engineering designs end up with the same result and no conclusions can be drawn.

5.5 ROGA

Like the Gretener method, the ROGA method looked promising, but when doing a more thoroughly study of the ROGA method it showed weaknesses when using it on the CERN case. With the method it was possible, and easy, to get a risk class for the fire hazards. The simplicity from this came from the clear red line in the method and well defined limits between the different values for each factor.

For the dependency class on the other hand the method was harder to use on the specific case, and the fact that the method are developed in the process industry could be noticed. One of the problems was that the method focuses mostly on preventive measurements and that the top event should not happen at all. The method only looks at hazards as a binary event. Either the event happens or not and the consequences stay the same independently of the measurements mitigating effects. The alarm system, both manually and automatic, could be given a dependency class. However, this depends on if they alert early enough so that the fire can be extinguished before it results in unaccepted consequences.

The other problem is that the dependency class is based on the fault frequency for measurements, which can be used for the alarm system and smoke extraction but not for the evacuation routes. Since the main objective is to compare the two design options, the ROGA method will give no clear result, as both designs will get the same outcome.

5.6 NFPA

Most of the building types in the NFPA index method refer to groups of people who by some reason need assistance to evacuate. Two examples is physical disability or in need of another person to unlock one or more doors. When comparing to CERN the most corresponding group was assumed to be business occupancies. Both groups are in general capable to evacuate by themselves. The exception is that the occupants at CERN will be more informed of the evacuation procedures and safety routines. When the condition of one factor in the tunnel exceeds the worst case condition in NFPA, the worst case value of the factor in the method was chosen.

With the NFPA method, it was decided to compare three different designs: Baseline configuration with and without rescue chambers and the alternative option. Between the three different designs, three factors changes in value; segregation of hazards, exit access and egress route. Otherwise, all values stay the same. The method does not consider fire load and since smoke detection and fire alarm is the same in both short and long technical stop, the two phases can be merged in to one analysis. The results, comparisons to baseline configuration and the highest recommendation from NFPA are presented in table 7. The reason why the calculations were made for the baseline configuration with and without rescue chambers was that there are discussions whether they can withstand a fire or not. This result is presented in the report 5512. The method is designed so that a high value is good and a low is bad.

Table 7. Result from NFPA method. Comparison between Baseline configuration with and without rescue chambers and with the alternative option.

Design	Fire control	Egress provided	General fire safety provided
Baseline without Rescue chambers	19	8	4
Baseline with Rescue chambers	23	21	17
Alternative option	23	22	18
Highest recommendations from NFPA	13,5	9,5	15

Table 7 shows that the only result that stands out from the other two is the baseline configuration without rescue chambers. This is also the only result that does not reach the recommendations from NFPA. As seen in table 7, all designs have high values on fire control. This is because the method is designed for business occupancies where this factor aims to describe the hazard with walls that support several floors. Since there are not several floors at CERN, the most important factors to compare are egress provided and general fire safety provided. As mentioned before it is only the baseline configuration, without rescue chambers, that stands out and the other two designs have higher results in the two parts. The chosen values and motivations are presented in Appendix IV.

5.6.1 Discussion NFPA

Even though the results cannot be directly implemented at the CERN facilities, the result shows that the baseline configuration is dependent on the rescue chambers in order to be an acceptable civil engineering design from a fire safety perspective. This conclusion comes partly from that the design fails to reach the recommendations but also that travel distances and lengths of dead-ends are much longer than the values used in the method, which also are the recommended max distances from NFPA (2012). Two examples of this is that the longest travel distance in one fire zone is 318 meters which can be compared to a maximum of 120 meter (400 feet) in NFPA (2012). And the dead-ends can reach up to over 400 meters and can be compared to a maximum distance of 30 meters (100 feet) in NFPA (2012). The maximum dead-end distance is not provided in the option with rescue chamber either with four dead-ends that are approximately 20 meters to long compared to the standard. However, since the standard is made for facilities with a higher number of occupants it is hard to say any exact conclusion from this without any further studies. The NFPA 101 does not consider asset protection.

The NFPA 101 gives the same result regardless of who uses it, which result in high reliability as long as it can be applied on the facility.

5.7 Summary of results from risk analysis methods

Event tree analysis:	The method shows that there are scenarios where the baseline configuration does not fulfil the demanded safety for personal safety. From the simulations, it is hard to give answer to the damages on assets.
Preliminary hazard analysis:	The method shows that the baseline configuration needs the rescue chambers to fulfil the demanded personal safety level but also the alternative option fulfils this demand. Regarding asset protection, the analysis shows that there is a risk of major damages if there is a fire in the facility. From this point of view, there are several proposed measurements to reduce the consequences of these scenarios.
What-if:	The method shows that only the alternative option fulfils the demanded personal safety. Regarding asset protection, the analysis shows that there is a risk of major damages if there is a fire in the facility. From this point of view, there are several proposed measurements to reduce the consequences of these scenarios.
Gretener:	The method was not suitable for the facilities.
ROGA:	The method was not suitable for the facilities.
NFPA 101:	The method shows that the baseline configuration needs the rescue chambers to fulfil the demanded personal safety level but also the alternative option fulfils this demand. The method does not consider asset protection.

6. Summary of risk analysis at MAX IV and ESS

In this chapter other unique facilities, with similarities to those at CERN, are presented. To get an overview on how other facilities handle risk the fire engineers Dadi Thorsteinsson, at MAX IV, and Fredrik Jörud, at ESS, has been interviewed. The two facilities are particle accelerators under construction in Lund, Sweden. In the interviews Thorsteinsson and Jörud explains how risk analyses are made at their facilities and their opinion on how they think that the development in the area should proceed.

6.1 Max IV

MAX IV is a national laboratory sited in Lund and Lund University is the host of the laboratory (MAX IV, n.d,a). The new facility at Brunnshög will be opened for users in 2016. The accelerators at MAX IV produce x-rays of very high intensity and quality.

The new and more advanced equipment in MAX IV will give exceptional resolution (MAX IV, n.d,b). The synchrotron radiation covers the wave-length range from the far infrared trough the UV, VUV, soft x-ray and up to the hard x-ray range using radiation from bending magnets or insertion devices (MAX IV, n.d,c). The techniques that will be used are amongst others:

- infra-red spectroscopy and microscopy,
- VUV and soft x-ray electron spectroscopy and microscopy,
- soft x-ray magnetic circular dichroism,
- x-ray fluorescence,
- x-ray absorption spectroscopy and
- different x-ray diffraction and scattering techniques

6.1.1 Comparison MAX IV and CERN

When interviewing HSE Manager at Max IV Dadi Thorsteinsson (26th of November 2015), he pointed out that the facilities at MAX IV and CERN are quite different. Firstly, Max IV is located mostly over ground with the maximum depth of 2 floors beneath ground level. This makes it possible for Max IV to have several evacuation routes from underground areas. HL-LHC at CERN is located approximately 100 meters below ground level and this complicates the possibility to evacuate.

The second big difference between the facilities is, according to Thorsteinsson, at Max IV there are no radiation after shut down. At LHC at CERN, there is still activated material after shut down, which leads to the risks remains even after shut down.

Thorsteinsson has not been involved in the risk analysis for MAX IV himself, but points out that the one that was performed only had focus on personal safety. This was due to the request of the property owner. Thorsteinsson would have preferred an analysis that also took property damage in to consideration. This is because of the very expensive equipment and all the investments in the facility. This could for example be the impact of smoke extraction. In the current risk analysis, this is not covered.

Thorsteinsson says that in general mostly qualitative analyses are used. Sometimes also semi-quantitative analyses with intervals are used. He informs that there is a new collaboration to gather statistics of incidents etcetera from this kind of facilities. The members of this collaboration are Max IV, ESS, CERN, Fermilab (particle accelerator laboratory in USA) and Brandteknik (Lund University). This will hopefully lead to more accurate quantitative methods in the future since statistics for this kind of unique facilities is very hard to find today.

6.2 ESS

The European Spallation Source (ESS) is a research centre that will be located outside Lund in the south of Sweden. The construction of the facility started in 2014 and it is planned to open for researchers 2020. In the multi-disciplinary centre, research will be performed with the world's most powerful neutron source. ESS will be up to 100 times brighter than existing facilities and it will enable new opportunities for researchers in the fields of for example life sciences, energy, environmental technology and fundamental physics (ESS, n.d).

The instruments at ESS can be compared with a giant microscope for the study of different materials. This microscope makes it possible to study everything from plastics, pharmaceuticals, proteins and nanoparticles. In this way, ESS is very important for the science of everyday life (ESS, n.d).

ESS will be a collaboration between 17 European countries and Sweden and Denmark will be the hosts. In total, 100 partner laboratories will contribute with knowledge, equipment and financial support during the construction phase. Scientists and engineers from these laboratories are working on how to use the ESS facility in an optimal way. It is planned for 2000 to 3000 guest researches that will use the facility every year (ESS, n.d).

6.2.1 Comparison ESS and CERN

There are several similarities but also differences between CERN and ESS. To begin with, the ESS will be a facility on ground level. CERN facilities are approximately 100 m below ground. The main evacuation problem at CERN will therefore not be the same issue at ESS. The possibility to solve multiple evacuation routes is far simpler on ground level compared to below ground level.

Since both ESS and CERN are colliding particles in their facilities, both have to handle the radioactivity that follows. CERN has however a much higher level of radioactivity and this is one of the reasons why CERN facilities are located below ground.

In an interview with Fredrik Jörud (27th of November 2015) who is Fire Protection Manager: Environment, Safety & Health at ESS, he says that his experience is that every risk analysis demands its own approach. It is hard to work after a fixed template because different clients have different perspectives and goals. During the interview the differences between countries, and how the approach to risk analysis differs, is discussed. In some countries, they are obliged to follow standards and give no room for analytical analyses. In Sweden however, it is very common to use the analytical design since it is often proved to be more flexible and give the client the most cost effective result. Jörud, however, definitely sees the benefits from using standards since it gives some level of authority to the analysis. It also makes it easier to apply on other areas.

When doing a quantitative risk analysis he recommends to use the values for frequency based on statistics from nuclear power plants in the Nordic countries, T-boken.

7. Discussion

In the following sections the results from the analysis is discussed. A discussion of the use of a specific risk analysis method can be found under each method's headline in chapter 4.

7.1 Design fires

When doing the design fires, the lack of information on the equipment that will be used made it necessary to do a number of assumptions. These assumptions are mostly connected to the cabinets. The lack of knowledge on how the equipment works has been a problem when making assumptions for the calculations. It is also hard to decide what kind of faults is reasonable and how often they occur. Even though some information and statistics have been found, when it comes to fault in electrical equipment most of the fires are summarized as a technical error with unknown start in the statistics. It was decided to focus on those fault that were explicitly accounted for which were arcing, overheating and short circuit which seemed reasonable for the technical equipment at CERN.

The values used in the design fires come from tests done in open air. Since this is not the case at CERN more uncertainties are introduced in the design fires. Examples of uncertainties are that the fire could become ventilation controlled in the tunnel at CERN, which results in a lower HRR. Another possible situation is that the hot gas layer will affect the fire propagation, resulting in a higher HRR instead.

The decision on what values to be chosen in the calculations was based on worst credible case and internal safety regulations at CERN. An example is that thermosetting cables are used in the thesis instead of thermoplastic. This assumption is based on that CERN's regulations demands cables with the highest possible fire rating.

7.1.1 Cabinets

When doing the HRR curves, it is hard to determine if the values from experiments are applicable at CERN. In general, it is hard to apply results from other experiments since the exact circumstances are unknown. Neither the exact information about the equipment that will be used at CERN is known. The chosen values comes from distributions created for nuclear power plants and are considered conservative. The values in the experiments varied significantly depending on what type of cabinet that was used. The conservative values were chosen due to the lack of information of the cabinets that will be used in the facility.

After the decay phase calculations it was noticed that a value in the middle of the interval for the decay time constant was chosen. This is a contradiction to the worst credible case. Since this was noticed in a late phase of the project, it was not possible to change because it would change the input of the simulation. This would have affected the other parties in the project too much. A quick control calculation showed that this would have resulted in a 10 % HRR increase after approximately 8 minutes for the first cabinet. The maximum HRR would have been 4 % higher if the value for worst credible case had been used. With this said, it is obvious that this is not a crucial error since there are several other assumptions and uncertainties in the thesis.

One problem in this thesis was to find representative data for electrical cabinets and the achieved statistics was widely spread over a large interval. This can also be seen as a weakness in the calculations comparing to cables, where CERN had very good document for calculating propagation speed and HRR. It is therefore recommended that the collaboration between similar facilities focus on the development of similar tools for calculating HRR for electrical cabinets. These tools would have made it easier to perform both simulations and hand calculations on fire and smoke spread.

7.1.2 Cables

CERN has a policy of using as safe cables as possible from a fire safety perspective. However, since the definite design of the facility and equipment are not determined yet, it is not possible to get information about what kind of cables will be used in the tunnel. Even though the majority of the cables will probably be in thermosetting and relatively fire proof, it cannot be excluded that thermoplastics will be used to some extent. In this thesis, it has been chosen to assume that all cables will be thermosetting. This is motivated with the safety regulations at CERN, which says that the cables with the highest possible fire rating should be used. There can be exceptions from this recommendation if the specific cable is not available with the highest fire rating. This exception is more accepted in current facilities but as this thesis treats a new facility, the assumption that thermosetting cables will be used is more realistic.

There are also uncertainties regarding different ignition temperatures for cables that were retrieved from the literature. Two sources with rather different values were found and the one with the lowest ignition temperature was chosen, since it was considered the most conservative. It was also decided that it would be more appropriate to be consequent by using the approach with the worst credible case throughout the thesis.

There are also some uncertainties regarding the calculation documents received from CERN. It was not clear whether the calculations are based on bundled cables or not and how well filled the cables trays were. This relates to the 5-4-3-2-1 method that was used to calculate the propagation between the cable trays. Experiments performed by USNRC (2012) showed that if the cables were loosely packed the method was accurate, but that tightly packed cables limited the fire spread to the trays above.

The total amount of cables in the facilities is unknown but the used values have been based on the size and amounts of cable trays. The approximated weight, of 40 kg per cable tray and meter, can however be seen as reasonable. Another assumption is that the amount of cables in the trays varies depending on location in the tunnel. However, exact information on this variation of cable load is unknown.

In the calculations, it is assumed that the cable trays are affected by the hot smoke layer, which results in the highest propagation speed. This assumption is based on the worst credible case since it is hard to say exactly when the hot smoke layer affects the cables. Since the propagation speed varies from 1,1-32 m/h the choice of this value has a strong influence on the calculations. Numerous simulations could have verified the time until the smoke layer would have affected the cables, but it was not possible to do due to the time constrains of this project.

7.2 RA- methods

When doing a risk analysis in an early stage of a design some difficulties were noticed. This was mostly due to all uncertainties connected to that the final design was not yet determined, but these uncertainties were the same in all analyses methods. However, there were also specific uncertainties that only appeared in a specific method.

The ETA can be used in any phase of the project since it could be made both qualitative and quantitative. It should be noticed that the method is rather time consuming and therefore it is recommended to use another and quicker method in the early design phase. A quicker method could easy point out where a more detailed analysis is needed and thereby make the risk analysis more effective regarding both time and other resources. It was relatively easy to get statistical data regarding when the equipment fails, but harder to get statistical data on when a fire actually had occurred due to a fault. The result of this is that the fire risk is overrated. Another disadvantage with the quantitative use of any risk analysis method is the difficulties to get statistical data on very specific equipment. This leads to several assumptions which ads uncertainties in the result. An example of this problem was to find representative statistic for start-up of a fan. Statistics for the availability for a fan could be found but was considered too high, as it would result in a lower probability of the failure compared to the fire detectors. Instead, the value for different pumps and diesel generators was used. The assumptions made in the risk analysis give the performers a big influence on the result, which can be used to put personal preferences in to the analysis. However, if the method is used on a well-known facility by experienced users the ETA has both high validity and high reliability. To get a complete picture of the risk situation the consequences must be taken into consideration. In this project, the consequences are investigated in report 5512 and 5513.

Despite having different focus, the PHA and What-if method have several similarities. For instance, both methods can be used in an early stage of a project. The result can be used to draw attention to which fire safety measures that need to be in place in an early design. This could for instance be measurements to prevent fire from occurring, limit fire spread and enable evacuation. However, when doing the literature study there was an impression that the What-if method is more accepted to use as a risk analysis method compared to the PHA. The experience from this thesis is that both methods are simple to use and gives very quickly results when study a design in an early stage. One difficulty when using the PHA and What-if methods is that it was hard to stick to one method and not use aspects from the other. This is because the methods have a rather similar approach since they both are based on the fact that the user questions what can happen in every location or with every fire safety measure. In the What-if method, the focus lays on the function of the equipment and how this can lead to a fire ignition. Meanwhile the PHA focuses on an overall identification of hazards and consequences. Compared to ETA, both What-if and PHA are more dependent on the performers and are therefore less reliable. However, the validity of the methods could still be high if the users have high knowledge and experience.

When comparing the index methods NFPA 101 and Gretener it becomes clear that the methods have different focus. Gretener takes for instance the fire load into account and NFPA focuses instead on the evacuation problematics. NFPA is developed for facilities that have specific problems with evacuation such as hospitals and others. It is however strange that Gretener which is developed specifically for fire hazards does not explicitly take evacuation into account. The Gretener method uses the size of the facility and proportions of the sides to make an assumption of provided evacuation possibility. In Gretener a facility that is long and narrow, like the tunnel at CERN, gets high value on provided evacuation possibility. This makes it very clear that Gretener is developed for facilities above ground. If it is possible to include the evacuation problematics in to the Gretener method, this one is to prefer. Both NFPA and Gretener can be used in an early stage of a project but they are more fixed in a specific template compared to PHA and What-if. In general, the index methods have high reliability due to the structure of the methods. The validity is dependent on how well suited the method is for the analysed project.

When using ROGA it became clear that the method had more focus on preventing the event. This made it rather difficult to apply the method on CERN, since it was the consequences that were supposed to be analysed. The approach made it obvious that the method is developed for the process industry where a fire can have catastrophic effects. However, it might be possible to use ROGA for the whole facility when it comes to prevent a fire from ever occurring. Even though the method is developed for the process industry, it can definitely be applied in other areas.

Paté-Cornell's (1996) different levels of treatment of uncertainty in risk analysis methods was used to try to rank the chosen risk analysis methods according to how well they handle quantitative uncertainties. This is one way to show how well the result represents the reality and how precise the methods are. By including more uncertainties in the presented results the more complete picture of the risk is presented. In this project, the ETA it was desired that most of scenarios should be included in the analysis and therefore level 2 was chosen instead of level 3. It is also possible to do an ETA on level 4 and 5 but this was not considered necessary in this phase due to the comprehensive work that needed to be done on these levels. It was also considered that level 2 would provide good results when comparing the designs in this phase and comparing different methods. Because the PHA and What-if do not treat quantitative uncertainties they were placed in level 0. Higher level results in better possibility to verify the methods due to the comprehensive statistical foundation. Therefore, it is easier to verify the ETA than PHA and What-if which are more based on experts opinions and estimations.

Three different types of risk analysis methods have been analysed; index methods (NFPA 101), simplified methods (PHA and What-if) and one method that is more complex (ETA). When the methods are used early in a design phase, as in this thesis, some advantages with some of the methods stands out. For example, the index methods easily and quickly provide the user with a number that can be used to compare different design options. The problem on the other hand, is that the index method has to be designed for the specific type of facility. This make the specifically designed index method time efficient for an early screening of different design options. The simplified methods like What-if and PHA are more resource demanding especially regarding personnel and time. On the other hand, it might fill in facility specific gaps that could be missed in the index methods. The simplified methods allow thinking that is more flexible and does not need to be specially designed for the type of facility. The complex methods, represented by the ETA, are even more resource demanding especially for time and computer capacity than the others are. It also demands many details to avoid assumptions and uncertainties. These limitations makes is less applicable in an early design phase where many details are unknown. In addition, the high time consumption makes it inappropriate to use when trying to compare several different options. However, when doing a final risk analysis the ETA is more suitable since it gives a more complete picture of the risks and if chosen safety measurements are sufficient.

The use of different risk analysis methods during the different phases of a project is more applicable for complex facilities, such as the new underground areas at CERN. The problem with unique facilities is that there are not much statistical data to be found. Therefore, most of the risk analysis methods are based on expert judgement, which is not seen as a reliable ground for many decision makers due to the high cost that can be connected to the alternative design. The simplified methods are more based on expert judgement than the others are, which make them harder to justify. This has been identified by the fire engineers at CERN, for example within the new HL-LHC project.

7.3 General discussion

Since the two design options with their advantages and disadvantages were presented early in the project, it was difficult to keep an open mind when it came to include other type of hazards. Therefore, the problem with only one evacuation route might have had more focus than it should. In addition, the other risks and problems connected to fire in the facilities might have been overlooked. This shows the need for a group with a mixed background to have as broad perspective as possible, when doing the hazard identification and early risk analysis.

The first reaction when the two options were presented was to choose the alternative option. This was the intuitive feeling due to the obvious evacuation problematic with dead-ends in the baseline configuration. However, those who make the decisions do not have the same background when it comes to investigate fire hazards. They need to consider several factors and therefore it is important to show the problematics with the baseline configuration. It is of the utmost importance to be transparent with what kind of assumptions, input data and other simplifications that had to be made in the risk analysis, to provide a comprehensive picture as possible. Every step of the analysis must be well motivated and thought trough. It must be understood that the analysis is based on many uncertainties but it is done in the best possible way. Even though there are uncertainties and assumptions made in the thesis, the results could give enough information on which of the designs that recommended from a fire safety perspective.

The risk analyse method should be decided by the needs of the project and in which phase of the project it is done. The choice of risk analysis method should also be done depending on the type of object that are being analysed. In an early phase a more simple method, like an index method or What-if, is to prefer when it comes to compare many different design options. In this phase, the details are not decided and therefore a more complex method still has disadvantages in assumptions and uncertainties. Further on in the project, when most of the design options are rejected and more details are decided, it is of more use to do a more complex method, for example an ETA. These conclusions are well in line with what is stated by Räddningsverket (2003), presented in chapter 4.

One scenario that has not been covered in this thesis is a smouldering fire due to hot works. It is not sure that the detection system is turned on after the hot works, which can result in that there is no detection in the facility over the night. If this goes unnoticed, the smouldering can increase to open flames that propagate without detection during the night resulting in large asset damages. To avoid this problem another less sensitive detection system can be installed that detects the fire but will not activate during hot works. Another option is to have a timer on the detection so that it starts automatically after a certain amount of time. This type of risk is better handled with, for example, a redundant and less sensitive fire detection that can detect a fire but not be activated by hot works.

The interviews with Dadi Thorsteinsson and Fredrik Jörud gave some valuable insight on how risk management works at MAX IV and ESS. When talking to Thorsteinsson and Jörud they had some different opinions on the use of standards. Both said that the method for every risk analysis has to be decided after the needs, which is in line with Räddningsverket (2003). Jörud also said that a joint standard for particle accelerator facilities would help the risk management. Since Jörud started in an earlier project phase of the two his work might be a better comparison to this thesis. Due to this, he also has more insight in the risk analysis that has been made for ESS. Instead, Thorsteinsson has a better knowledge on risk management during operational phase for MAX IV. Thorsteinsson mentioned that most of the focus in the risk analysis he has read was at personal safety and almost no focus at the protection of equipment. It is natural that the focus is at personal safety but as the equipment in this type of facilities is very expensive, it might be necessary to add another aspect of safety focusing on the equipment. It is often a winning concept to focus on several aspects. For example, having two separate routes for evacuation also makes it possible for the fire and rescue service to reach a fire from two directions and limit the damage on equipment. This is also preferred by the CFRS, as mentioned in chapter 2.3.

Just as Thorsteinsson mentioned, most of the risk analysis methods focus on the consequences of personal safety. There could be at least two reasons for this kind of focus. Firstly, the fire safety measures are easier to motivate if it could be crucial for personal safety and also because the cost of a human life is rated very high. The focus on personal safety has also resulted in a more researched area compared to operating protection and asset protection. Since most companies use standard equipment that is easy to replace this can be seen as a reasonable development. However, in organisations like CERN, MAX IV and ESS where the equipment might be unique for the facilities and therefore can be expensive and hard to replace, there should be more attention to asset protection and operating protection. Another argument for more focus on asset and operating protection is that there will be no occupants in the tunnel most of the time.

There were some limitations with the interviews and in hindsight, they might have been done in another way. The interviews was held in a way which allowed the fire engineers to speak as freely as possible, but maybe they could have been notified in beforehand more in detail what was the aim with the interviews. The result from the interviews was not as comprehensive as expected and it was a good to learn that interviews are hard and need a lot of preparation.

Just as stated in Räddningsverket (2003), this thesis show that different phases in a project set different demands on what type of risk analysis method that should be used. For unique facilities like CERN, MAX IV and ESS, it is clear that they would benefit from using a template, which could guide them in the different phases. There is an ongoing collaboration between these facilities and several others where one part is that they are collecting fault data that can be shared in the network. Hopefully this new collaboration will help the participating partners to make structured and clear risk analysis for their own facility and make it possible to exchange lessons between the parties.

7.4 Methodology

The risk analysis methods that was used for the comparative study was traditional risk analysis methods. This is due to the way that the literature study was performed and it could have been expanded to include newer or more specified methods for tunnels. One reason that these methods were not included was because it was decided that CERN’s facilities had more in common with nuclear facilities than for example road tunnels. In hindsight it can be seen that that these methods should have been included in order to embrace other aspects.

Overall, the methodology presented in chapter 1.3 has worked well with some exceptions. Especially in the early phase of the thesis when the structure still was unclear and the project was separated by the work at CERN and the comparative study. The methodology lead to that the most of the sub objectives and the overall objective was fulfilled. The exception was that no specific risk analysis method could be identified as most a more suitable method for the case study. However, some conclusions in the area could be drawn. The other exception was that the investigation of how risk analysis methods are used in other particle accelerator facilities was limited and the interviews did not result in a comprehensive complement to the literature study as wanted.

The objectives can also be used to draw conclusions on how well the thesis fulfils its purpose. Most of the purpose can be seen as fulfilled, even though the non fulfilled objectives reflects in the purpose in that way that no specific risk analysis method can be recommended. Instead, the focus was on the different types of risk analysis and in which phase they could be suitable. For the case study, the conclusion was that more simplified methods are to prefer in an early phase of a design.

For the validity of the report, there are no major concerns. There have been several assumptions made in the risk analyses. In the comparison, this has however been seen as a disadvantage for the method and should therefore not affect the validity of the overall report.

8. Conclusions

During the different phases of a project, different risk analysis methods could be most suitable. In an early phase, the project could benefit from a more simple method such as an index method or a simplified risk analysis method, like What-if or PHA. Later in a project when more information is achieved, a more complex method could provide results that are more accurate. The collaboration between the different particle accelerator facilities could benefit from designing a collaborated index method specifically for this type of facilities. This could give an early estimation if a design is considered safe or not and would help to justify an alternative design when proposing it to decision makers. Another tool that could be developed by a collaboration with similar facilities is a method to calculate the HRR for different equipment, such as electrical cabinets.

Instead of using computer simulations, hand calculations could be made in the early design phase in order to cover more scenarios in a shorter amount of time but with less accuracy. However, it is easier to do a sensitivity analysis with quick hand calculations to compensate the uncertainties in the parameters.

It is always important to keep an open mind and to be flexible in order to choose the best risk analyse method. One method might not be the solution to every design or phase of a project and the method also depend on the type of project.

8.1 Conclusions case study: CERN

The results from the risk analyses show that the most common problem with the baseline configuration is the evacuation possibility. The ETA method is limited in this thesis due to the short simulation times. However, it can be shown that the baseline configuration is not recommended for two of the scenarios that were simulated in the UA gallery. The PHA method shows that the baseline configuration needs alternative evacuation routes. This could be provided by an extra evacuation route, either to the surface as in the alternative option, or by rescue chambers.

Both NFPA and What-if show, that the rescue chambers can be used in the baseline configuration, if they are considered reliable. If the rescue chambers cannot be trusted in case of a fire, the baseline configuration cannot be considered safe. The alternative option is to prefer even if the rescue chambers can be trusted since it provides better evacuation possibilities due to the lack of dead-ends which there is in the baseline configuration. The cost-benefit from the different designs is not evaluated in this thesis.

Regarding asset protection, the alternative option is to prefer due to the enhanced capacity for the CFRS given by the multiple attack points.

9. Future research

In this thesis, several different areas of future research have been found.

Firstly, development of a specific risk analysis method for cable tunnels, for example an index method that quickly can show if a design fulfils the safety criteria. Examples of factors can be geometry, length, amount of cables, location of cables, type of cables and compartmentation.

The second area is to gather and compile failure data of similar facilities to simplify and unify risk analysis done on new facilities in the future. This can be done in a similar way as T-boken for nuclear power plants in the Nordic countries.

Another development that could arise from the collaboration between facilities is a joint tool for calculating fire spread in cabinets and other equipment.

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Appendix I

In this appendix, the different compartments in the new underground facilities are evaluated regarding their probability for ignition.

PM access shaft

The first location for a design fire is a fire that starts in the PM access shaft, outside the concrete modules that forms the safe zone for staircase and elevator. In the shaft, there will be cable trays from the US57 cavern to the surface. A fire that starts in this location could have a severe impact on the entire tunnel since no one can access/regress. The fire load in PM access shaft consists of cable trays. Since the cable shaft is separated from the access shaft, it is only possible to fill the access shaft with smoke if smoke reaches the top of the cable shaft or if the door is open in the underground area. In the shaft the fire safety measures consists of fire doors to UR57 tunnel and UA57 gallery, evacuation alarm and smoke extraction.

US cavern

The second location for the design fire is a fire that starts in the US cavern for cryogenic equipment. The cavern consists of one ground floor and a mezzanine. The main fire load consists of cable trays under the mezzanine. There are also electrical cabinets on the mezzanine. A fire in the US cavern could have a severe impact on the entire tunnel since no one can access/regress. It is assumed that all fire safety measures works as they should and that the ventilation is turned off. In the cavern the fire safety measures consists of fire doors to UR57 tunnel and UA57 gallery, evacuation alarm and smoke extraction. A fire in the US cavern is decided to be one of the most critical locations since evacuating personnel must pass through on their way out.

UA53/57 galleries

The third location for the design fire is a fire that starts in the UA57 gallery, which is a wide equipment gallery. Due to the extensive technical equipment in this location, the probability for ignition is high due to technical error. It is also more common to have occupants in this part of the tunnel. In this location the fire safety measures consists of a fire detection, evacuation alarm, smoke extraction and a fire door where the UA57 gallery connects to the US cavern. The fire load in the UA57 gallery consists of cable trays and electrical cabinets, however to less extent compared to the UR tunnel. With a quick fire detection, it would be possible for occupants in other locations in the tunnel to have time to evacuate or go into the rescue chambers. The worst case scenario is that the fire starts on the other side of the fire door. This makes it hard for the occupants to discover the fire and if the fire detection does not work, the occupants might be trapped in the UA57/53 galleries.

UR57 tunnel

The fourth location for the design fire is a fire that starts in the UR57 tunnel. The UR tunnel house RF power converters and klystrons for the crab cavities, as well as equipment for magnet protection. This tunnel is slightly larger than the other connecting tunnels and therefore it is possible for small trucks for transport of equipment to be used here. In this location, the fire safety measures consist of a few smoke curtains throughout the tunnel and fire doors where UA57 gallery connects with other tunnels, evacuation alarm and smoke extraction. Three of four transversal galleries are connected to the UR tunnel and it is the only evacuation path in the baseline configuration. If a fire starts in the UR tunnel when occupants are working in different locations in the tunnel and the detection system fails, it is possible for the fire to propagate beyond manageable size before someone notice it. If the fire detection system fails, the smoke curtains will not activate, allowing the smoke to spread throughout the tunnel. There are two critical locations for a fire in the UR57 tunnel and they are both connected to the location of the rescue chambers. These locations are in the middle of the UR tunnel and in the far end close to UA53 gallery. The entire UR tunnel is where it seems most likely for a fire to occur due to all the technical equipment such as high voltage cabinets and power converters that is placed here. The UR tunnel is also the where there are the highest fire load, due to the amount of cables and cabinets.

Remark

Three galleries will not be included in this thesis, UL53/57 galleries and UW57 cavern. The UL galleries can be compared to the UA galleries in that way that all are transversal to the UR tunnel but for the UL galleries the fire load is almost none existing. For the UW57 cavern the fire load can be seen as high but it is an own fire compartment and is not part of the evacuation route for any other part of the facilities. The equipment in the UW57 cavern is mainly water pumps and ventilation fans and cannot be classified as unique as much of the equipment in other galleries. If these parts will be used for something else in the future that changes the fire load an analysis could be done where the UL galleries might be compared to the UA galleries. The UW57 cavern will need a new risk assessment. This master thesis will be made in such way that the work can be applicable if a new analysis have to be done later because of changes in the underground areas.

Appendix II

In this appendix, it is shown how the risk analysis methods meet the chosen criteria.

Criteria 1: The method should not be developed for a specific industry unless for mining or nuclear facilities. This is because CERN's facilities are partly comparable to mines and nuclear power plants.

Criteria 2: The method should be applicable for risks including fires.

Criteria 3: The method should preferably be qualitative and semi-quantitative methods due to the lack of statistics in this kind of facility. In this thesis semi-quantitative means that the method divides several input data or intervals into groups instead of using the exact values. The time aspect is also crucial for the selection of this criterion.

Table 8. Table of the first selection of risk analysis methods. QuaN = Quantitative; QuaL = Qualitative

Methods	**Criteria 1**	**Criteria 2**	**Criteria 3**	Motivation
What-if	ok	ok	QuaL	A quick method. The result of the What-if analysis depends on knowledge, thinking processes, experiences and attitudes of the team members. It allows out-of-the-box thinking. Questions the function of the system and tries to analyse possible deviations from normal function and suggest solutions.[1,2,3]
FMEA & FMECA	Not ok	ok	QuaL	Qualitative, but can in some cases quantify how often a function fails. Answers the question: What can go wrong with this component? FMEA sees a systematic approach to evaluate the impact of a single equipment failure. The reason or cause for the equipment failure is not specifically considered. FMEA may be time consuming and expensive. Not chosen because more process industry focus.[1,2]
HAZOP	Not ok	Depend on the case	QuaL	HAZOP evaluates the impact of a deviation in operating conditions outside the design range. Focuses on the causes. HAZOP is commonly used in the chemical industry. Uses keywords, for example more or less flow. Not applicable.[1,2]

Reliability Block Diagram (RDB)	ok	ok	QuaL	For identifying series dependence or independence of major components, subsystems, or detail parts in performing required functions. Illustrates the dependence or independence of the systems or components contribution to specific functions. It is assumed that a component has only two possible states: operational or faulty. Can be both series and redundancy function or a combination of these. Similar to fault tree analysis.(1)
Fault Tree Analysis (FTA)	ok	ok	QuaL/ QuaN	The top of a fault tree represents a system event of interest and is connected by logical gates to component failures known as basic events. Not applicable because more focus on prevention than mitigation.(1)
Event Tree Analysis (ETA)	ok	ok	QuaL/ QuaN	Identifies start events, map all following events. The method should preferably be quantitative, but could be quantitative. Is most effective for modelling accidents in which multiple safeguards are in place as protective features. Often used with FTA and RBD.(1,2)
Monte Carlo Methods	ok	ok	QuaN	Works in all industries. Complex mathematical model. The model needs to be built for each system but are then quickly updated if needed. Computer resources needed. Needs input data to be reliable but sometimes there is no data. Not applicable, not enough fault rate.(4)
Cause-consequence analysis(CCA)	ok	ok	QuaN	A blend of FTA and ETA in that it combines cause analysis (described by fault trees) and consequence analysis (described by event trees). CCA is used to identify chains of events that can produce undesirable consequences. The probabilities of various events listed in a CCA diagram allow the calculation of the probabilities of the various consequences and ultimately establish the risk level of a system.(1) Choses Event tree instead

Markov analysis (MA)	ok	ok	QuaN	Markov analysis is used for availability and reliability in a time dependent system with strong dependencies between components. The model makes the assumption that the system have no memory and therefore only is depending on the current state.(1)
PRA & PSA	ok	ok	QuaN	Used often in nuclear power plants. Needs to address unlikely events, which means non-existing empirical data. Comprehensive set of scenarios. PRA is needed when decisions need to be made that involve high stakes in a complex situation.(2,5,6) To time consuming to do a complete PRA.
Checklists	ok	ok	QuaL	Comparative method. Often ordinal scale: less/ more. Can be used in a more detailed analysis. For example, checklists dealing with equipment failures are used in FMEAs. More to use for control of existing systems.(1,2,3)
Risk Matrix	ok	ok	QuaN	Often used together with another method to group and present hazards.(7)
Deviation analysis	ok	ok	QuaL/ QuaN	Reports deviations. Not applicable due to low fault rate.(2)
Preliminary hazard analysis (PHA)	ok	ok	QuaL	Undesired events are identified and then handled separately and measurements are provided. This is done on a shallow level of approach.(8)
NFPA 101A Guide on alternative approaches to life safety.	ok	ok	QuaL	An index method to calculate the fire risk.(1,9)
Gretener system	ok	ok	QuaL	An index method to calculate the fire risk.(10)
ROGA	ok	ok	Semi-QuaN	A semi- qualitative risk analysis method. Divide hazards into risk groups and measurements into dependability classes.(11,12)

GO-FLOW	ok	ok	QuaN	The GO-FLOW method is mostly suitable for repairable systems and their availability. The system is simplified to 40 different types of operators and then set up in a logical system tree.[13] To time consuming.
Dynamic event logic analytical methodology (DYLAM)	ok	ok	QuaN	A framework that takes dynamic changes over time into account. Instead of something having a constant probability of occurring, as in ETA and FTA, the probability changes with both time and when new events happen. This solves some of drawbacks in ETA and FTA but requires more experience and much more resources.[14] To time consuming.
Dynamic Event Tree Analysis Method (DETAM)	ok	ok	QuaN	DETAM uses the same thinking as DYLAM but with an aim to work as a dynamic substitution for event tree analysis. To time consuming.[15]

[(1)](Stamatis, 2014); [(2)](Ingvarsson & Roos, 2003); [(3)](Nilsson, 2003); [(4)](Rasche, 2001); [(5)](Stamatelatos & Dezfuli, 2011); [(6)](Siu & Collins, 2008); [(7)](Räddningsverket, 2003); [(8)](Kemikontoret, 2001); [(9)](Crowley et al, 2014); [(10)](Kaiser, 1980); [(11)](Bock & Haferkamp, 2014a); [(12)] (Bock & Haferkamp, 2014b);[(13)](Yang et al, 2014); [(14)](Cojazzi, 1996); [(15)](Acosta & Siu, 1991);

Appendix III

In this appendix, the input data to the ETA is presented.

T-boken is a statistical analysis of availability on components at nuclear power plants in Sweden and Finland. The oldest data used in the analysis is from 1977 and in the used version of the book, version 6, the last data is from 2002. All error rates are numerical calculated with gamma distributions and are presented with the 5, 50 and 95 percent limits of the distributions. The distributions are updated with Bayes' theorem approximately every 6th year to get a better view of the statistical probability of a major fault or in worst case a nuclear meltdown (T-boken, 2005).

In this thesis, the statistics for power transformers from T-boken will be used. In T-boken distributions for three different types of transformers are calculated; main transformer, start and station transformer (130/6 kV, 70/6kV and 20/6 kV) and transformer U<6 kV (T-boken, 2005).

Table 9. Distribution for different transformers in T-boken.

	Lambda [h^{-1}]	5 %	50 %	95 %	Average
Main transformer	10^{-7}	0,0	0,0	30,4	8,9
Start and station transformer	10^{-7}	0,0	4,5	31,0	9,0
Transformer U<6 kV	10^{-8}	0,0	0,0	32,6	8,9

Other statistics for the ETA

Table 10. Statistics from different sources used in the ETA.

Event	**Probability/frequency**
Fire in electrical cabinet	0.007884/year*
Automatic fire alarm system reliability (smoke and heat detection)	0.97**
Fire door, door closing	0.9***
Fire door, smoke sealing	0.7***
Evacuation alarm, same as fire alarm	0.97**
Smoke extraction (fan)	0.948****

* T-boken (2005)
** Johannson (1999)
***Räddningsverket (2003)
****Mean value from T-boken (2005) and Isaksson et.al. (1998)

Values for fan

Total number of faults: 14 (T-boken, 2005):

Standby time: $1{,}47490*10^7$ h (T-boken, 2005):

Average reparation time: 3 h (T-boken, 2005):

Total reparation time: 14*3 = 42 h

Possibility of dysfunction during an event: $42/1{,}47490*10^7 = 0{,}999997152$

Because of these values only show the possibility of a fan being under reparation when a fault event occurs but the actual values needed for this thesis is the possibility of fault when starting the fan. Because of this, the value of the availability is considered too high to represent the correct statistic. Instead, the fan is compared to diesel generators in nuclear power plants and diesel generators and different types of pumps in the off shore industry.

$1{,}7*10^{-3}$ Diesel generators at nuclear power plants (T-boken, 2005).

$2{,}3*10^{-2}$ OREDA, offshore industry, all types of pumps (Isaksson et.al., 1998).

$3{,}3*10^{-2}$ OREDA, offshore industry, diesel generators (Isaksson et.al., 1998).

This gives a mean value of: $5{,}2*10^{-2}$ for mixed pumps and generators.

In figure 23, the comprehensive event tree for the UR tunnel is presented.

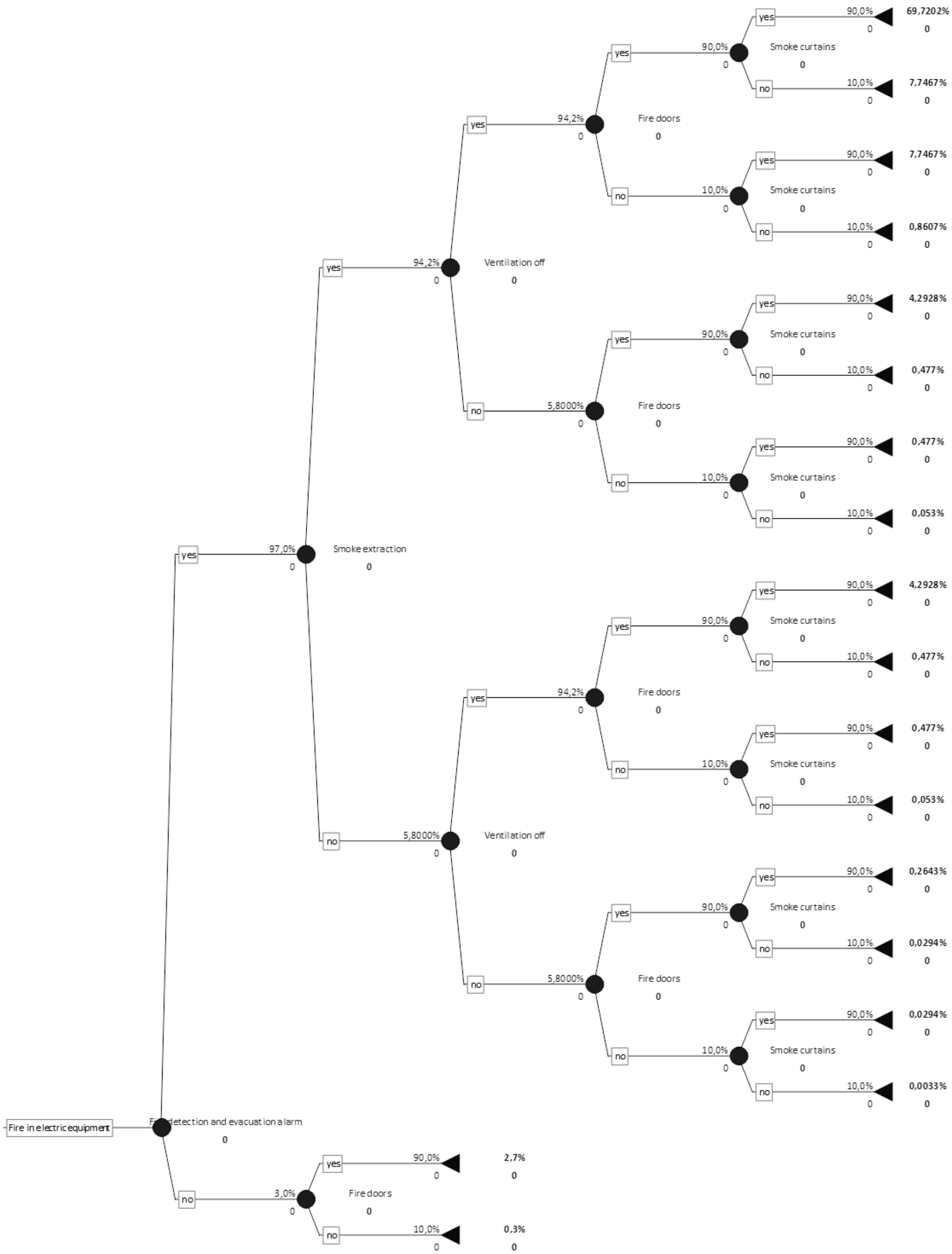

Figure 23. Comprehensive event tree for UR.

Appendix IV

In this appendix, the chosen values and motivations for the NFPA method are presented. The method uses a number of factors that are given a value depending on the design of the analysed facility. The method is designed so that a high value is good and a low is bad. The table is based on the information in NFPA 101A (2012).

Table 11. Baseline configuration without rescue chamber.

Factor	**Value**	**Value description**	**Motivation**
Construction	0	Type I None combustible 1-2 stories	The alternative 1-2 floors is chosen since it is interpreted as the durability between floors during a fire. It is also the most conservative value.
Segregation of hazards	-4	Exposed exit system with single deficiency	Not structurally endangering, no protection due to very high fire load potential (uncertainties regarding the requirements). This leads to a single deficiency.
Vertical openings	0	1 story	Can be seen as a 1 story even though there is a big access shaft. The vertical opening factor has to do with smoke spread between floors.
Sprinklers	0	None	
Fire alarm	4	Fire alarm with fire department notification and voice communications	Two way communication and notification to fire department
Smoke detection	4	Total building	
Interior finish	2	Flame spread rating <25	highest fire rated material as possible
Smoke control	3	Active smoke control with sprinkler parameter <10	
Exit access	-2	Max dead-ends >75-200 ft (23-60 m)	The shortest dead-ends exceed 49 m (160 ft).
Egress route	-6	Single egress route	
Compartmentation	3	Door closer and more than 1 h	
Occupant emergency program	0		The frequency of the emergency drills is not known, but this parameter has no impact on the results since it will be the same in both solutions.

Table 12. Baseline configuration with rescue chambers.

Factor	Value	Value description	Motivation
Construction	0	Type I None combustible 1-2 stories	1-2 floors is chosen since it is interpreted as the durability between floors during a fire. It is also the most conservative value.
Segregation of hazards	0	Segregation from exit routes, single def.	Not structurally endangering, no protection due to very high fire load potential (uncertainties regarding the requirements). This leads to a single deficiency.
Vertical openings	0	1 story	Can be seen as a 1 story even though there is a big access shaft. The vertical opening factor has to do with smoke spread between floors.
Sprinklers	0	None	
Fire alarm	4	Fire alarm with fire department notification and voice communications	Two way communication and notification to fire department
Smoke detection	4	Total building	
Interior finish	2	Flame spread rating <25	Highest fire rated material as possible
Smoke control	3	Active smoke control with sprinkler parameter <10	
Exit access	-2	Max dead-ends >75-200 ft (23-60 m)	The shortest dead-ends exceed 49 m (160 ft).
Egress route	3	Smoke proof enclosures	smoke proof safety chambers
Compartmentation	3	Door closer and more than 1 h	
Occupant emergency program	0		The frequency of the emergency drills is not known, but this parameter has no impact on the results since it will be the same in both solutions.

Table 13. Alternative design option.

Factor	**Value**	**Value description**	**Motivation**
Construction	0	Type I None combustible 1-2 stories	1-2 floors is chosen since it is interpreted as the durability between floors during a fire. It is also the most conservative value.
Segregation of hazards	0	Segregation from exit route	Not structurally endangering, no protection due to very high fire load potential (uncertainties regarding the requirements). This leads to a single deficiency.
Vertical openings	0	1 story	Can be seen as a 1 story even though there is a big access shaft. The vertical opening factor has to do with smoke spread between floors.
Sprinklers	0	none	
Fire alarm	4	Fire alarm with fire department notification and voice communications	Two way communication and notification to fire department
Smoke detection	4	Total building	
Interior finish	2	Flame spread rating <25	Highest fire rated material as possible
Smoke control	3	Active smoke control with sprinkler parameter <10	
Exit access	-1	No dead-ends, between 200-400 ft travel distance	
Egress route	3	Multiple routes, smoke proof enclosures	
Compartmentation	3	Door closer and more than 1 h	
Occupant emergency program	0		The frequency of the emergency drills is not known, but this parameter has no impact on the results since it will be the same in both solutions.

Appendix V

The input data for the cabinet HRR calculations are presented in table 14.

Table 14. Input data for cabinet HRR curve calculations.

		Cabinet						
Growth phase	**Unit**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Delay to ignition	[min]	0	10	10	20	20	30	30
Max HRR (Q_{max})	[kW]	1000	450	450	450	450	450	450
Q_0	[kW]	1000	1000	1000	1000	1000	1000	1000
Growth time (t_g)	[s]	600	600	600	600	600	600	600
Time to max HRR	[s]	600	402	402	402	402	402	402
Steady state								
Time	[s]	480	1000	1000	1000	1000	1000	1000
Decay phase								
Q_{t_d}	[kW]	1000	450	450	450	450	450	450
Decay time constant (τ)	[s]	1080	1080	1080	1080	1080	1080	1080
Time from ignition to decay (t_d)	[s]	1080	1402	1402	1402	1402	1402	1402

The input data for the plume temperature are presented in table 15.

Table 15.Input data for plume temperature calculations.

Constant	**Unit**	**Value**	**Reference or motivation**
Height (z)	[m]	2	Approximated height from centre of cabinet to cable tray.
$T_{ambient}$	[K]	293	Approximated ambient temperature
Base with	[m]	0,6	Cabinets base measurements
Base length	[m]	0,6	Cabinets base measurements
Characteristic base diameter	[m]	0,677028	Cabinets base measurements
g	[m·s^2]	9,81	
$\rho_{ambient}$	[kg·m^{-3}]	1,2	Based on $T_{ambient}$
$c_{p,air}$	[kJ·kg^{-1}·K^{-1}]	1	(Karlsson & Quintere, 2000)
Convection factor	[-]	0,7	Assumption

The input data for the propagation to cable trays are presented in table 16.

Table 16. Input data for the propagation to cable trays.

Constant	Unit	Value	Reference or motivation
Specific heat capacity	$[J \cdot kg^{-1} \cdot K^{-1}]$	1289	(Corsanego, 2014)
T_0	[C]	20	Approximated ambient temperature
Temperature of ignition	[C]	250	(Mangs, 2004)
Cable diameter	[m]	0,01	Assumption after visit at CMS
Cable area per meter cable	$[m^2]$	0,031416	Based on diameter
Cable volume per meter cable	$[m^3]$	7,85E-05	Based on diameter
Cable density	$[kg \cdot m^{-3}]$	2500	(Corsanego, 2014)
h	$[W \cdot m^{-2} \cdot K^{-1}]$	10	(Wickström, 2011)

Appendix VI

The input data used for the calculation of fire load per meter cable tray and the result is presented in table 17.

Table 17. Input data for fire load calculations.

Constant	Unit	Value	Reference or motivation
Height	[m]	0,06	Drawing
Width	[m]	0,6	Drawing
Density of cables	[$kg \cdot m^{-3}$]	2500	(Corsanego, 2014)
Energy content	[$MJ \cdot kg^{-1}$]	20	(Corsanego, 2014)
$\varphi_{plastic}$	[-]	0,5	(Corsanego, 2014)
φ_{air}	[-]	0,15	(Corsanego, 2014)
Fire load per meter	**[$MJ \cdot m^{-1}$]**	**765**	Calculated with the other variables

The input data used for the calculation of the HRR curve is presented in table 18.

Table 18. Input data for cable tray HRR curve calculation.

Constant	Unit	Value	Reference or motivation
HRR per square meter	[$kW \cdot m^{-2}$]	150	(Corsanego, 2014)
Combustion efficiency	[-]	0,8	(Corsanego, 2014)
Start length	[m]	1,00	Assumption based on width of cabinets
Initial burning area	[m^2]	0,60	Based on start length and tray width
Burn area adjust constant	[-]	1	Asuming solid bottom tray
Propagation speed	[$m \cdot h^{-1}$]	5,5	(Corsanego, 2014)
Propagation direction	[-] (1 or 2)	2	Assuming worst case
Flame front (width)	[m]	1,2	Based on propagation direction and tray width
Distance between trays	[m]	0,25	Drawing
Spread angle	[°]	35	(EPRI/NRC-RES, 2005)
Calculated values			
α	[$kW \cdot min^{-1}$]	16,5	Calculated with the other variables
Start HRR	[kW]	90	Calculated with the other variables
time to max HRR	[min]	113,3333	Calculated with the other variables