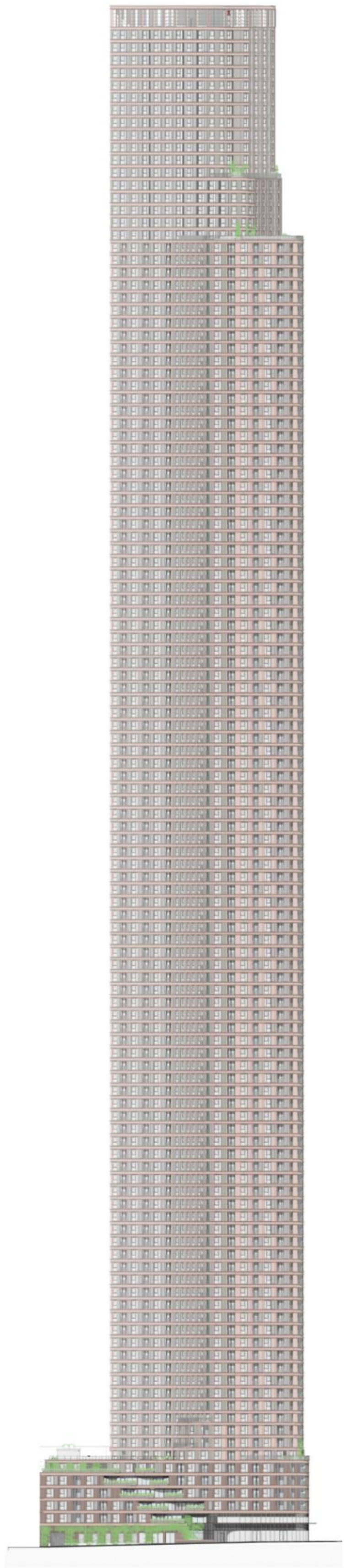
EINDHOVEN UNIVERSITY OF TECHNOLOGY

Quantitative assessment for fire safety of super-tall residential buildings with a probabilistic analysis



Master Thesis

J. (Joost) Dumas

Eindhoven, 3nd July 2023

Quantitative assessment for fire safety of super-tall residential buildings with a probabilistic analysis

7S45M0 – GRADUATION PROJECT BUILDING PHYSICS AND SERVICES

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Preface

This master thesis is the final product of my graduation project to complete the master program Building Physics and Services at the Eindhoven University of Technology in Eindhoven. The research towards the use of a quantitative assessment with a probabilistic analysis has been done in collaboration with Nelissen Ingenieursbureau B.V..

The research started after speaking with Ruud van Herpen about the fire safety of super-tall buildings. A probabilistic approach has been used in the high-rise guideline and he mentioned the opportunity to use a probabilistic approach in order determine the fire safety level of super-tall buildings between 200 and 400 meters by comparing it with the fire safety level of a low-rise reference building designed according to the national building code BBL.

I would like to thank Ruud van Herpen for his feedback and support throughout the research. Within Nelissen ingenieursbureau, I was supported by Joppe Leenaars. I would like to thank Joppe for his critical view on the practical application of a probabilistic approach and for his feedback during the research. I also want to thank Rick Kramer of the Eindhoven University of Technology for his feedback.

Finally, I would like to thank everyone that supported me during this research, family, friends, colleagues and fellow students!

Enjoy reading,

Joost Dumas

Eindhoven, July 2023

Executive summary

Low-rise buildings below 70 meters and tall buildings between 70 to 200 meters are common in the Netherlands, super-tall buildings however are not. Regulation for super-tall buildings have not yet been written in the Netherlands. Regulations for tall buildings between 70 to 200 meters have been developed based on a probabilistic approach, related tot the Dutch Building Code. The probabilistic approach for the regulations of tall buildings has been translated to active and passive preventive measure, which are applicable to multiple building functions. In this study the use of a quantitative assessment with a probabilistic analysis has been assessed in order to see if this method can be used and what kind of framework for a probabilistic approach is needed in order to show that a super-tall building is just as safe as a low-rise building. Based on a literature study, simulations have been performed in order to assess the level of fire safety of a low-rise residential reference building and the level of fire safety of a super-tall residential building.

Numerical simulations of the low-rise residential reference building and the super-tall residential building have been performed with multizone-models: OZone, developed by Arcelormittal and the Universite de Liege and Consolidated Fire and Smoke Transport Model (CFAST), developed by NIST. A natural fire concept has been used in both simulations in order to assess the fire safety of the risk-subsystems as used in the Dutch Building Code. By performing simulations of a low-rise reference building, the base level of fire safety expressed in cumulative probabilities, can be determined. These probabilities are the reference values, which the results of the simulations of the super-tall building need to comply with.

The fire safety levels of both a low-rise building and a super-tall building are project specific because a performance based approach is always project specific. For other buildings (low-rise or high-rise) with other layouts or other functions the fire safety level may be different. Even tough the fire safety level of both a low-rise building and a super-tall building and the building function are project specific, a framework based on the risk-subsystems used in the Dutch national building code BBL could be applied to all buildings with the same building function(s). By using this framework the fire safety level of the reference project can be compared to that of the designed project.

The low-rise residential reference building study show that a probabilistic analysis based on a natural fire concept for buildings designed according to the Eurocode NEN-EN 1990:2002, consequence class CC2, results in the same requirements for fire safety as set in the Dutch National Building code. The results also show that the escape routes can be safely used during the evacuation time of the fire scenario.

Results of the super-tall residential building show that a probabilistic analysis based on a natural fire concept for building with consequence class CC3 according to the Eurocode NEN-EN 1990:2002 results in an improvement of the fire resistance of the structural elements from 120 minutes to 135 minutes and that the fire resistance of the compartmentation does not have to be improved in order to have at least the same level of fire safety as the low-rise residential reference building. The results also show that the application of a sprinkler system does not affect the AST (Available Safe Time) but it does affect the RST (Required Safe Time) of the separation constructions in a positive way. The application of a pressurization system in the stairway lobbies does affect the ASET (available Safe Egress Time) in the horizontal escape routes, however the ASET in the vertical escape routes is not affected by using a pressurization system. Based on the results of this research the application of a pressurization system on the stairway lobbies is not necessary and is a redundant system. The results also show that a full evacuation concept using stairs only can be use in a super-tall residential building when a suppression system and a pressurization system are installed. However the results also show that a full evacuation using stairs only is not the most suitable evacuation concept, because the RSET (Required Safe Egress Time) is longer than the fire scenario. The use of a hybrid concept using refugee floors is a more suitable evacuation concept for super-tall buildings.

There should be enough distance between the fire and the refugee floors in order to avoid smoke propagation towards the refugee floors. In this evacuation concept elevators could be used as shuttles between refugee floor and the ground floor in case the situation develops in a negative way and a full evacuation is necessary.

Although the fire safety level of buildings is project specific, a quantitative assessment with a probabilistic analysis using the framework of risk-subsystems mentioned in the Building code can be used in fire safety engineering in order to assess the fire safety level of super-tall buildings so that the fire safety level of the super-tall buildings at least corresponds to the fire safety level of low-rise buildings with the same building function(s) according to the Building Code. And therefor a quantitative assessment of fire safety using a probabilistic analysis can be used as an equivalent solution in the application of a building permit.

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Nomenclature

Terminology	Explanation
ASET	Available safe egress time
AST	Available safe time
BBL	Dutch National building code: 'Besluit bouwwerken leefomgeving' after 01-01-2024[1]
BENG	Almost energy neutral buildings: 'Bijna energie neutrale gebouwen'
Bouwbesluit	Dutch National building code: until 01-01-2024[2]
BSI	British Standards Institution
High-rise building	Building above 70 meters, the requirements of the Dutch National building code are not directly applicable
Low-rise building	Building between -8 and 70 meters, built and designed according to the BBL, the requirements of the Dutch National building code are directly applicable
NEN	The Royal Netherlands Standardization Institute
NIPV	National Institute of Public Safety: 'Nationaal Instituut Publieke Veiligheid'
NTA	Dutch technical agreement: 'Nederlandse technische afspraak'
RHR	Rate of Heat Release
RSET	Required safe egress time
RST	Required safe time
SBRCURnet	Former Dutch building research foundation
Super-tall building	Building between 200 and 400 m
Tall building	Building between 70 and 200 m

[1] Proposed regulations; intended entry of use 01-01-2024; the BBL filter is a beta version which remains subject to adjustments until it comes into effect [7].
[2] Current regulations; intended end of use 01-01-2024[7].

1. Introduction

1.1 Problem definition

The PBL Netherlands Environmental Assessment Agency (Planbureau voor de Leefomgeving') and the Statistics Netherlands (Centraal bureau voor de statistiek) predicts that the Dutch population will grow from 17.6 million to 19.6 million inhabitants in 2050. The population will grow in urban areas [1]. Because of the growing population municipalities need to expand the number of households. Between 2018 and 2020 58% of the new households have been built in the existing cities and the vision of the Dutch government states that the urbanization that takes place needs to be at least 40% within the existing cities [2]. This means that there will be a densification in the cities.

Because of the urbanization and the densification, high-rise buildings are gaining popularity in the Dutch municipalities. There is a lot of development regarding high-rise buildings, especially in The Hague and in Rotterdam. Both municipalities have published their visions for high-rise buildings in the city. The Hague published the high-rise building vision in 2017 [3] and Rotterdam published its high-rise vision in 2019 [4]. The Tallest building of the Netherlands, 'De Zalmhaven I', is located in Rotterdam, as shown in Figure 1-1. The tower has a height of 215 meters. Because the highest residence floor is located just below 200 meters the SBRCURnet publication fire safety in tall buildings (handreiking brandveiligheid hoge gebouwen) is applicable [5]. The high-rise vision of Rotterdam will even allow buildings up to 250 meters, which is outside of the scope of SBRCURnet publication. The municipality of Rotterdam and the Safety region Rotterdam-Rijnmond published the Rotterdam Fire safety vision for tall buildings and super-tall buildings, which states the requirements for these buildings in Rotterdam [6]. The Dutch national building code (BBL; Besluit Bouwwerken leefomgeving) is applicable for buildings below 70 meters [7]. When buildings exceed the 70 meters mark the SBRCURnet publication is applicable. The SBRCURnet publication has regulations for buildings between 70 and 200 meters and is based on a probabilistic approach related to the Dutch national building code. Because Rotterdam allows buildings upwards to 250 meter, the question arises whether the probabilistic approach used in the SBRCURnet publication can also be used to design buildings that are 200 to 400 meters tall.

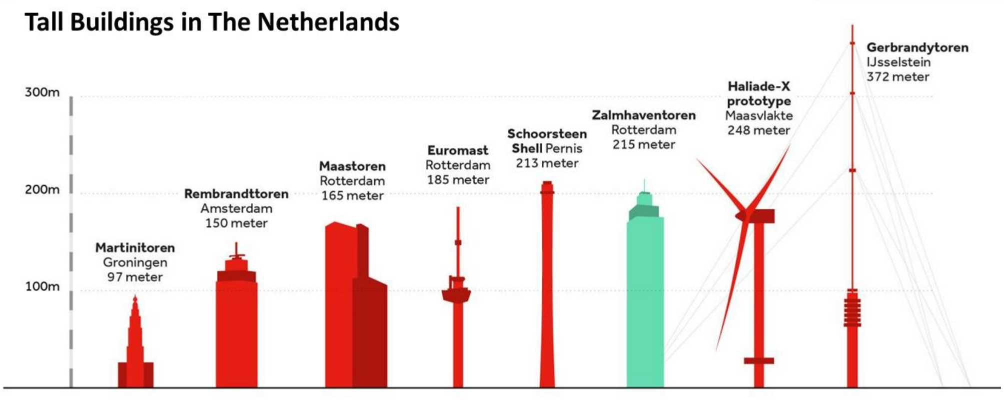

Figure 1-1. Tall buildings in The Netherlands. [8]

The problem definition consists of two aspects: the probability of a fire increases and the consequence of a fire increases. The consequences increase because both the floor area and the egress time increase. A tower of 400 meter is twice as high as a tower of 200 meter and the floor area is also twice as much, resulting in a risk increase of 4 times, as both the probability and the effect increase by a factor 2. Increasing the height of a building also increases the required safe egress time. When comparing the height and floor area of a 70 meter building with a 400 meter building with the same design, fire risk in a 400 meter tall tower is 36 times higher than the probability of a fire in a 70 meter tower as both the probability and the effect increase by a factor 6. The egress time of a 200 meter tower is between 30 and 120 minutes for 50 to 200 people per floor as shown in Figure 1-2, when we extrapolate that to a 400 meter building, the egress time varies between 60 and 240 minutes.

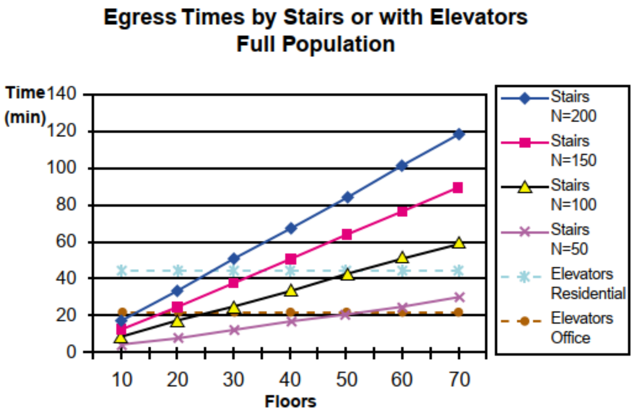

Figure 1-2. Egress time in relation to building height and occupancy [9].

In 2020 there are over 220 buildings that exceed the 70 meter and are classified as high-rise buildings in the Netherlands. Another 45 high-rise buildings are being constructed and 180 high-rise buildings are planned to be built in the next 10 years [10]. When comparing Dutch high-rise buildings with high-rise buildings across the world, The Zalmhaven I, is small in comparison to the Burj Khalifa of 829 m or the planned Jeddah Tower of 1000 meter, as shown in Figure 1-3. In this way the Dutch legislation can learn from these buildings and the legislation that is used to design these buildings.

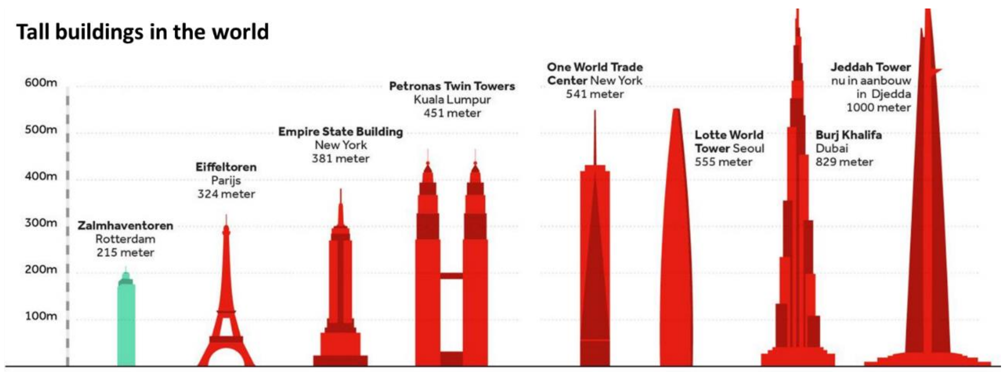

Figure 1-3. Comparing Zalmhaven I with tall buildings in the world. [8]

The fire safety regulations of tall buildings in the Netherlands are stated in the SBRCURnet publication. The SBRCURnet publication prescribes sets of measures that arise from a risk-based approach. In the risk-based approach, risk-subsystems are tested against which can also be found in the building code. The project-specific characteristics are important for a risk-oriented approach based on a natural fire scenario. According to the NIPV (Dutch Institute of Public Safety; Nederlands Instituut Publieke Veiligheid) the project-specific characteristics are human characteristics, building characteristics, fire characteristics, intervention characteristics and environmental characteristics. All the characteristics influence the behavior of a fire in a different way and all the characteristics are connected, see Figure 1-4. Generic boundary conditions are used for the human and fire characteristics in the project-specific characteristics according to the NIPV.

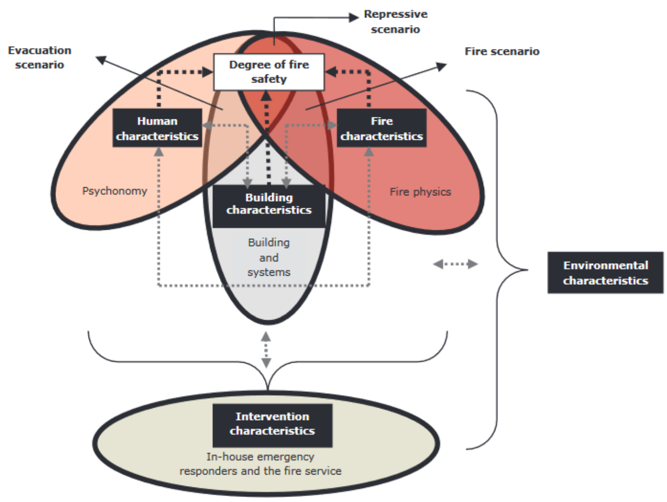

Figure 1-4. The characteristics of the degree of fire safety in a performance-based approach [11].

The fire safety of tall buildings between 70 and 200 meters is based on prescriptive regulations of the BBL. These prescriptive rules do hardly take human characteristics into account and do not take fire characteristics into account. Both characteristics are important factor when determining the fire safety of super-tall buildings between 200 and 400 meters.

Human characteristics are important when people need to evacuate: is it safe to stay in the fire compartment? Can de elevator be used to evacuate? Is the stairwell the only evacuation route? What is the walking speed? How long are people willing to wait for an elevator? How long are people willing to stay on a safe floor? Human characteristics are not only applied to the building occupants but also the internal organization of a company and the fire and rescue services.

Fire characteristics are important when the fire is developing. What type of fire curve is used? Where did the fire originate? Is it an oxygen-controlled fire or a fuel-controlled fire? Is it a pre or a post flashover fire?

The building characteristics can affect both the human and the fire characteristics and need to be project based. What kind of fire suppression systems are used? Which evacuation routes can be used? Where are the fire compartments located? How is the building compartmentalized? What is the structural capacity of the building?

1.2 Research objectives

This graduation project intends to gain insight into the possibility of using a probabilistic approach for fire safety engineering of super-tall buildings between 200 and 400 meters. By analyzing the Dutch National building code, the 'Besluit bouwwerken leefomgeving' (BBL) and the SBRCURnet publication, conducting literature reviews and by analyzing super-tall buildings around the world the fire safety concept of similar buildings can be determined. Based on the literature study performance objectives and performance criteria can be formulated and project specific simulations for assessing the fire safety can be made for super-tall buildings. With the results of the assessment a recommendation can be made regarding the use of a probabilistic design approach for super-tall buildings.

An essential part of this research is using the knowledge gained by the literature review and by analyzing the Dutch National building code (BBL), which will be formally used from January 1st 2024. The knowledge gained from the literature review will be applied on a super-tall building study of a ≈ 400 meter tall building which is extrapolated from a Dutch high-rise building < 200 meters. To validate the results of the super-tall study a low-rise reference study of a ≈ 40 meter tall building based on the same building will be conducted.

The gained insight in the fire safety of super-tall buildings between 200 and 400 meters must provide knowledge for fire safety engineers and the authorities. The results of this research will show to what extend the fire safety engineering in super-tall buildings between 200 and 400 meters can be used, and it can potentially contribute to the design and/or adjustment of the regulations for these type of buildings in the future.

The subject of this thesis is the fire safety of super-tall buildings between 200 and 400 meters in which a quantitative assessment with a probabilistic analysis is used to show that the fire safety level is comparable to low-rise buildings. Therefor the following main research question is put forward:

What does the framework of a probabilistic analysis in a quantitative assessment of fire safety for super-tall residential buildings between 200 and 400 meters in the Netherlands look like and how do you guarantee a level of personal safety for the building occupants comparable to the Dutch national Building Code?

The main research question can be divided into two parts:

I. Which framework could be used for a probabilistic approach in a quantitative assessment of fire safety of super-tall residential buildings?
II. How can the level of personal safety for building occupants be guaranteed in super-tall residential buildings?

In order to answer the research questions the following sub questions are addressed in this research:

a. What is the fire safety level of low-rise residential buildings in the Netherlands?
b. How does the framework of a probabilistic approach in a quantitative assessment look like?
c. What should be the level of fire safety of a super-tall residential building between 200 and 400 meters in the Netherlands?
d. What should the evacuation concept for a super-tall residential building between 200 and 400 meters in the Netherlands look like?
e. To what extend does an automatic suppression system and a pressurization system guarantee personal safety of building occupants in super-tall residential buildings between 200 and 400 meters?

1.3 Research relevance

Because cities get denser and building single story buildings or buildings with up to 10 story’s is not economically interesting anymore, taller buildings are designed. Currently the highest building is the Netherlands is the Zalmhaventoren, which stand 215 meters tall. This is the first building in the Netherlands that passes the 200 meters mark and will not be the last, in the city of Rotterdam plans have already been made for buildings up to 250 meters. To keep building occupants save is super-tall buildings, research needs to be conducted, on whether or not the current publication can be used for super-tall buildings. Besides that, the SBRCURnet publication: Fire safety for Highrise buildings from 2014, needs to be revised in order to be incorporated in the new Building code, the ‘Besluit bouwwerken leefomgeving’: BBL. High-rise buildings such as tall and super-tall buildings are not only gaining popularity in The Netherlands but are also increasing in popularity internationally. A quantitative assessment of fire safety of super-tall buildings with a probabilistic analysis can also be interesting to quantify the level of fire safety of buildings internationally.

2. Methodology

In order to answer the main research question, quantitative research is carried out in this research. The research approach is shown in Figure 2-1. The problem definition is described in the introduction (section 1). By conducting literature research, the relevance of the topic is indicated, the research objective can is formed, and research questions are formulated in order to fill the research gap. After completion of the first step, the second step continues with defining the methodology of the research (section 2). A theoretical framework is formed to answer the research question (section 3 and 4). In step 3 a low-rise reference study is performed to analyze the safety level of low-rise buildings in the Netherlands (section 5), based on the performed low-rise reference study a super-tall study of a super-tall building will be performed (section 5). Step five is a perspective view on the research conducted, formulated in a discussion (section 6). Step six will be the conclusion of this research in which the research questions will be answered based on the literature and the results of the low-rise reference study and super-tall study (section 7).

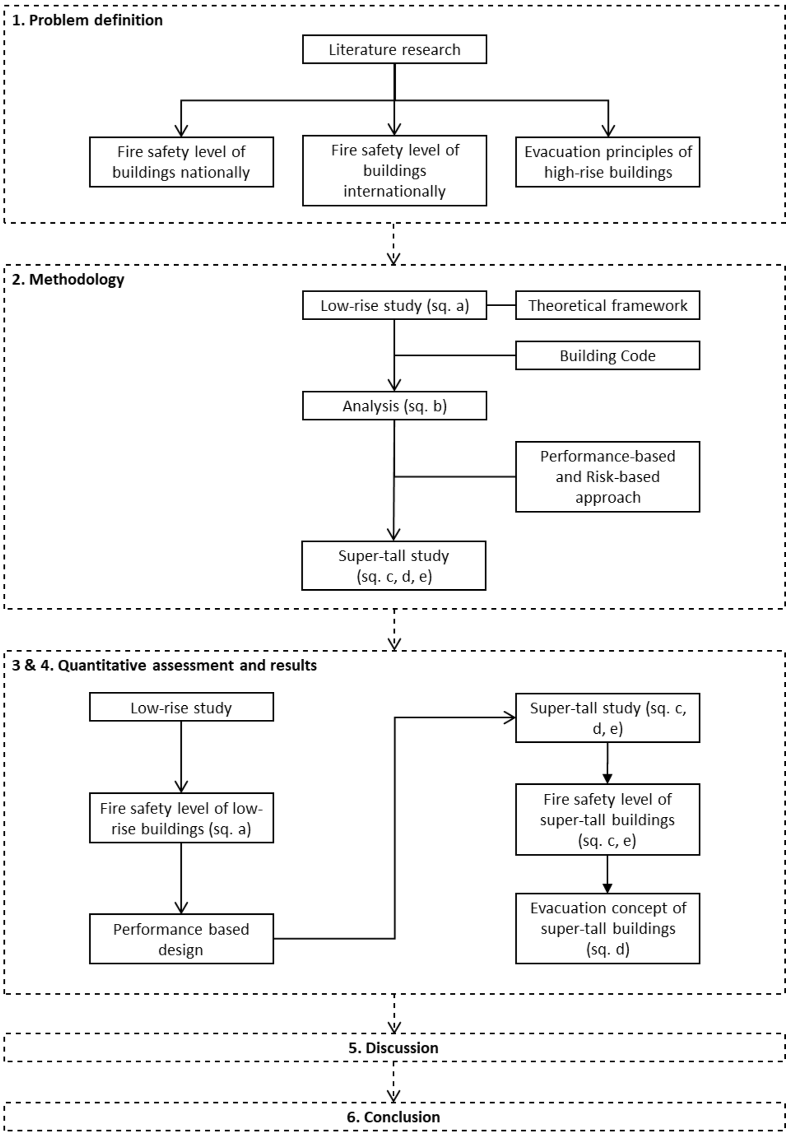

Figure 2-1. Research methodology.

2.1 Literature review

The literature research focused on fire safety engineering in regard to prescriptive based approaches, performance-based approaches, evacuation methods and smoke spread in low-rise buildings and high-rise buildings, specifically: tall buildings and super-tall building. Buildings with residential, office and hotel functions are included in the literature review.

Inclusion and exclusion criteria
In the low-rise reference study, the prescriptive based fire safety requirements for a new residential building are analyzed according to the Dutch National building code (BBL) and in a performance-based approach quantified as risk factors. Risk factors for the probability of fire ignition, structural integrity in case of fire, smoke spread, fire spread and escape routes will be quantified.

In the super-tall study, a super-tall residential building will be compared with a low-rise residential reference building based on the risk factors obtained in the low-rise reference study. In a performance-based approach, a concrete building design is needed to take into account the project specific boundary conditions. For both the low-rise residential building and the super-tall residential building the design of the Brinktoren will be applied. The Brinktoren will be built in the Netherlands in the coming years.

In the low-rise reference study, a 13-floor low-rise building will be analyzed according to the Dutch National Building code, the BBL. In the super-tall study, a 130 floor super-tall building will be analyzed to have at least the same level of fire safety as the low-rise reference building.

Data analysis
The data collected in the low-rise reference study contains deterministic average values for fuel characteristics, building characteristics and human characteristics. For the characteristics used in the simulations a sensitivity analysis will be conducted based on a standard variation to get the probabilistic values.

Risk factors used in the analysis are based on the compartment area [m^2], design lifetime [yrs.], ignition probability [m^{-2}] and for the load bearing structure on the Eurocode classification CC1, CC2 and CC3.

Validity and reliability
The internal validity of the research is guaranteed using a validated simulation program, the use of regulated Eurocode classifications and the use of a sensitivity analysis based on statistics. The external validity of this research can be achieved by the general application of the method used. By examining different cases generalization can be achieved. Generalization in this study is difficult to achieve because only one case is examined. However, the buildings are analyzed according to the Dutch National building code, which is generic for all buildings.

The reliability of the low-rise reference study depends on the requirements set in the Dutch National building code (BBL) and the software used: Ozone V3.0.4 and CFAST 7.7.4. It can be assumed that the requirements set in the Dutch National building code (BBL) are reliable. Although it is a new building code, it is based on the old building code that has been used since 2012 and has been under consideration since 2018. The reliability of the super-tall study results is based on the data gathered from the low-rise reference study. A margin of error can be expected in both studies as the standard deviations used in both studies are the same but are not regulated in any standard.

2.2 Building characteristics

For the evaluation of the safety level, a building with a residential function has been chose. The high-rise buildings being built or the plans that are proposed in the Netherlands are mostly residential buildings [12], [13]. Most of the world tallest skyscrapers have a mixed used of offices, hotel or residential function. In the Netherlands the functions are more divided: the building mostly has one function [14].

Figure 2-2. Design of the Brinktoren.

The Brinktoren

As mentioned before the low-rise reference study and the super-tall study are based on the design of the Brinktoren [15], as shown in Figure 2-2. The Brinktoren is high-rise tower designed by Mecanoo Architecten B.V. The Brinktoren is a 28 floors, 90 meters tall residential building with 401 apartments in total. In both the low-rise reference study and in the super-tall study each apartment will be its own fire compartment. Each apartment has a combined living room and kitchen, a bedroom, a bathroom, an entrance hall, a storage room and a small utilities room. The surface area of the apartments is between 33.64 m^2 and 57.33 m^2 for the most common floors. Each apartment has a balcony attached to the living room. Two vertical shafts connect the apartments with the apartments above and below. The shafts will have a 60 minute fire separation. The technical drawings of the building are shown in attachment Appendix 6. Architectural drawing of the Brinktoren, floor 11. In Figure 2-3 the floorplan of the most common floors, floor 10 to 13, is depicted.

Figure 2-3. Geometry of the most common floor layout in the building, the 10^{th} to 13^{th} floor.

Building physics

The building physics of the Brinktoren are other important building characteristics. The Brinktoren is a thermal heavy building with concrete walls and floors as load bearing structures. The façade of the Brinktoren is a thermal heavy construction made of concrete sandwich panels finished with brickwork. The thermal resistance of the external separation constructions is 5.0 m^2*K/W for the floor, 6.0 m^2*K/W for the façade and 8.0 m^2*K/W for the roof. The daylight openings have a thermal resistance coefficient of 0.85 W/m^2*K and make up 41% of the façade. The external airtightness/$Q_{v;10;lea;ref}$ is 0.30 dm^3/s per m^2.

Low-rise residential reference building

The low-rise residential building is an interpolation of the Brinktoren. The building design that is used in the low-rise reference study is a 13 floor, 44,5 meters tall residential building, with the highest residential floor at 41.5 meters. The building will have 220 apartments in total. Each floor will have approximately 16 apartments ranging from 33.64 m^2 to 53.10 m^2. Each apartment is a separate fire compartment. The total gross surface area of the building is 17,590 m^2. The design lifetime of the building is 50 years (standard design lifetime). A comparison between the low-rise residential reference building and the Brinktoren is shown in Appendix 7. Comparison of the low-rise residential building, the Brinktoren and the super-tall residential building.

Super-tall residential building

The super tall residential building is an extrapolation of the Brinktoren. The building design that is used in the super-tall study will be a 130 floor, 395.5 meters tall residential building, with the highest residential floor at 392.5 meters. The building will have 2033 apartments. Each floor will have approximately 16 apartments ranging from 33.64 m^2 to 53.10 m^2. Each apartment is a separate fire compartment. The total gross surface area of the building is 140,577 m^2. The design lifetime of the supertall residential building is proposed to be 100 years. A comparison between the low-rise residential reference building, the Brinktoren and the super-tall residential building is shown in Appendix 7. Comparison of the low-rise residential building, the Brinktoren and the super-tall residential building.

Fire compartments

Each apartment is a separate fire compartment. The fire resistance of the walls and floors in the low-rise reference study will be according to the national building code, BBL. The fire resistance of the walls and floors of the super-tall study will be determined based on the reliability of the low-rise reference study and the sensitivity analyses.

2.3 Fire characteristics

Fire object

A natural fire is used in the simulations. The natural fire used in the Ozone model is based on Annex E of NEN-EN 1991-1-2/NB Eurocode 1. The heat release rate of the fire is shown in Figure 2-4. The growth rate of the fire is a medium growth rate (300 seconds to a 1 MW fire) according to NEN-EN 1991-1-2/NB Eurocode 1: Belastingen bij brand.

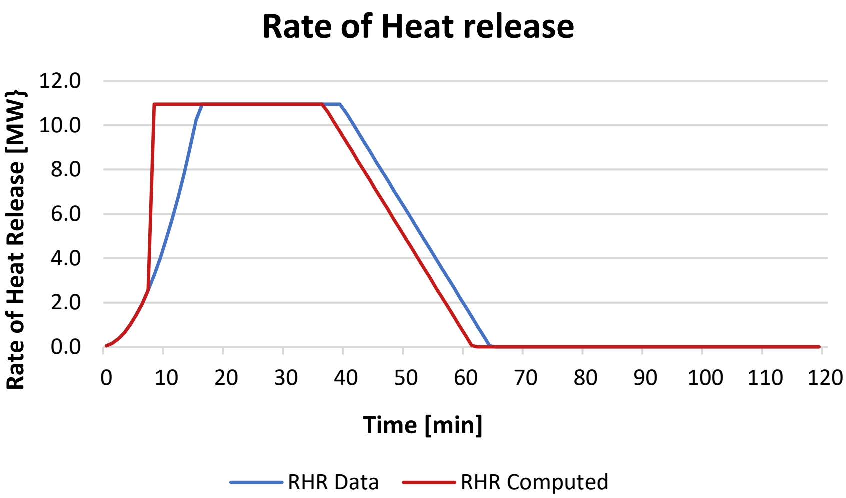

Figure 2-4. Rate of Heat Release (RHR) of natural fire according to Annex E of NEN-EN 1991-1-2/NB, used in the Ozone model.

Stochastic boundary conditions and the variations of these conditions used in the simulations are shown in Table 2-1 and have been based on the Eurocode 1 NEN-EN 1991-1-2/NB [16], Nieman report Wu040430abA0.rhe [17] and the NIPV publication 'Rookverspreiding en persoonlijke veiligheid' [18].

Table 2-1. Stochastic boundary conditions in in a performance-based approach, using a natural fire concept for a residential building function [18].

	Average (AVG)	Variation	Standard deviation (SD)
Heat release rate [kW/m²]	250	0.4	100
		-0.3	-75
Fire growth rate [s]	300	0.25	75
		-0.5	-150
Fire load density [MJ/m²]	780	0.15	117
		-0.15	-117
Combustion efficiency factor	0.8	0.08	0.06
		-0.08	-0.06
Stoichiometric coefficient	1.27	0.5	0.6
		-0.25	-0.3
Lower oxygen limit [%]	0.1 [19]	0.5	5.0
		-0.5	-5.0
Soot yield – no sprinkler	0.0264	1.0	0.0264
		-0.3	-0.0079
Soot yield – sprinkler	0.0528	1.0	0.0528
		-0.3	-0.0158

Heat of combustion [kJ/kg]	17,500
CO yield	0.0104
Danger of activation	1

Fire elevation	1.0 m
Fuel height	1.5 m

The soot yield and the CO yield are applicable of fuel-controlled fires, when there is enough oxygen in the room. The yields will increase when the fire is a ventilation-controlled fire, as shown in Figure 2-5 [20]. In which an equivalence ratio Φ < 1 is a fuel-controlled fire and an equivalence ratio Φ > 1 is a ventilation-controlled fire. The molecular formula of the combustion materials used in the CFAST model is $C_4H_6O_3$.

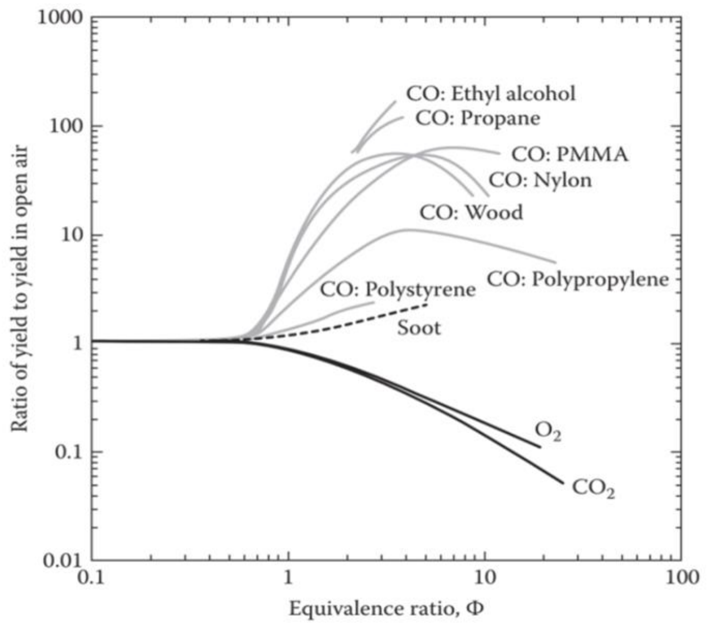

Figure 2-5. Ratio of yield to yield in open air.

2.4 Computational models

In order to predict the behavior of fire and smoke, computational models are used. There are three computational models used in fire safety engineering: network models, zone models and computational fluid dynamics (CFD) models. Multizone models are used for buildings with hundreds or even thousands of compartments, such as large high-rise buildings. Zone models are mostly used to predict the behavior of fire and smoke in multiple compartments, where the two-zone model is valid, whereas CFD models are mostly used to predict the behavior of fire and smoke in large compartments or in complex geometries [21]. Zone models can be divided into one-zone models, two-zone models or a combination of the one-zone and two-zone model. Most of the models used in fire safety engineering are two-zone models. In two-zone models a room is to be considered divided into two homogeneous layers or zones, and the connecting plume. In a two-zone model, equations for the conservation of mass, momentum and energy are applied to each zone to calculate the size, temperature and concentration of species of each zone and to calculate the flow of smoke and toxic products. This is done in a dynamic process [22].

The quantitative assessment with a probabilistic analysis in this research is carried out based on simulations made in OZone and CFAST. CFAST[23], [24] is one of the most versatile and widely used zone models [22]. CFAST can calculate the movement of smoke and hot gases in interconnected rooms. Ozone, developed by Arcelormittal and Universite de Liege and CFAST, developed by NIST are both two-zone models, which have an uniform distribution of fire load density. In some cases, it is better to use the actual distribution of combustibles [21]. However, since this research is carried out for a residential function an uniform distribution of the fire load density is assumed. By using an uniform distribution of the fire load, the interior design of the compartment can be changed during the life cycle of the building.

The CFAST simulations for the low-rise study are based on the Dutch national building code in which automatic suppression systems and/or pressurization systems are not used. The CFAST simulations for the super-tall study is based on the SBRCURnet publication for high-rise buildings, in which an automatic suppression system and a pressurization system are assumed. The automatic suppression system used in the super-tall study simulations is an automatic sprinkler based on the computer model DETACT [26]. The automatic sprinkler system is a quick response sprinkler with a response time index (RTI) of 50 $(m*s)^{1/2}$ and an actuation temperature of 68°C. The pressurization system used in the super-tall study simulations is a stairway lobby pressurization system in which fresh air is supplied via a shaft. NEN-EN 12101-6:2022 [27] prescribes pressurization systems in the stairways, pressurization in the stairway lobbies is an alternative directed in the SBRCURnet publication and is much more applicable in super-tall buildings. The test criteria for pressure difference for closed doors and the air speed in open doors prescribed in the NEN 12101-6:2022 are used. There will be an airspeed of 2 m/s over each door with a maximum pressure of 50 Pa. By supplying air through a separate shaft instead of via the staircase the air supply will be constant. If the air would have been supplied via the staircase as stated in the NEN-EN 12101-6:2022, there should be enough air supplied through three doors: the door on the fire floor, the floor below and the door on ground level. However, it is theoretically possible that more than 3 doors are open at the same time, which would result in a lower air supply on the desired floor and decrease the effect of the pressurization system. To prevent this from happening a stairway lobby with supply via a separate shaft has been used in the simulations.

Geometrical configuration

In Figure 2-3 the floorplan of the most common floors, floor 10 to 13, is depicted. This floorplan is used for the calculations made with the programs OZone and CFAST. The simulations use a simplified version of the floorplan or the compartments on this floor. By simplifying the geometry of the building, the computational power needed for the simulations is decreased. The floor consists of 16 apartments, 5 elevators of which 2 firefighting elevators, 3 staircases, 3 smoke lobbies, multiple corridors, multiple shafts, and some storage areas. A schematic overview of the floorplan is shown in Figure 2-6. The fire compartments will be modelled as one area, not considering the rooms of the apartment, since these separation constructions are not fire resistant. The geometrical configuration, the building characteristics and the fire characteristic used in the OZone models and in the CFAST models are shown in Appendix 3. Computational models.

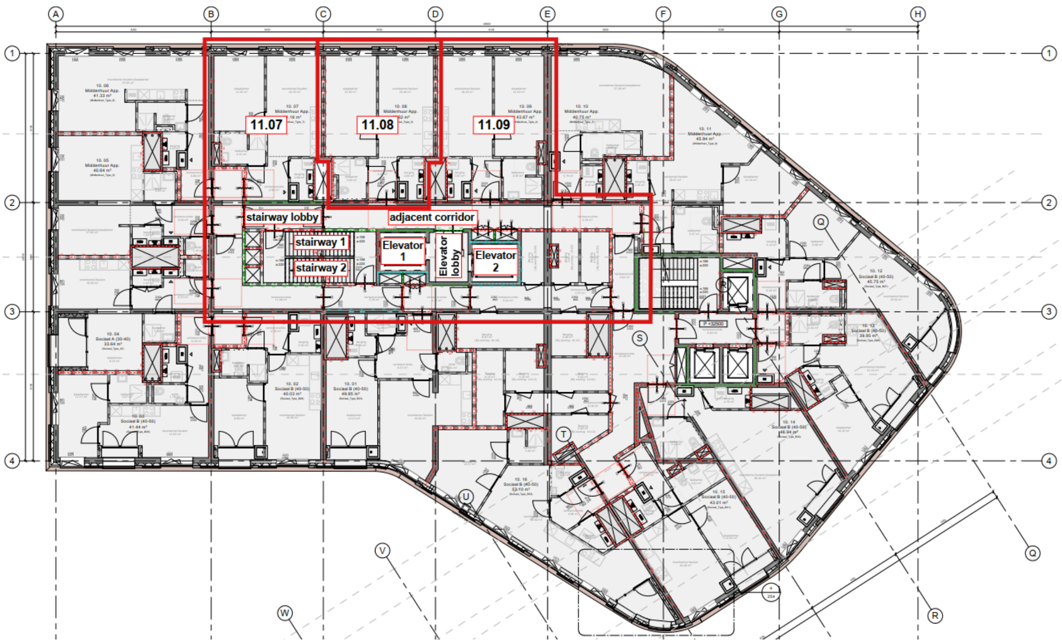

Figure 2-6. Schematic overview of the computational models.

3. From prescriptive design to performance-based design

In this chapter the theoretical framework of this research is presented. The level of fire safety of buildings below 200 meters will be discussed. In this part the fire safety of Dutch regulations regarding low-rise and high-rise buildings will be analyzed by the two principal components of fire safety: egress strategy and building performance. Building performance consists out of structural performance and fire spread mitigation (compartmentation) [28]. In high-rise buildings the height of the building and the limited vertical escape routes increase the evacuation time from minutes, for low-rise buildings, to possibly hours depending on the height as shown in Figure 1-2, coupling the evacuation time to the structural and compartmentation time. Because there is no Dutch regulation for buildings above 200 meters, international regulations will be analyzed for the safety level of buildings between 200 and 400 meters.

3.1 The fire safety level of the building code in The Netherlands

Buildings in the Netherlands are design and built according to the technical regulations of the Dutch national building code: 'Besluit bouwwerken leefomgeving, BBL'.

The Dutch national building code is a prescriptive based building code that has two main public objectives when it comes to fire safety:

- Personal safety (of building occupants and fire and rescue services)
- Protection of neighboring plots and adjacent building

Preserving the building and preventing damage to the environment, monuments or public services are not the goals of the Dutch national building code.

The regulations consist of functional requirements that are subsequently secured in performance requirements. The functional requirements can be divided into passive fire safety measures and active fire safety measures. The passive fire safety measures can also be seen as risk subsystems.

The following passive fire safety measures can be distinguished:

- Conservation of the environment: preventing the spread of fire to neighboring plots
- Conservation of the building: structural safety regarding collapse
- Limiting the ignition of fire: fire rating classification of building materials
- Limiting the spread of fire and smoke: fire compartmentation using fire resistant separation constructions and smoke compartmentation using smoke resistant separation constructions
- Conservation of the escape routes: fire resistance of the structural components, fire and smoke resistance separations constructions of the escape routes and Eurocodes of the materials
- Conservation of the attack routes: fire resistance of the structural components, fire and smoke resistance separations constructions of the escape routes and Eurocodes of the materials

And the following active fire safety measures can be distinguished:

- Fire safety installations: fire alarm system, evacuation alarm system, fire hoses, fire pipes, emergency lighting, fire elevator
- Fireproof use of the building: organization and management
- Services for the fire and rescue services: communication

Characteristics, limits, and methods have been prescribed to the functional requirements in order to comply with the goals. These characteristics, limits and methods are the performance requirements. The functional requirements and the performance requirements related to the fire safety of new buildings are described in the Dutch national building code BBL, chapter 4, section 4.2 safety and in section 4.7 building installations. Paragraphs 4.2.2, 4.2.6, 4.2.7, 4.2.8, 4.2.9, 4.2.10, 4.2.11 and 4.2.12 of section 4.2 prescribe the passive sire safety requirements and paragraphs 4.7.6, 4.7.7 and 4.7.8 of section 4.7 prescribe the active fire safety requirements. Fire safety requirements during the use of the building are prescribed in chapter 6, section 6.2 fire safety, paragraphs 6.2.1 and 6.1.2 prescribe the requirements that need to be met during the use of the building.

The performance requirements prescribed in the paragraphs related to fire safety of the building are prescriptive and not performance based. Except for the NEN 6079, which provides an equivalent level of fire safety when used. The NEN 6079 standard is a standard for the fire safety of large compartments > 1000 m^2 and is a performance-based approach, using risk factors to calculate the performance of the building. In the NEN 6079 standard it is explicitly noted that the standard cannot be used for buildings with a residential function or for a building in which less/non-self-reliable people are residing. NEN 6079 can be used for large fire compartments of office, industry or sports functions. Some of the risk factors used in the NEN 6079 match the risk factors used in the NEN-EN 1991-1-2:2002+C3:2019+NB:2019. One of these factors is the frequency of fire k [1/(m^2*y)] which is 0.04*10^{-5} [29][30], the frequency of fire is specific for the industrial building function. The NEN 6079 also states the chance of failure for multiple separation constructions. Failure probabilities are stated for separation constructions made of stone and metal-stud and for stone or metal-stud constructions with openings in appendix 1, 'Bijlage B'. NEN 6079 is not applicable for high-rise buildings. Nieman Raadgevende Ingenieurs conducted an analysis of the thermal load and the mechanical response of the safety level of the Dutch national building code (Bouwbesluit) in 2014: Risk based fire safety of load bearing elements [17]. In this research risk factors were used to determine the safety level of several cases. The risk factors used in the research are shown in Table 3-1.

Table 3-1. Risk factors for building function according to Nieman report.

Building function	P Fire ignition [1/yr.] [BSI]	P Fire ignition [1/m^2/yr.] [BSI]	P Local fire [1/m^2/50yrs.] [Handbook]	P Construction threatening fire [1/m^2/50yrs.] [Nieman report]
Residential (low-rise)	3 e-3		1 e-5	1 e-6
Residential (high-rise)	3 e-3			
Office	6 e-3	1 e-5	2 e-5	2 e-6
Hotel			2 e-5	

The information in Table 3-1 is gathered from the BSI: Application of fire engineering principles to the design of buildings – code of practice BS 7974, BSI, London; and the handbook: Schleich et al. – Leonardo da Vinci, Handbook 5, Fire Design [31]. The risk factors used in the BSI do not use a specific area but is specific for a building with that function. The risk factors used in the Leonardo da Vinci handbook 5 uses a failure probability of fire extinguishing by occupant of 0.4 and a failure probability of fire extinguishing by the fire department of 0.1.

The probability of fire given the design of the building can be compared to the probability of fire calculated by using the Eurocode method. This method uses the compartment area or the building area, the design lifetime and the ignition probability in order to calculate the probability of fire for 3 consequence classes. The ignition probability per m^2 per year is determined by dividing the number of fires per year in a building function, by the surface area of that building function in that year. The amount of residential fires over the last 10 year in The Netherlands are shown in Figure 3-1, Table 3-2 and Appendix 5. Statistics of residential fires in the Netherlands for the past 10 years.

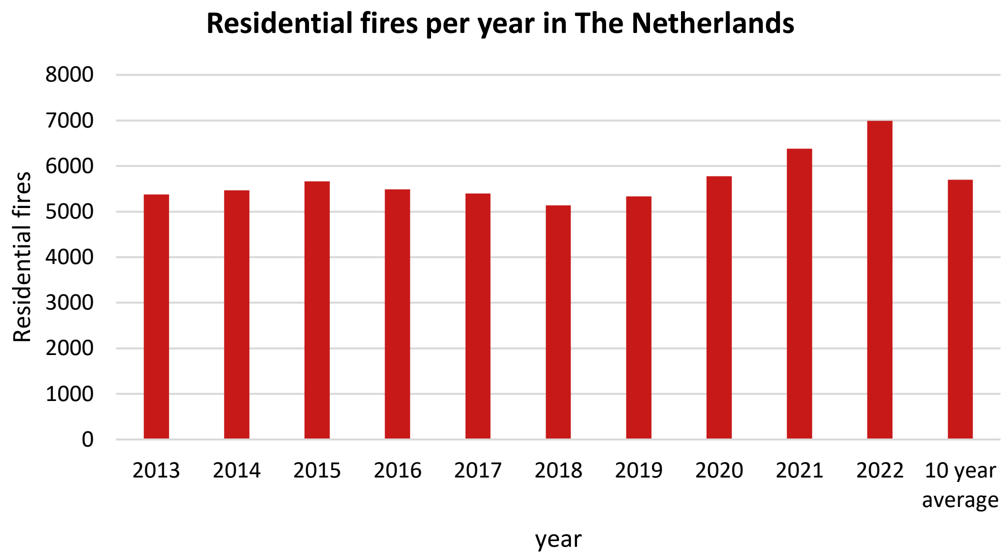

Figure 3-1. Residential fires per year in The Netherlands [32], [33].

Table 3-2. Probability of fire for a residential function in The Netherlands from 2013 to 2022.

	10-year average 2013-2022
Total residential fires	5701
P fire [1/yr.]	7.36E-04
P fire [1/m2/yr.]	6.18E-06

A summary of the probability of fire per year and per m^2 per year in The Netherlands is shown in Table 3-2, the full analysis of the last 10 years is shown in Appendix 5. Statistics of residential fires in the Netherlands for the past 10 years. When comparing the probability of fire per year based on Dutch statistics with the probability of fire per year as stated in the BSI, as shown in Table 3-1, the probability of fire per year in The Netherlands is a factor 4 smaller. A comparison between the Handbook [31], which is the basis for the Eurocode, and the Dutch statistics the probability of fire per m^2 per 50 years is a factor 31 larger, as shown below:

- Probability of fire according to the Handbook: 1E-5 [1/m^2/ 50yrs.]
- Probability of fire according to Dutch statistics: 6.18E-6 * 50 = 3.09E-04 [1/m^2/50yrs.]

The difference in the probability of fire between the Eurocode and the statistics might be explained by the fact that the probability of fire according to the Eurocode is for low-rise buildings and the probability of fire according to the Dutch statistics is for a residential building, low-rise and high-rise. The difference in probability of fire could also be explained based on the difference in time. The statistics in the Handbook are based on a period between 1970 and 1990. An increase in electrical appliances, PV-panels and other similar equipment may have caused an increase in the probability of fire.

3.2 The fire safety level of tall buildings in The Netherlands

The Dutch national building code does not have regulations for buildings lower than -8 meters below measurement level or for buildings taller than 70 meters above measurement level. Paragraph 4.2.13 of the national building code, tall and subterranean buildings, is used for buildings below -8 m and above 70 meters. Artikel 4.88 states that buildings taller than 70 meters above measurement level is arranged in such a way that the building is firesafe. Artikel 4.89 of paragraph 4.2.13 states that a building with a floor 70 meters above measurement level is arranged in such a way that it has same level of fire safety as prescribed in paragraphs 4.2.2, 4.2.6, 4.2.7, 4.2.8, 4.2.9, 4.2.10, 4.2.11 and 4.2.12 or complies to the SBRCURnet publication for fire safety for tall buildings. For buildings above 70 meters and below 200 meters the SBRCURnet publication is prescribed for the design of tall buildings.

The SBRCURnet publication for fire safety in tall buildings between 70 and 200 meters is a publication with performance requirements that are based on a quantitative risk assessment in which the level of fire safety in a tall building is at least the same as in a normal building (building built/designed according to BBL < 70 meters.) The publication can be used for buildings with residential, office and/or hotel function.

The risk-subsystems that are implemented in the BBL can be translated into acceptable failure probabilities:

- Safety of building users will be expressed in an acceptable failure probability of the escape route because of fire
- Safety of the environment will be expressed in an acceptable failure probability of fire spread to neighboring plots
- Safety of the building will be expressed in an acceptable failure probability of the failure of the load bearing structure because of fire
- Safety of the fire compartment will be expressed in an acceptable failure probability of fire spread to another fire compartment in the same building
- Safety of the smoke compartmentation will be expressed in an acceptable failure probability of failure of preventing internal smoke propagation.
- Safety of fire and rescue services will be expressed in an acceptable failure probability of the attack route as a result of fire

The failure probabilities of the risk subsystems can be used to support the main goals of the BBL and of the SBRCURnet publication. The acceptable failure probabilities of the risk subsystems as mentioned above are the basis on which the SBRCURnet publication is based to achieve the same level of fire safety as buildings below 70 meters.

Evacuation is one of the main subjects of the SBRCURnet publication for fire safety in tall buildings. Evacuation of tall buildings takes longer in comparison to normal buildings because the distance that building occupants need to evacuate over is longer/higher. In order to evacuate tall buildings, the SBRCURnet publication distinguishes four different evacuation concepts:

A. Total evacuation with standard evacuation time (evacuation time according to BBL);
B. Total evacuation with extended evacuation time;
C. Phased evacuation (with extended evacuation time);
D. Partial evacuation (evacuation of the emergency area to a safe haven)

Evacuation concepts A, B and C are elaborated in the publication, concept D however is not. Partial evacuation is not a conventional evacuation strategy in The Netherlands. It is explicitly noted that partial evacuation might be necessary in super-tall buildings and needs to be project specific.

The repressive actions taken by the fire department have been taken into account in the SBRCURnet publication and can be divided into four ways of repressive action, see Figure 3-2:

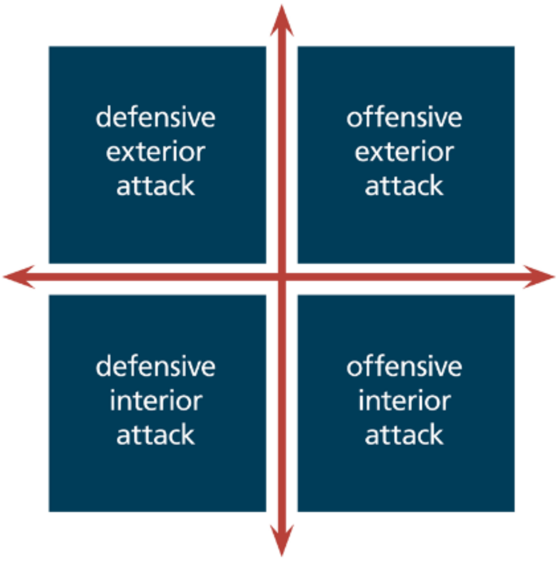

Figure 3-2. Repressive actions of the Dutch fire brigade. [34]

In order to assess the risk of fire for building occupant and fire and rescue services the repressive actions of the fire brigade need to be taken into account when designing tall buildings. For tall building repressive action like the defensive exterior attack and/or the offensive exterior attack will most likely not be used because of the limited reach of the fire brigade on the exterior/facade of the building.

To be able to implement the evacuation concepts and to be able to take repressive actions the SBRCURnet publication has directives for the strength of the construction in case of fire, fire propagation, fire spread, escape routes, fire repression and fire safety installations. The fire safety of tall buildings is linked to the evacuation concepts used in the building.

The performance requirements prescribed in the paragraphs related to fire safety of the building are prescriptive and not performance based. Except for the NEN-EN 1991-1-2:2002+C3:2019+NB:2019 and the NTA 4614-3.

The SBRCURnet publication for fire safety in tall buildings has prescriptive measures for fire safety based on a quantitative risk assessment and describes fire safety based on project specific characteristics. These project specific characteristics are related to the building and the fuel/fire load. The following building characteristics need to be used:

- Size and geometry of the fire compartment
- Size and position of external openings (windows, doors)
- Thermal accumulation and insulation of the fire compartment

The following fuel characteristics are related to the permanent and variable fire load:

- The reference fire load density, time constant and fire load
- Stoichiometric constant and fire model
- Flash-over criteria

The standard fire curve is used to calculate the fire resilience of constructions. The standard fire curve is a normalized curve that indicates the relation between time and temperature and is used internationally for assessing and classifying structures. Instead of the standard fire curve a more realistic natural fire curve can also be used. The SBRCURnet prescribes the use of a natural fire concept based on the NEN-EN 1991-1-2 (the Eurocode) and the NTA 4614-3 convenant hoogbouw; covenant high-rise buildings. A project specific natural fire curve can be determined with NEN 6055, which describes the natural fire concept based on project specific characteristics. The thermal load caused by the natural fire needs to be translated to a standard fire curve, since the fire rating of constructions is also expressed in minutes standard fire curve.

In order to get an equivalent level of fire safety as buildings below 70 meters, a comparison has been made between two buildings with the same function, lay-out, construction, internal and external separation constructions and fire compartments. The only difference is the height of the building. In this way the height of the building is almost a factor 3 this as high as a 70 meters building (200 / 70 = 2.86 ≈ 3). In a risk assessment this factor needs to be used both on the risk side as on the effect side of the assessment, resulting in level of fire safety that needs to be 10 time higher than that of a building below 70 meters [5]. Project specific parameters have not been used in the quantitative risk assessment, which means that the publication is not based on Fire Safety Engineering.

Fire safety during construction

Fire safety is of importance during the use of the building and during construction of the building. While the building is being constructed the construction workers are inside the building and a fire may occur.
The National building Code BBL does not prescribe requirements for fire safety during construction. Local governments can make demand regarding fire safety and for large constructions/buildings a construction safety plan needs to be composed. For tall buildings, the SBRCURnet publication prescribes requirements for fire safety during the construction of the building. Just as during use the accessibility, the possible deployment of the fire brigade and the escape possibilities are important. In order to have a fire safe building during constructions the following requirements must be taken into account:

a. Accessibility of the construction site by the fire brigade
b. Usability of at least one dry pipes for fire hoses (droge blusleidingen) when the building construction exceeds 20 meters and the usability of wet pipes for fire hoses (natte blusleiding) when the building construction exceeds 70 meters
c. During construction at least one portable fire extinguisher should be available at a central point of every floor
d. A temporary fire alarm needs to be put in place on every floor during construction and the fire alarm needs to be connected to the office of the construction foreman
e. During construction at least two separate escape routes need to be accessible
f. Building equipment and building materials need to be stored in a separate fire compartment that has a fire resistance of at least 60 minutes.

3.3 The fire safety level of super-tall buildings in The Netherlands

For buildings between 200 and 400 meters the Dutch national building code BBL does not have regulations. The national building code has regulations for building up to 70 meters and the directed SBRCURnet publication has regulations for building between 70 and 200 meters, which need to provide the same level of fire safety as for building below 70 meters. Based on paragraph 4.2.13 of the national building code it is possible to design and built a building higher than 200 meters if the building is designed in such a way that it is fireproof and the building provides at least the same level of fire safety as intended in paragraphs 4.2.2, 4.2.6, 4.2.7, 4.2.8, 4.2.9, 4.2.10 and 4.2.12.

Because the Dutch national building code is prescriptive and not risk based it is hard to design a building higher than 200 meters that has the same level of fire safety as a building below 70 meters. There are no risk factors that can be compared. Therefor a risk-based approach could be applied using the same risk subsystem as described in section 3.2.

The city of Rotterdam published its vision on high-rise buildings in 2019, which states that the theoretical maximum height of buildings is 250 meters, based on urban planning and design. This theoretical maximum height is a dynamic height and can grow in time [4]. Because buildings with a height of 250 meters are not directed in the Dutch national building code nor in the SBRCURnet publication, the city of Rotterdam and security region Rotterdam-Rijnmond published a concept version of The Rotterdam Fire Safety vision (De Rotterdamse Brandveiligheidsvisie), their fire safety concept for tall buildings (70 – 200 m) and for super-tall buildings (200 – 400 m). The fire safety vision of the city of Rotterdam has a few additional guidelines for the SBRCURnet publication for fire safety of tall buildings and has additional guidelines for buildings between 200 and 400 meters. The guidelines for buildings between 200 and 400 meters are based on the SBRCURnet publication guidelines. The Fire safety vision prescribes requirements that need to be met when designing a super-tall building in Rotterdam.

3.4 Assessment in a risk-based approach

The performance requirements for low-rise building prescribed in the BBL, for tall buildings prescribed in the SBRCURnet publication and for tall+ buildings prescribed in the Rotterdam Fire Safety vision, can also be used in a risk-based assessment. In a risk-based approach assessment the criteria are used to perform an AST-RST analysis in every risk subsystem. For risk subsystems with requirements related to the thermal load (loadbearing structure and compartmentation) the AST and RST are expressed in minutes SFC. For evacuation routes (personal safety) the ASET and RSET are real clock time. An AST-RST analysis is made for building components such as the load bearing structure or the compartmentation. In this analysis the equivalent fire duration of the standard fire curve is used to calculate the failure probability. For personal safety an ASET-RSET analysis is made using the evacuation time of building occupants. The results of the AS(E)T-RS(E)T analyses are shown probabilities with a reliability. This can be expressed as AST > RST + safety margin. The probability that AST doesn't exceed RST must be very small (P(AST<RST) < P(acceptable)). The acceptable failure probability depends on the risk subsystem and the requirements of the Building Code. As mentioned in section 3.2 the SBRCURnet publication has been made based on a risk-based assessment, which has later been translated to prescriptive assessment criteria.

3.5 The Fire safety level of buildings internationally

3.5.1 Design methods

In order to determine the fire safety level of buildings there are two design methods: prescriptive or analytical. In a prescriptive design method relevant deemed to satisfy solutions are used to finalize the design and to comply with the regulations. In an analytical design method, the design needs to meet the performance criteria in order to comply with the regulations [35]. To show that the performance criteria meet the regulations a verification method needs to be available. Some of the criteria used for an analytical approach are described by Yung [36], The New-Zealand Centre for Advanced Engineering (CAENZ) [37] and Hadjisopocleous and Bénichou [38]. Nystedt [35] describes available methods of screening for the performance criteria.

Yung [36] introduced barrier groups for describing and categorizing the fire safety of buildings. The barrier groups of Yung use the ‘defense in depth’ principle which is strongly related to redundancy. In a systems using redundancy, the system keeps working when one of its components fail. The New-Zealand Centre of advanced engineering (CAENZ) [37] discusses fire safety measures in a similar way to Yung and, CAENZ relates fire safety measures in terms of barriers to the fire development in a building. The barrier groups used are:

- Prevent ignition;
- Control fire growth;
- Control smoke spread;
- Limit fire spread within building;
- Prevent spread to other building;
- Means of escape;
- Facilitate rescue service options.

According to Hadjisopocleous and Bénichou [38] a performance-based fire safety design should at least follow the following four generic steps:

1. Identification of the performance objectives and requirements
2. Establishment of performance criteria
3. Quantification process
4. Presentation of design documentation to the Authority Having Jurisdiction for approval

Overall objectives of the fire safety systems in buildings that need to be met according to Hadjisopocleous and Bénichou [38] are:

- Minimizing risk to life and injury of people from fires
- Minimizing property loss in the building of fire origin and adjacent buildings
- Limiting economic, operational, social and environmental impact of fires

The fire safety objectives and requirements that need to be considered by the design team in order to make the above-mentioned objectives:

- Fire outbreak and development
- Spread of fire and smoke
- Means of notification and evacuation
- Fire resistance and structural stability
- Emergency response operations
- Economic and social impact
- Environmental protection

In order to meet the fire safety objectives and requirements as stated by Hadjisopocleous and Bénichou performance criteria that are verifiable and enforceable need to be established. Designers should be able to easily demonstrate that their designs meet the performance criteria, by using engineering tools, and that code authority can enforce the performance criteria.

Hadjisopocleous and Bénichou summarized different deterministic criteria, which present upper and lower limits of various criteria. The range of these criteria are not set because project specific and even occupancy or use specific circumstances effect the values of the criteria. The performance criteria should be dependent on the use and occupancy of the building. When using deterministic analyses for the designs of buildings safety factors may need to be included. In literature the safety factors used in general range from 1 to 3 [39]. A low level of uncertainty is indicated by a low value (i.e., 1) and a high level of uncertainty is indicated by a high level (i.e., 3). Although a deterministic analysis provides clear information about room conditions, a deterministic analysis has a limited ability to consider the level of safety of an entire building with all it systems and functions.

In order to provide information about the level of safety of an entire building, a probabilistic method providing a risk estimate can be used. Statistical data is used to form the risk criteria used in a probabilistic method. Risk factors calculated by a probabilistic approach can be compared to the risk criteria for a design to be accepted by the authorities [38]. In order to compare the calculated risk factors with the risk criteria it is better to conduct the evaluation for several sub-systems separately [40]. The following sub-systems should be considered for the quantification process:

1. Fire outbreak and development;
2. Spread of smoke;
3. Spread of fire;
4. Fire resistance and structural stability;
5. Fire detection;
6. Fire suppression;
7. Emergency/firefighting response operations;
8. Means of notification and evacuation;
9. Continuity of operations;
10. Environmental protection.

Probabilistic or stochastic fire models and deterministic fire models can be used in a performance-based design. In probabilistic fire models the probability of risk due to fire based on the probability of all parameters influencing the fire are evaluated. In deterministic fire models the impact of fire is calculated based on physical, chemical and thermodynamic relationships and empirical correlations. According to Hadjisopocleous and Bénichou deterministic models can be classified as zone models and field models, which can be very simple or highly complex.

In the British standard the risks shown in Table 3-3 are used.

Table 3-3. Tolerability of risk [41].

Category	Probability
Maximum tolerable risk to individual member of the public	10^{-4} probability of death per year
General acceptable risk to individual member of the public	10^{-6} probability of death per year
Individual risk from fires only	
(1) At home or sleeping	1.5 * 10^{-5} per individual per year
(2) Elsewhere	1.5 * 10^{-6} per individual per year
Risk of multiple deaths from fires only	
(1) > 10 deaths	5 * 10^{-7} per building per year
(2) > 100 deaths	5 * 10^{-8} per building per year

To verify design alternatives used in an analytical approach of fire safety Paté-Cornell [42] present a structure for threatening uncertainty in risk analysis and proposes six different levels of uncertainties:

- Level 0, risk screening and failure mode identification
- Level 1, worst case scenario
- Level 2, quasi-worst case/worst credible approach
- Level 3, design scenarios and average values
- Level 4, event tree and fault tree analysis using point values
- Level 5 event tree and fault tree analysis using statistical distributions

In order to solve the uncertainties three methods can be used:

- Qualitative risk assessment
- Quantitative assessment with deterministic analysis
- Quantitative assessment with probabilistic analysis

In a qualitative assessment initial risk screening is conducted to identify relevant fire risk and in order to present a trial design solution that solves these risks. Logic reasoning, statistics, experience and results from testing are used to support the assessment.

In a quantitative assessment with deterministic analysis the safety of a number of independent fire scenarios are measured based on the consequence of the solution. By complying to the acceptance criteria of a number of pre-defined fire scenarios a sufficient level of safety is shown. However, this level of safety is not explicitly calculated in a deterministic analysis. A quantitative assessment with probabilistic analysis also measures the safety of a number of independent fire scenarios just like a deterministic analysis, but in a probabilistic analysis a specific level of fire safety is calculated. This is done by evaluating the relationship between different scenarios and the probability and consequence of each individual scenario. In a complicated design of the building which uses 'new' solutions to comply with fire safety objectives it a quantitative assessment should be used. This assessment can be either a deterministic or probabilistic analysis. To make sure that the design meets the fire safety requirements of the regulations a design review is required. The Authority Having Jurisdiction (AHJ) is responsible for the quality of the design [35]. According to Lundin [43] there are three possible levels of review: a self-check, an internal review and a third-party review.

3.5.2 International building codes

Most international building codes are prescriptive building codes. These prescriptive building codes cannot keep up with the development of (new) technologies and buildings that are more complex, dynamic and interconnected [44]. Besides the purely prescriptive codes there are prescriptive building codes with performance-based options, purely performance-based building codes and building codes that know both prescriptive and performance-based approaches but only allow one approach to be used in a design. Prescriptive buildings codes are directed in European countries such as, Hungary [45], Portugal and Belgium [46] and internationally in, Israel [45]. A lot of international building codes now have performance-based options within the current codes which allows for performance-based design. Countries using prescriptive building codes with optional performance-based requirements are: Poland [45], Austria, Germany, Greece, France, Italy and Spain in Europe [46] and the United states [44], [47] and Canada [47] [48]. Fully performance-based building codes are used in Denmark [46], Slovakia [45], Hong Kong [49], Japan [38], New Zealand [38], [48] and Australia [40]. And there are countries where it is possible to either use prescriptive or performance-based building codes, such as: Slovenia, Sweden, the United Kingdom [46] and Singapore [50]. In order for countries to start using a performance-based building code, the International Standard Organization (ISO) and the Conseil International du Bâtiment (CIB) have published guidelines with general principles of performance-based design [38].

Most of the above-mentioned performance-based building codes apply to the general building codes. Performance based building codes specifically for fire safety are used in Australia, the United Kingdom, Japan, Canada, Sweden, Norway, New Zealand, Germany, and Singapore [38], [45], [50], [51]. Performance based codes can be used in the United States of America, but prescriptive codes are the preferred codes to be used [50].

3.6 Evacuation principles of high-rise buildings

Evacuation principles or egress strategies are one of the two principal components of fire safety engineering. In most cases evacuation takes place in the order of minutes, for high-rise buildings however this is not the case. The height of the building and the limited vertical escape routes increase the required safe egress time. This is the case for a full or phased evacuation concept. In an evacuation concept in which the building occupant stay in their apartments for a stay-in-place concept or when a safety floor is used to evacuate several floors, the evacuation time changes.

The behavior of building occupants in case of evacuation can be different around the world because of culture and fire department capabilities. Because occupant behavior and fire department capabilities differ it is necessary to use an experimental model to validate the minimum level of safety [52].

Evacuation in high-rise buildings occurs in two directions, horizontal and vertical. Horizontal evacuation takes place on the floor where the building occupant is residing and on ground floor level. Vertical evacuations takes place between floors. Vertical evacuation is conventionally done by using the stairs and implies 'in case of fire, do not use the elevator'. Both the BBL and the SBRCURnet publication use the conventional egress principle for evacuation. The BBL describes an evacuation route as: a route starting in a space/room/area for building occupants, using floors, stairs or ramps and ends in a safe place, without the need to use an elevator [7]. While explicitly stating not to use the elevator, the elevator can be used as a means of egress. Elevators can be divided into two groups: fire services elevators and building users elevators. Fire service elevators are used since the 1980s by fire fighters during firefighting operations in many countries, among which The Netherlands. However, the elevators can be used as a vertical escape route in combination with the stairs or as a separate evacuation system. The use of evacuation elevators can significantly reduce the evacuation time [9], [53]–[56].

Besides the stairs and elevators there are more alternatives to use when escaping a building. More common alternative means of egress are: evacuation escalators, sky bridges and refuge floors. Uncommon alternative means of egress are: use of helicopters, use of facades [57] or inflatable ejection modules [58], parachutes, ropes, slides or temporary elevators connected to the side of the building. According to Wood [59] the above-mentioned evacuation systems are conceptual designs that step back from the existing evacuation methods and are therefore met with almost universal scepticism from the larger professional safety community.

3.6.1 Dutch evacuation principles in high-rise buildings

Evacuation principles in high-rise buildings in The Netherlands are prescribed in the SBRCURnet publication for tall buildings and in the NTA 4614-2.

SBRCURnet publication

Evacuation principles of high-rise buildings is legislated in the SBRCURnet publication for tall buildings. In the SBRCURnet publication for fire safety in tall buildings evacuation is one of the main subjects. Evacuation of tall buildings takes longer in comparison to normal buildings because the distance that building occupants need to evacuate over is longer/higher. In order to evacuate tall buildings, the SBRCURnet publication distinguishes four different evacuation concepts:

A. Total evacuation with standard evacuation time (evacuation time according to BBL);
B. Total evacuation with extended evacuation time;
C. Phased evacuation (with extended evacuation time);
D. Partial evacuation (evacuation of the emergency area to a safe haven)

The main escape route as mentioned is the staircase, however evacuating via the elevator is also a possibility. This evacuation principle is directed in the NTA 4614-2 Covenant high-rise buildings – Part 2: Evacuation of high-rise buildings with elevators and evacuation staircases. In the SBRCURnet publication the NTA 4614-2 is mentioned but not directed because it is not validated

NTA 4614-2 Covenant high-rise buildings – Part 2: Evacuation of high-rise buildings with elevators and evacuation staircases

The NTA 4614-2 describes the method of calculating the evacuation time for high-rise buildings between 70 and 250 meters for buildings with a residential, office and/or hotel function. In order to use the NTA 4614-2 the following boundary conditions need to be taken into account:

- In case of fire there will be a partial evacuation
- In case of other calamities, the building will be fully evacuated
- All elevators have emergency power
- There are at least two fire fighter elevators
- The loadbearing structure is at least 120 minutes fire resistant

- The building has a sprinkler installation
- The evacuation time is maximum 60 minutes

In order to evacuate tall buildings the NTA 4614-2 distinguishes five different evacuation concepts:

0. Full evacuation using stairs only
1. Full evacuation using elevators only
2. Full evacuation using stairs and partially using elevators by less self-reliant and not self-reliant building occupants
3. Full evacuation with refuge floors using stairs and elevators as shuttle
4. Full evacuation, free choice in stairs or elevators

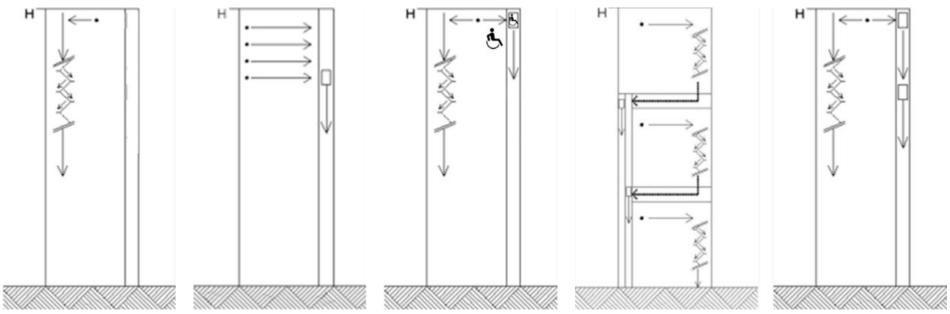

Figure 3-3. evacuation concepts of the NTA 4614-2, from left to right: 0, 1, 2, 3 and 4 [60].

Evacuation scenario 0 is the most common and most basic evacuation principle in a building, building occupants use the stairs to evacuate the building and a common phrase in this scenario is: in case of fire do not use the elevator. Evacuation scenario 1 is a less common evacuation principle in which only the elevators are used to evacuate the building. This evacuation scenario is not advised in high-rise buildings. In evacuation scenario 2 the main evacuation route for building occupants is the stairs, only less self-reliant and not self-reliant building occupants use the elevators as means of evacuation. In buildings with an office function or hotel function the fire and rescue services assist the less self-reliant or not self-reliant building occupants. When using evacuation scenario 3, the building is divided into multiple section that are separated by a safe haven or refugee floor. In this scenario building occupants in a section evacuate towards the refuge floor by using the stairs. When building occupants have reached the safe haven or refuge floor, the evacuation is continued by evacuation elevators called shuttles. In evacuation scenario 4 building occupants are free to choose to take the stairs or the elevator to evacuate the building. Fire and rescue services do not support building occupants during the evacuation [60].

3.6.2 International egress components

After the terrorist attacks on the World Trade Center and the collapse of the World Trade Center Towers, on September 11th, 2001, in New York, a lot of research has been conducted internationally in order to improve structural systems, fire proofing and evacuation systems in high-rise buildings. A lot of characteristics affect the evacuation process of a high-rise building, both building/design characteristics as well as human characteristics. High-rise evacuation concepts/design should consider (changing) occupant demographics [61], occupant behavior [62], technological advancements and the increasing height and complexity of buildings [63]. In this paragraph the most commonly used evacuation systems used in high-rise buildings internationally are described.

Stairs

Traditionally the evacuation of buildings vertically takes place by the use of stairs. Both low-rise and high-rise buildings use stair for the evacuation of building occupants. Building characteristics and evacuation concepts influence the width and/or the number of stairs used in a building. The design of the stair(s) taking into account the evacuation concept is dependent on: the number of stairs, stair width, staircase length, location in the building [64], slope of the stairs [65], value of capacity of stairs [66] and the occupancy level per floor [67]. Different methods of design are provided by the aforementioned studies while taking evacuation considerations into account. The design of the stairs and the structural design are connected. When using stair egress as the only evacuation concept the structural design of the building should be at least the required safe egress time (RSET). Besides structural criteria and design aspects, demographical aspects need to be considered [68]. Functional aspects such as the merging of evacuation streams in the floor-stair aspect and personal/demographic aspects such as fatigue need to be considered in and evacuation scenario, as both aspects can influence the evacuation time [61], [68], [69].

Evacuation elevators

As the built of tall buildings continued, elevators became a more likely consideration for the evacuation of building occupants. Since the 1970's elevators have been recognized as a means of evacuating building occupants [70]. In the 1980's and 1990's elevators became more common as a means of evacuating building occupants, particularly building occupants that are less or not self-reliant [71], [72]. Research into the use of elevators for building evacuation has been conducted since the 1930's [73], but the attack on the World Trade Centre on 9/11 has pushed the research of vertical evacuation using elevators [63].
Traditionally elevators should not be used during an emergency, however that concept had been discarded. Evacuation in tall buildings should be faster and more effective than a concept which only uses stairs, in particular the evacuation of less or not self-reliant building occupants benefit from elevator evacuation. Using elevators for evacuation purposes is complex, especially in super-tall buildings. Design factors such as the limited space in elevators [74], the piston effect caused by the movement of the elevators [52], [75]–[77], emergency power, water protection [78], [79] and the spread of smoke, fire and heat complicate the usage of evacuation elevators. The location of the evacuation elevators in relation to the refuge areas, exit of the stairs and the pick-up locations should be on a floor that can occupy a large population [80]. This location is mostly referred to as a refuge floor or a safe haven.

Because the traditional notion of not using elevators in case of an emergency the behavioral factors of building occupants need to be considered when designing an evacuation strategy using elevators. The behavior of building occupants can be influenced by the waiting time [81], building height and personal fitness [53], [61], [62]. The use of evacuation elevators can be regulated by fire and rescue services. fire and rescue services can coordinate the number and order of people entering the elevators.

Evacuation escalators

Escalators in buildings are usually not used for evacuation purposes in residential or office buildings. In subway stations however escalators are used for evacuation purposes. A lot of studies have been conducted for upward evacuation of subway stations by escalators [82]–[85], however little studies have been conducted in the downward evacuation by escalators. Using escalators in an evacuation design can be beneficial for the evacuation time, minimize the effect of fatigue and can direct people in the right direction by continuing, stopping, or reversing depending on the fire scenario [82]. The use of escalators for evacuation can also save valuable floor area when additional evacuation stairs are not required anymore. However, at the same time, several risks can be introduced when using escalators for evacuation. During stoppage or reversal of escalators the risk of personal injuries can be increased, flow rates can be lowered, and power outages can cause partial loss of essential escape routes.

Refuge floors

In an evacuation system refuge floors can be used to hold building occupants in a building and act as a (temporary) safe haven. Instead of evacuating building occupants to the ground floor and outside of the building, a refuge floor offers safety for building occupant for a certain time without a full building evacuation. Refugee floors are a part of an evacuation system in which stairs and/or elevators need to be used in order for building occupants to reach the refugee floors. Refuge floors have several advantages:

1. Evacuees can rest at a refugee floor
2. It reduces the possibility of smoke in stairs or elevator shafts

3. Less self-reliant people can be protected at a refugee floor [86]
4. The rescue team can use a refugee floor as a command point
5. Refuge floor can be used as a fire-fighting base [59]
6. Evacuating building occupant with elevators can be easier as the refugee floor acts as a pickup point. [87]

According to Alianto et al. [52] the refugee floors can also be used as sky lobbies, connecting multiple sky lobbies or multiple building via sky bridges with each other.

Skybridge

As mentioned in the previous paragraph refuge floors or sky lobbies can be connected to each other via a skybridge. A skybridge is an alternative means of escape in high-rise buildings as it connects two buildings or two towers of the same building (for example the Petronas towers [88]) via a bridge at height. A skybridge introduces a horizontal means of evacuation instead of a vertical evacuation. Building occupant do not evacuate via the ground floor but enter another building/safe haven via a skybridge on a building level other than the ground floor. Wood [59] pointed out that the effectiveness of a skybridge depends on the evacuation strategy adopted in the building design and the other egress components such as stairs and elevators. Wood [89] also pointed out that for maximum efficiency of egress the location of the skybridge should be at a level of changeover between lifts, for instance a sky lobby or a refuge floor. The position of this level of changeover should be placed between the upper and lower part of the building, preferably at a location where the population of the building is split in two [87], [89]. According to Ronchi and Nilsson there is a lack of knowledge about the effectiveness of skybridges in evacuation scenarios, which requires further studies of the subject [63].

3.6.3 International egress strategies

Egress components as mentioned in the previous paragraph and egress strategies are both part of the fire safety design of high-rise buildings. Egress components are used in egress strategies in order for occupant to evacuate the calamity zone. The most common egress strategies used internationally can be divided into four strategies:

1. Total evacuation
2. Phased evacuation
3. Defend-in-place/stay-put tactic/stay-in-place tactic
4. Delayed evacuation

The application of an egress strategy depends on the building characteristics, occupant characteristics and fire characteristics.

Total evacuation

The total evacuation strategy is an egress strategy in which all building occupants evacuate the building at once to a designated safety area. Total evacuation of a building is more common in low-rise buildings than in high-rise buildings because high-rise buildings have longer vertical travel distances. Total evacuation in buildings is mostly initiated by the fire department or by a spontaneous decision of the building occupants [63]. However total evacuation in high-rise buildings may not be necessary because not all building occupants in high-rise buildings are directly exposed to a hazard.

Phased evacuation

When a total single staged evacuation strategy is not practical a total phased evacuation strategy can be adopted. In a phased evacuation strategy building occupants evacuate the building in phases, the building occupants directly exposed to a hazard or close to a hazard evacuate the building first, while the other building occupants need to remain in the building for a certain time. When a phased evacuation strategy is used in a building the fire compartmentation plays a key role. A common phased evacuation procedure is to evacuate three floors first: the fire floor, the floor above and the floor below. After the evacuation of the first three floor the other floor can be evacuated.

Defend-in-place/stay-put tactic/stay-in-place tactic.

The defend-in-place, stay-put tactic or stay-in-place concept is not an evacuation strategy in which building occupant evacuate the building in case of fire. In the defend-in-place, say-put tactic or stay-in-place concept building occupants that are directly in danger evacuate the fire compartment, while the other building occupants stay inside their fire compartment. In buildings that use defend-in-place, building occupants should stay inside their compartment and wait for rescuers. The stay-put tactic or stay-in-place concept is mostly used in buildings with a residential or hotel function. For less reliant or not self-reliant people this strategy can be beneficial since these people need assistance in case of an emergency. There are several case studies that support this strategy, while there are other case studies that do not. Arewa et al. [90] conducted research in the application of the stay-put tactic and pointed out that there is a difference in opinion between firefighters and building occupant. They concluded that building occupants find the stay-put tactic a misjudgment, while firefighters find the stay-put tactic a good solution. The fire fighters do have the opinion that it is dependent on building characteristics, people characteristics and fire characteristics.

Delayed evacuation/progressive evacuation

A delayed/progressive evacuation strategy is the same as a phased evacuation, except that the building occupants evacuate to a safe area within the building. The building occupants can remain in the safe area until the fire has been extinguished or they evacuate to another safe area within the building [91] or to a safe location outside the building [63]. In high-rise buildings refuge floors are mostly used as safe areas within the building. Refuge floors for delayed evacuation are mandatory in Hong Kong according to the Hong Kong Building Department [49].

4. Risk-based approach

In a performance-based design, two options are available: 1. complying to pre-accepted solution, 2. by means of analyses and/or calculations which document that the fire safety level is satisfactory. Verification is a key component in a performance-based code. In order to comply to pre-accepted solutions, the designer verifies that the building has been built according to the specifications of the pre-accepted solution. When a designer performs analyses and/or calculations, the designer uses tools to show that the proposed design solutions have a fire safety level that complies with the formulated performance requirements of the building code [35].

The Besluit Bouwwerken Leefomgeving has both pre-accepted solutions and performance requirements. However, these performance requirements are formulated for buildings between -8 to 70 m and for buildings between 70 and 200 m in the directed SBRCURnet publication. Most of the requirements set in the Besluit Bouwwerken Leefomgeving are pre-accepted requirements which designers need to comply to. In order to design a super-tall building between 200 and 400 meters the pre-accepted solutions can be translated into risk factors. These risk factors can then be used as a baseline to calculate the risk factors of a super-tall building.

4.1 Objectives in a performance-based approach

Performance requirements set in the BBL are categorized per building feature and in the order of the fire development: structural fire safety, preventing ignition, controlling fire growth, control smoke and fire spread within the building and control fire spread to other buildings, means of escape and means of attack.

4.1.1 Limiting the probability of fire ignition

A building is designed in such a way that the ignition of a fire is sufficiently limited. The term 'sufficient' depends on the surface materials used in specific aspect of the building. The BBL states fire rating classification for building materials for specific aspects of the building and are dependent on heat flux, temperature and surface area/size.

The probability of fire according to Dutch statistics as shown in paragraph 3.1 is higher than the probability of fire according to the Eurocode. The probability of fire according to the Eurocode is based on the building area, building function, active fire repression systems and the consequence classes. Because the Dutch national building code BBL is based on the Eurocode, the probability of fire used in the Eurocode is used in this research. The probability of fire in a compartment is related to building function and floor area of that compartment. There is no significant difference between low-rise and high-rise buildings.

4.1.2 Limiting the development of fire and smoke

A building is designed in such a way that the development of fire and smoke is minimized. The development of fire and smoke is minimized by using materials with a fire rating classification and a smoke rating classification. The applied fire and smoke rated materials are dependent on the surface area and height of the building.

4.1.3 Limiting the spread of fire and smoke

A building is designed in such a way that the spread of fire to neighboring plots is sufficiently limited and that the spread of fire does not cause danger to the evacuation of building occupants or to the fire and rescue services. The BBL states that a building needs to be divided into fire compartments and that the sections between fire compartments have a resistance to fire propagation. The term 'sufficiently' depends on the building function, location and size of the fire compartments, fire load, the fire resistance of separation constructions to fire propagation through penetration and flashover and the resistance of materials to smoke propagation.

Spread of fire and/or smoke is possible via several connections, of which the façade is one of the possible ways fire and smoke can spread in a building. The spread of fire and smoke via the façade is not included in this research. However, a key point that needs to be mentioned is that the façade does not shortcut the fire compartment and the façade has no ignition sources. The façade is an adjoining external separation construction of the compartment and is therefore part of the risk-subsystem compartmentation.

4.1.4 Conservation of load bearing structure

The BBL states that a building shall be sufficient structurally safe and shall not collapse during evacuation of the building occupants and the attack/support of fire and rescue services. The term 'sufficient' depends on the building function, the building height and the fire load of the fire compartments. The structural safety is expressed in time and applies to low-rise buildings between -8 and 70 meters. Collapse is allowed in low-rise buildings but not before all building users have left the building. Super-tall buildings that might not be the case because the damage of a collapse can be much bigger.

4.1.5 Conservation of the escape routes

In a building the escape routes are designed in such a way that the building occupants can reach a safe haven in case of fire. In order for building occupants to reach a safe haven fire resistance of the structural components, fire and smoke resistance of separations constructions of the escape routes and classification of building materials as stated in the previous paragraphs are needed. The maximum length of the escape routes in fire compartments is dependent on the building function and the occupancy rate. The BBL states that the capacity of escape routes is sufficient enough for building occupants to reach a safe haven. Functional requirements are stated for the height and width of the escape routes and for the flow rates trough or over escape route aspects.

4.1.6 Conservation of the attack routes

The attack routes in a building are designed in such a way that fire and rescue services can rescue building occupants and fight the fire for a reasonable time. The attack routes used by the fire and rescue services are the same as the escape routes used by the building occupants. Therefore, the requirements mentioned in the previous paragraph also apply to the attack routes. Additionally, the BBL states the availability of a firefighting elevator and the length of the attack route. The conservation of the attack routes is not part of the public law and can therefor be left out of a quantitative assessment.

4.2 Design alternatives

In a prescriptive based building code, the buildings are designed according to the prescribed solutions, in a building code which has is both prescriptive and performance-based, a mixture of prescribed solutions and solutions derived from analytical methods are used. In most building designs the prescribed solutions are used as a starting point. When these solutions do not fit the building design or conflict with other design objects, an analytical method for alternative design solutions is used. To verify the design alternatives Nystedt [35] and Paté-Cornell [42] mentioned three possible assessment methods: a qualitative risk assessment, a quantitative assessment with deterministic analysis and a quantitative assessment with probabilistic analysis.

A qualitative risk assessment can only be applicated when the design alternatives are limited when compared to the prescriptive design. In order to use a qualitative risk assessment, the proposed design solutions need to be well documented. Test results, research publications and relevant regulations in other countries can be used to substantiate the proposed design solutions. For design solutions that deviate too much from the prescriptive design, "evidence" of equivalent safety must be presented by the engineer. This can be done by a deterministic or probabilistic quantitative assessment. The use of a deterministic or a probabilistic analysis is not related to the needs of verification, but it depends on the degree of conservatism that the designer is allowed to have in order to verify a sufficient level of safety [35].

4.2.1 Qualitative risk assessment

In a qualitative risk assessment, the initial risk is identified and design solutions are presented in order to cope with the risk. The design solutions used in a qualitative risk assessment are logic reasoning, statistics, experience and results from testing [35]. Design solutions can also be presented by making a comparison with building regulations in other countries. Although testing is a quantification of the performance of a system, test results and the comparison of test results is a qualitative approach because the results can comply with the relevant requirements. Testing can be useful when calculation methods are not suited to evaluate the performance of a safety system.

4.2.2 Quantitative assessment with deterministic analysis

When a proposed design deviated too much from the prescriptive solutions a qualitative risk assessment cannot be used and then a quantitative risk assessment with a deterministic analysis can be used. A deterministic analysis in a quantitative assessment is generally more conservative than a probabilistic analysis in a quantitative assessment. In a deterministic analysis, criteria for a number of pre-defined fire scenarios need to be met to show a sufficient level of safety. In a pre-defined fire scenario, a sequence of possible events and set of conditions that describe the fire development and the spread of combustible products are defined. The outcome pre-defined fire scenarios of the proposed design are compared to the acceptance criteria. The fire scenarios used to substantiate the design are dependent on the building use and can be adapted to the building. The risk assessment can be made by comparing the design of the proposed building with a reference building that is design according to the prescriptive design solutions. An example of this analysis is an ASET-RSET analysis for building evacuation or an AST-RST analysis for load-bearing structures and fires spread/compartmentation.

4.2.3 Quantitative assessment with probabilistic analysis

It is not possible to evaluate the overall performances of a safety barrier using a deterministic analysis. In order to evaluate the overall performance a probabilistic analysis can be used. In a probabilistic analysis a risk analysis technique, such as an event tree analysis or a sensitivity analysis, are used to provide the designer with information about the importance, probability and consequence of different scenarios.

The scenarios used in a probabilistic analysis and in a deterministic analysis are practically the same, resulting in a strong link between the two analyses. In a probabilistic analysis the risk can be quantified by calculating and comparing different measures of risk. The fire safety measures used in a building can be adapted based on this quantification.

Where a deterministic analysis can be too conservative because of its weaknesses, a probabilistic analysis can offer realistic scenarios. The relationship between different scenarios and the probability and consequences of these scenarios can be evaluated in a probabilistic analysis but cannot be evaluated in a deterministic analysis. Therefor the probabilistic analysis can provide a better understanding of the possible scenarios and the relative importance of those scenarios.

The four steps used in a quantitative assessment with probabilistic analysis are: structure, estimate consequences, estimate and evaluate risk and document.

The data used in the different scenarios of a probabilistic analysis, should be reliable data. This data should be based on statistics or by engineering judgement. With the probability data, the probability of each scenario can be calculated. The evaluation of the calculated risk is done comparing performance criteria. The calculated risks of the proposed design are compared with the calculated risk of a reference building. This reference building is designed according to the prescriptive requirements. The individual risk, the risk profile and the average risk are suitable risk measures in a comparison.

4.3 Performance criteria

Performance criteria can be divided into two different sets that could be used to verify that the proposed design has a sufficient safety level. The two sets of performance criteria are:

- Absolute criteria
- Comparative criteria

Absolute criteria
The designer of a building can choose to verify the fire safety of a building with absolute criteria. Some examples of absolute criteria for fire safety of a building are: untenable conditions for life-safety purposes or limit states for fire spread.

Comparative criteria
When absolute criteria are not provided in a building code, a designer can choose to use comparative criteria in order to verify the fire safety of a building. The proposed design is compared to a design based on the prescriptive design solutions. In order to use this method, the proposed design of the building must be as much similar to the reference building as possible. A comparison with the absolute criteria, for instance on life-safety or fire spread, is not needed. The design is considered safe if the proposed design performs at least better than the reference building with the pre-accepted solutions.

4.4 Risk based assessment criteria

In quantitative assessment quantitative assessment criteria are needed. For each of the performance objectives/risk subsystems mentioned in paragraph 4.1 an AST-RST analysis can be made. Internationally risk-based assessment criteria are mentioned in the BBRAD [92] and the FED (fractional effective dose) values can be used as criteria. Assessment criteria mentioned in the BBRAD are visibility and temperature criteria. Personal safety can be assessed by different criteria. According to the SFPE Handbook of Fire Protection Engineering there are carbon monoxide concentrations, hydrogen cyanide concentrations, carbon dioxide concentrations, oxygen concentrations, indirect radiant heat flux to subject, air temperature, smoke optical density (and particulate concentration), irritant acid gas concentrations and concentrations of organic irritant species [93].

Risk based assessment criteria are not mentioned in BBL or any other Dutch Legislation, however the NIPV [18] recently (2022) published a report about smoke propagation and personal safety, in which a risk-based assessment is used in order to assess the personal safety of building occupants. Risk based assessment criteria for the evacuation concepts are mentioned for self reliant building occupants:

- FED_{IN} 0.3
- FED_{heat} 0.3
- FEC_{smoke} 1

The FED values mentioned in the NIPV report can be used in an ASET analysis for personal safety: risk sub system conservation of the escape route. As mentioned before an ASET analysis for personal safety can also be made based on the visibility and the temperature. The visibility is related to the amount of (toxic) particles in the air and can therefore be used a a criteria. The toxicity of smoke becomes insignificant when the visibility in a compartment is more than 5 meters [94]. In order for residents to stay-in-place during a fire in an adjacent compartment, the temperature cannot exceed 70°C. These values are used in this research to evaluate the level of personal safety.

For the other risk subsystems, the AST-RST is based on different values. For the conservation of the building the AST-RST analysis is based on the R-criterium for load bearing structures, according to the EN 13501-2 [95]. The AST-RST analysis for the fire-resistant separation constructions is based on the EIW criteria, which is also according to the NEN-EN 13501-2 [95].

5. Quantitative assessment of fire safety

The fire safety level of the low-rise building and the super tall building is assessed with a quantitative assessment with a probabilistic analysis and is presented in risk factors. The risk factors for the low-rise residential reference building are calculated by using the minimum requirements directed in the Dutch National building code. The goal is to obtain risk factors for fire safety of a buildings designed according to the BBL. The risk factors for the super-tall residential building are calculated by using the same scenario's as for the low-rise residential reference building. The goal is to obtain comparable risk factors for fire safety of a super-tall buildings as for a low-rise building designed according to the BBL.

The available data is the requirements set in the BBL, the design of the building, the design lifetime, ignition probability and the Eurocode classification.

5.1 Set-up

In order to calculate the risk factors of the low-rise residential reference building and the super-tall residential building a sensitivity analysis has been performed. A sensitivity analysis can be defined as the study of how uncertainty in the outcome of numerical simulations can be attributed to different sources of uncertainty in the model input parameters. The uncertainty of parameters can be investigated by doing a sensitivity analysis. The effect of change in one parameter on the outcome of the numerical simulation is examined by performing the sensitivity analysis. The method for performing a quantitative sensitivity analysis is based on earlier research carried by Van Herpen et. al [30] and by the NIPV [92].

The first part of the sensitivity analysis is the determination of the RST and AST for the risk subsystems that are affected by the thermal load and thermal/mechanical response. The RST is determined by the thermal load, based on the building characteristics and fuel characteristics, as shown in Appendix 3. The AST is determined based on the fire resistance of the separation construction and the load bearing structure. The first part of the analysis is performed for an average compartment in the low-rise residential reference building and for the low-rise residential reference building.

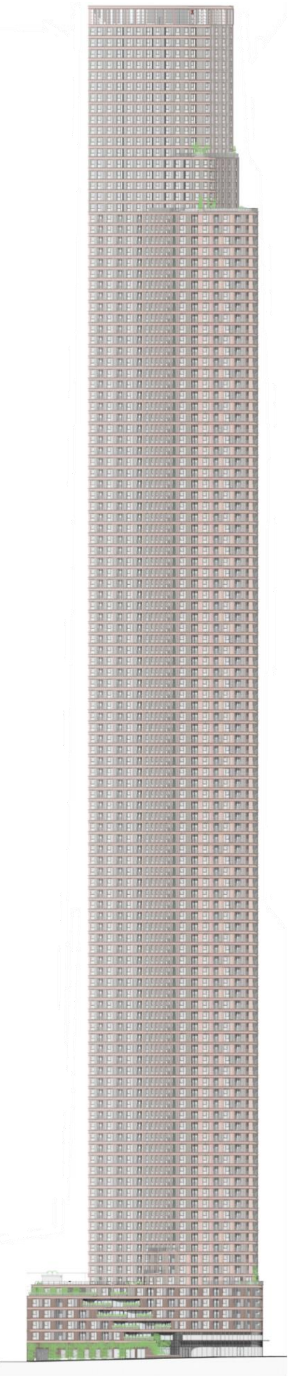

Figure 5-1. Design of the low-rise residential reference building (l) and the super-tall residential building (r).

The second part of the sensitivity analysis is the determination of the RSET and ASET for the risk subsystems that are affected by acceptable conditions for building occupants. The RSET is determined by the required time to evacuate room and human characteristics. The ASET is determined based on building characteristics and fire characteristics, as shown in Appendix 3. Computational models.

The second part of the sensitivity analysis is performed for the following compartments:

- The adjacent apartments
- The apartment above
- The adjacent corridors
- The stairway lobbies
- The stairways
- The elevator lobbies
- The elevator shafts

All other input parameters for the low-rise residential reference building are shown in Appendix 8. OZone input and in Appendix 9. Low-rise residential reference building model, CFAST input. The complete sensitivity analysis is included in Appendix 10. Probabilistic approach low-rise residential reference building. The input parameters for the super-tall residential building are shown in Appendix 8. OZone input and Appendix 11. Super-tall residential building model, CFAST input. The complete sensitivity analysis is included in Appendix 12. Probabilistic approach super-tall residential building.

In order to analyze the effect of the suppression system (automatic suppression system like sprinkler protection) and of the pressurization system on the ASET in the super tall residential building an analysis has been made based on the base-model used for the simulations of the super tall building. An overview is shown in Table 5-1. As mentioned in paragraph 2.4 the automatic sprinkler system used in the super-tall study simulations is a quick response sprinkler with a response time index (RTI) of 50 $(m*s)^{1/2}$ and an actuation temperature of 68°C and the pressurization system used in the super-tall study simulations is a stairway lobby pressurization system in which fresh air is supplied via a shaft with an airspeed of 2 m/s over each door with a maximum pressure of 50 Pa in case of closed doors.

Table 5-1. List of performed AS(E)T analysis.

Simulation	Variation of building services
1	Suppression + pressurization
2	Suppression
3	Pressurization
4	Neither

5.2 Quantitative sensitivity analysis

The quantitative sensitivity analysis is performed based on the stochastic boundary conditions mentioned in Table 2-1. These boundary conditions are different for the thermal load on the building structure and separation constructions and for personal safety. Stochastic boundary conditions are boundary conditions with an uncertainty or bandwidth around a mean value. These stochastic boundary conditions are part of the fire and fuel characteristics. The uncertainties of the stochastic boundary conditions depend on the materials, constructions and quality of the building constructions.

In the sensitivity analyses each stochastic boundary conditions is varied separately. The simulations are performed for each variation in the stochastic boundary conditions, the average value is replaced with the average value + standard deviation (AVG+SD) and with the average value - standard deviation (AVG-SD). Variations in the stochastic boundary conditions result in variations of the simulation results. This is repeated for all stochastic boundary conditions. With the results of the simulations a probability distribution can be determined. The stochastic boundary conditions used in this research are shown in Table 2-1.

For each stochastic boundary condition in Table 2-1 the following conditions apply for each boundary condition (x_i):

- Average value (AVG): $\bar{x}_i$
- Variation coefficient: V_i
- Standard deviation: $s_i = V_i \cdot \bar{x}_i$
- Variation: dx_i

The variation coefficient is the standard deviation at an average value of 1. In the sensitivity analysis each stochastic boundary condition is separately interchanged with its standard deviations: $dx_i = s_i$ or $dx_i = -s_i$. The impact of the outcome is of the AST-RST (t) sensitivity analysis depends on the following conditions:

- Variation: dt
- Specific variation: dt/dx_i
- Specific variance: $(s_i\ dt/dx_i)^2$

The total variance is the sum of each specific variance and can be derived with the following formula:

- Total variance: $var = \sum_i (s_i\ dt/dx_i)^2$
- Standard deviation (SD): $= \sqrt{var}$

With the total variance the standard deviation can be calculated. The standard deviation is used the determine the (cumulative) probability of AST-RST. The cumulative probability of AST-RST has an average value (AVG) and a standard deviation (SD). The sensitivity analysis results in an average value of RST for thermal load on the building structure or AST for personal safety and the corresponding standard deviations.

The thermal load on the building structure (RST) can be compared with the fire resistance of the building structure (AST) in order to determine the cumulative probability of the load bearing structure or the compartment separation construction. For personal safety a similar comparison can be made. The acceptable safe time (AST) is compared with the required safe time (RST) in order to determined the cumulative probability of personal safety.

5.3 Results

The results of the simulations for the low-rise residential reference building and the super-tall residential building are shown in the paragraphs below and are compared for each risk-subsystem. An AS(E)T-RS(E)T analyses has been made for each risk-subsystem based on a natural fire scenario and the consequences for the risk-subsystems are expressed in failure probabilities and corresponding reliability. Average statistical values of project specific quantities have been used in the calculations and in the sensitivity analyses, the results for each individual simulation is shown in Appendix 10. Probabilistic approach low-rise residential reference building and in Appendix 12. Probabilistic approach super-tall residential building.

5.3.1 Limiting the probability of fire ignition

According to the Eurocode, the probability of fire ignition is dependent on the size of the building and the life cycle of the building, as can be seen in paragraph 5.3.4 and Table 5-5 and Table 5-6.

Low-rise residential reference building

The probability of fire ignition for the low-rise residential building is 1.00E-05 /m^2/50 years. The probability of fire ignition can change based on the size of the building or based in the lifecycle of the building. By increasing the size of the building, the probability of fire ignition increases or decreases by the same factor. Because the low-rise residential reference building is smaller than 70 meters and has more than 4 floors, the building has a reliability class RC2/ a consequence class CC2. The reliability index for that class is 3.8, which takes into account the accepted or assumed statistical variability of resistances and load effects and modeling uncertainties [96]. For the low-rise residential reference building with a floor area of 17.590 m^2 the probability of fire ignition during a lifecycle of 50 years is 1.76E-01. The probability of fire ignition based on the compartment size is 4.38E-04 for a compartment size of 43.82.

Super-tall residential building

The probability of fire ignition for the super-tall residential building is 2.00E-05 /m^2/100 years. By increasing the size of the building the probability of fire ignition is also increased, as can be seen in Table 5-6. By increasing the life cycle of the building by a factor 2, from 50 to 100 years, the probability of fire ignition during the lifetime of the building also increases by a factor 2. Because the super-tall building is taller than 70 meters, the building has a reliability class RC3/ a consequence class CC3. The reliability index for that class is 4.3, which takes into account the accepted or assumed statistical variability of resistances and load effects and modeling uncertainties [96]. For the super-tall residential building with a floor area of 140,577 m^2 the probability of fire ignition during a lifecycle of 100 years is 2.81E+00. This means that based on the statistics, 3 fires would happen during the 100-year lifecycle. The probability of fire ignition based on the compartment is 8.76E-04 for a compartment size of 43.82.

Evaluation

As mentioned in paragraph 5.3.1, the probability of fire ignition dependent on the size of the building and the lifecycle of the building. The low-rise residential reference building has a probability of fire ignition over 1.76E-01. By increasing the size by a factor 8 and the life cycle of the building by a factor 2 the probability of fire ignition in the super-tall building is increased to 2.81E+00.

The probability of fire ignition based on the compartment size is increased by a factor 2. The size of the compartment does not change, but the life cycle of the compartment does by a factor 2. Resulting in an increase from 4.38E-04 to 8.76E-04.

5.3.2 Limiting the development of fire and smoke

Limiting development of fire and smoke is based on building characteristic and is done by regulating the permanent fire load and the fire ratings of building materials as well as by regulating the airflow in and out of the fire compartment. The permanent fire load in a building or in a fire compartment consists of the fixed building materials, such as walls, floors and ceilings. Interior design such as furniture and appliances in a building or fire compartment are part of the variable fire load. This fire load is different for each building function and can be different for each building occupant. General values for the fire load density are stated in the NEN 6060 and in the NEN 6090. The growth of a fire can be limited by applying a sprinkler system or by applying fire resistant glass in the façade. By using fire resistant glass instead of regular glass, the façade will not break and no extra air will be supplied to the fire.

Low-rise residential reference building

The development of fire and smoke in the low-rise residential reference building is limited by complying to the requirements set in chapter 4, section 4.2 of the BBL. Other options to limit the development of fire and smoke such as a suppression system are not applied in the low-rise residential reference building. The development of the fire is limited to almost 11,000 kW, as shown in Figure 5-2. The fire is self extinguished after 3960 seconds (66 minutes).

Figure 5-2. Heat release rate of a fire in a compartment of the low-rise residential reference building.

Super-tall residential building

As mentioned in paragraph 2.4, the suppression system used in the super-tall study simulations is a sprinkler based on the computer model DETACT [26]. The pressurization system used in the super-tall study simulations is a stairway lobby pressurization system in which fresh air is supplied via a shaft. The pressurization system is conform NEN-EN 12101-6:2022 [27], there will be an airspeed of 2 m/s over each door. The development of fire and smoke is limited when the automatic sprinkler system is activated, as shown in Appendix 4. Sprinkler activation DETACT and in Figure 5-3. The automatic sprinkler system is activated after 188 seconds after when the actuation temperature has reached 68°C and after a response time index of 50 $(m*s)^{1/2}$. The development of the fire is limited to a heat release rate of 360 kW in both the defined fire and in the calculated fire, as shown in Figure 5-3 and Figure 5-4. Just as in the low-rise residential building the fire is extinguished after 3,960 seconds (66 minutes).

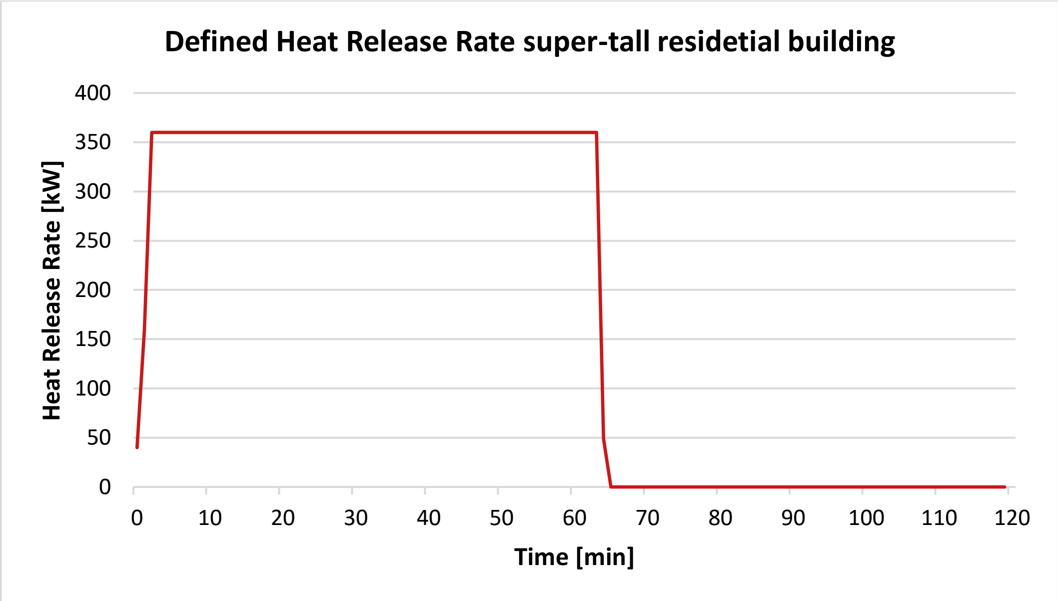

Figure 5-3. Defined Heat Release Rate in a sprinklered compartment of the super-tall residential building.

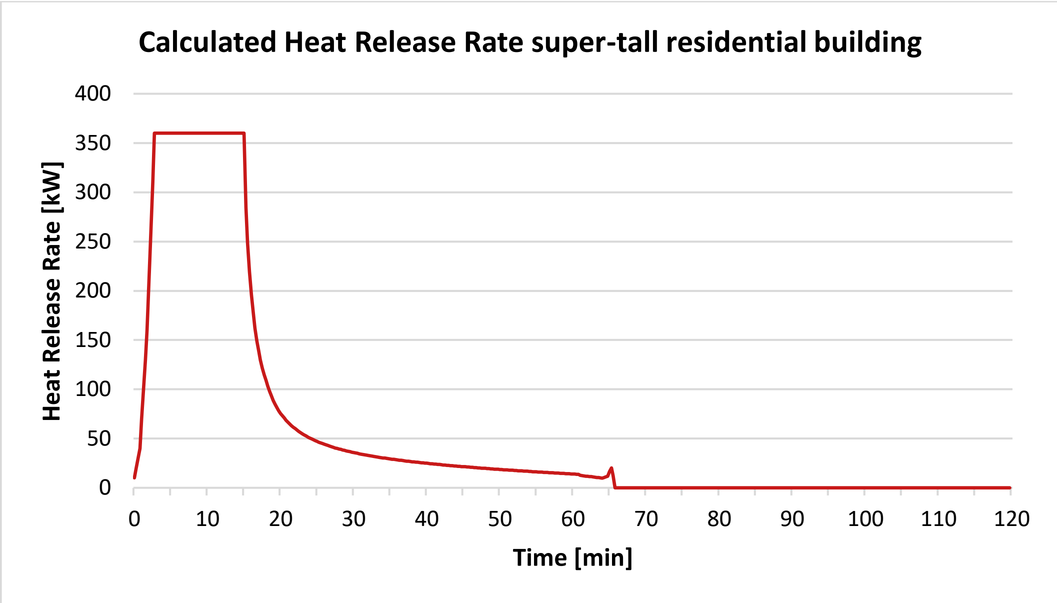

Figure 5-4. Calculated Heat Release Rate in a sprinklered compartment of the super-tall residential building.

However, by applying an automatic suppression system the soot production by the fire is increase, as shown in Figure 2-5. As a result applying an automatic suppression system the lack of oxygen in the room decreases the Heat Release Rate of the fire after 900 seconds, as shown in Figure 5-4. This scenario could also occur in a situation where the automatic suppression system completely extinguishes the fire.

Evaluation
Limiting the development of fire and smoke has been analyzed for a the low-rise residential reference building and the super-tall residential building. In both buildings a fire compartment with the same size has been simulated.

Limiting the development of fire in the low-rise residential reference building has been done by applying the requirements set in chapter 4, section 4.2 of the BBL. The natural fire in a compartment of the low-rise residential reference building is developed to a heat release rate of 10,954 kW. The fire scenario in the low-rise residential reference building is 3,960 seconds (66 minutes).

In the super-tall residential building however, an automatic suppression system has been applied, limiting the development of the natural fire to 360 kW. The applied automatic suppression system is limiting the development of fire but increases the development of smoke. The fire scenario in the super-tall residential building is 3,960 seconds (66 minutes). The duration of the fire in the super-tall residential building is an assumption that is determined with the DETACT calculation sheet and may differ in reality.

5.3.3 Limiting the spread of fire and smoke

Limiting spread of fire and smoke is based on building characteristic and is done by using fire resistant and smoke resistant compartments in the building. Fire resistance of the compartmentation is expressed in minutes. According to the BBL the fire resistance of the compartmentation needs to be 30 minutes towards escape routes and 60 minutes towards other compartments. The smoke resistance of the compartmentation is express is the classes Ra or R200. The smoke classes are expressed as internal airtightness in the simulations and have an equivalent surface are through which smoke and air propagates.

5.3.3.1 Limiting the spread of fire

In order to determine the reliability of the separation construction to limit the spread of fire towards adjacent compartments and towards the adjacent corridor, the equivalent fire duration (in minutes standard fire curve) of the natural fire has been evaluated. The fire duration of the natural fire is 51 minutes, as shown in Figure 5-5. The available safe time for which the escape route needs to be available is 30 minutes according to the BBL.

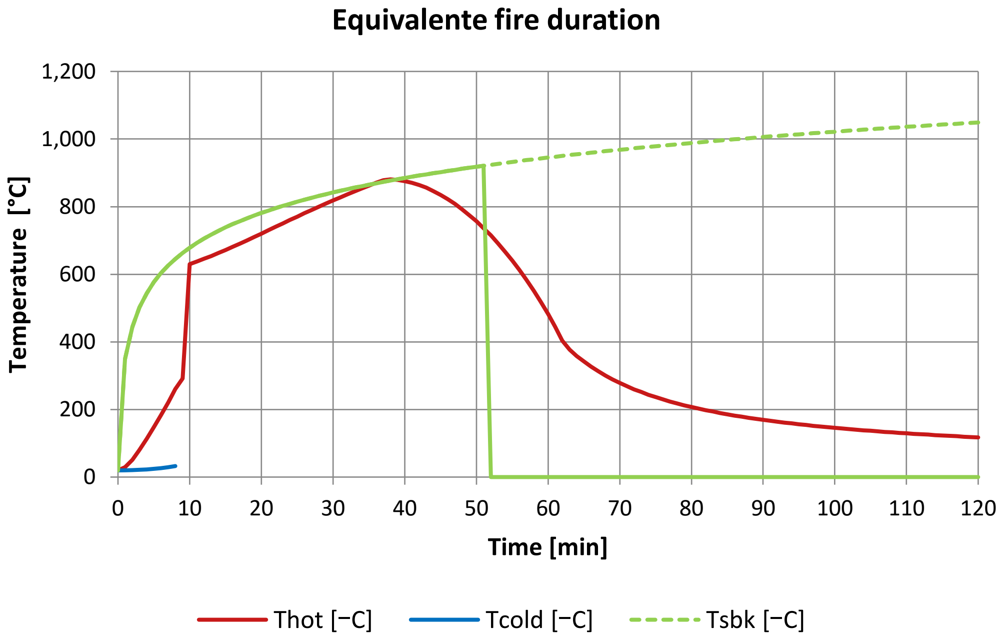

Figure 5-5. Equivalent fire duration for the low-rise residential reference building and the super-tall residential building.

Low-rise residential reference building

In the low-rise residential reference building uses an evacuation concept as directed in the BBL. The available same time for the low-rise residential reference building would be 30 minutes as set in the BBL. The fire duration of the natural fire is the required safe time (RST) in minutes standard fire curve. An AST-RST analysis would leave a margin of -21 minutes: AST – RST = 30 – 51 = -21 minutes standard fire curve. Therefor the available safe time has been set to 60 minutes for this project. With an available safe time of 60 minutes the margin would be 9 minutes: AST – RST = 60 – 51 = 9 minutes standard fire curve.

With a sensitivity analysis the reliability of the separation constructions between apartments and between apartment and escape route has been determined based on the stochastic variables, as shown in section 2.3. the results of the sensitivity analysis are shown in Appendix 10. Probabilistic approach low-rise residential reference building. The results of the sensitivity analysis is an average thermal load on the separation construction is 51 minutes standard fire curve, with a standard deviation of +17.9 and -14.5 minutes standard fire curve. The cumulative probability of this distribution is shown in Figure 5-6.

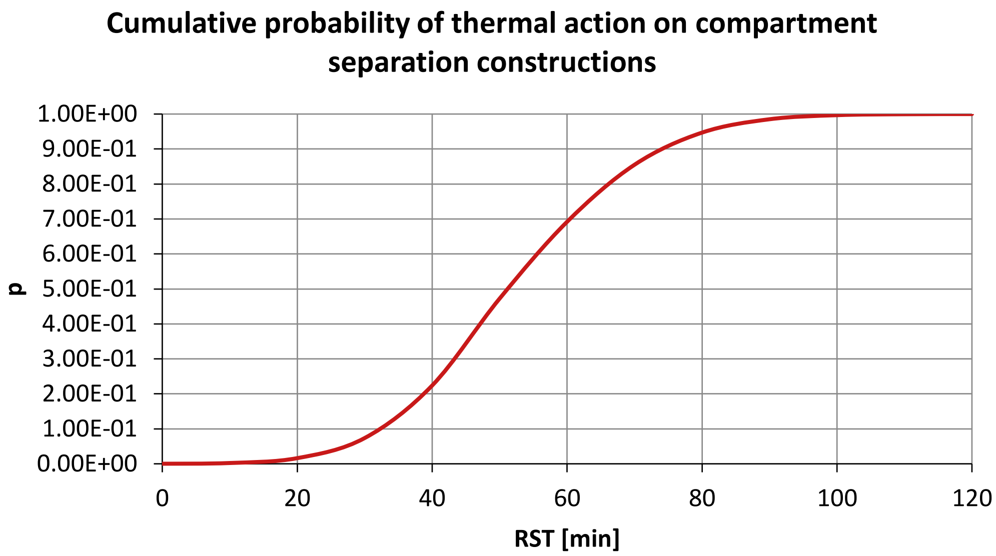

Figure 5-6. Cumulative probability of thermal action on compartment separation constructions.

With a 60 minutes fire resistant separation construction the probability of a safe evacuation is 69%. This means a reliability of 69% for a safe evacuation based on the thermal load on the separation construction and the building structure at a required safe time of 60 minutes.

Super-tall residential building

In the super-tall residential building an evacuation concept as used in the low-rese residential reference building would take longer than the equivalent fire duration (in minutes standard fire curve) of the natural fire. Just as in the low-rise residential reference building the fire duration of the natural fire is the required safe time (RST) in minutes standard fire curve. The available safe time in the super-tall residential building has been set to 60 minutes for this project. With an available safe time of 60 minutes the margin would be 9 minutes: AST – RST = 60 – 51 = 9 minutes standard fire curve.

With a sensitivity analysis the reliability of the separation constructions between apartments and between apartment and escape route has been determined based on the stochastic variables, as shown in section 2.3. the results of the sensitivity analysis are shown in Appendix 12. Probabilistic approach super-tall residential building. because the compartmentation in both the low-rise residential reference building ans the super-tall residential building are the same, the results of the sensitivity analysis of the average thermal load on the separation construction is the same. The results of the sensitivity analysis is an average thermal load on the separation construction is 51 minutes standard fire curve, with a standard deviation of +17.9 and -14.5 minutes standard fire curve. The cumulative probability of this distribution is shown in Figure 5-6.

With a 60 minutes fire resistant separation construction the probability of a safe evacuation is 69%. This means a reliability of 69% for a safe evacuation based on the thermal load on the separation construction and the building structure at a required safe time of 60 minutes.

Evaluation

The results of the sensitivity analyses for the low-rise residential residence building show that the requirement for the available safe time as set in the BBL is not sufficient enough for the natural fire concept. The equivalent fire duration is 51 minutes standard fire curve for both the low-rise residential building as the super-tall residential building. Therefor the available safe time has been set to 60 minutes. The reliability of 60 minute fire resistant separation constructions is 69% in the low-rise residential building. The spread of fire from compartment to compartment in the super-tall residential building without a suppression system is the same as in the low-rise residential reference building. Adding an automatic suppression system, like a sprinkler system, is a redundant system and the compartmentation should individually still work the same as with or without a suppression system. Therefore a worst-case scenario in which the sprinkler system fails has been simulated of the super-tall residential building.

The reliability of the fire resistant separation constructions in the super-tall residential building is also 69%. Because the evacuation time in the super-tall building is longer than the equivalent fire duration, the reliability of the separation constructions needs to be improved or a larger safe distance between the fire and the escape routes needs to be created. As shown in section 5.2.5 the evacuation time of a total evacuation in the super-tall residential building would take 87 minutes. Based on the performed scenarios the reliability of the fire resistance of the separation const can be improved to 99% when the separation construction is fire resistant for at least 90 minutes.

5.3.3.2 Limiting the spread of smoke

The spread of smoke is limited by using smoke resistant compartmentations in the building. Each apartment in low-rise residential reference building and in the super-tall residential building is a separate smoke compartment with a smoke resistance class of Ra between the apartments and a smoke resistance class R200 between the apartments and the corridors. The smoke resistance classes in the simulation are expressed as the internal airtightness.

Low-rise residential reference building

The cumulative probability for smoke spread towards adjacent compartments for an average compartment of 43.82 m^2 in the low-rise residential building is shown in Figure 5-7. Within 5 minutes the spread of smoke towards the adjacent compartments has reached the limit for optical density. The probability of an available safe time that exceeds 4 minutes in the adjacent compartments is almost 0. The reliability depends on the RST, if the RST is longer than the AST the reliability is almost 0. In this case the RST is longer than 5 minutes and therefore the adjacent compartments are no longer safe after 5 minutes for building occupant to stay in because the reliability of the compartments is almost 0% at that time. The probability of smoke spread towards the adjacent compartment after 5 minutes is almost 1.

Table 5-2. Average AST in the adjacent apartments.

		AST [min]		
	Floor	average	SD	
11.07	11	2.75	-0.50	0.25
11.09	11	2.75	-0.50	0.50
12.08	12	1.5	-0.56	0.25

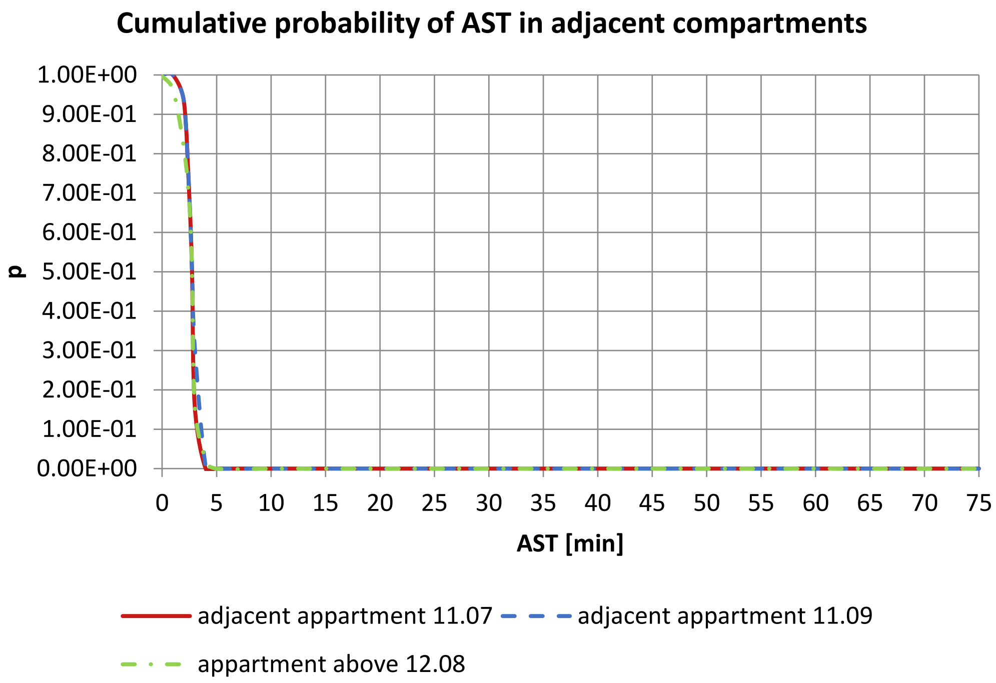

Figure 5-7. Cumulative probability of AST in adjacent compartments.

Super-tall residential building

The cumulative probability for smoke spread towards adjacent compartments for an average compartment of 43.82 m^2 in the super-tall residential building is shown in Figure 5-8. Within 3 minutes the spread of smoke towards the adjacent compartments on the same floor and the floor above has reached the limit for optical density. The cumulative probability of an available safe time that exceeds 3 minutes in the adjacent compartments is almost 0. The reliability depends on the RST, if the RST is longer than the AST the reliability is almost 0. In this case the RST is longer than 3 minutes and therefore the adjacent compartments are no longer safe after 3 minutes for building occupant to stay in because the reliability of the compartments is almost 0% at that time. The limit for optical density in the adjacent compartment on the floor above (compartment 12.07) has also been determine in the super-tall residential building because that of the possible use of an evacuation concept with a refugee floor for which that compartment can be used. The limit for optical density in the adjacent compartment on the floor above (compartment 12.07) has been reached after 11 minutes. At 11 minutes the reliability of compartment 12.07 is 50%.

Table 5-3. Average AST in the adjacent compartments.

		AST [min]		
Compartment	**Floor**	**average**	**SD**	
11.07	11	2.50	-0.66	0.00
11.09	11	2.25	2.25	0.35
12.07	12	11.00	-4.92	154.17
12.08	12	1.00	-0.61	0.25

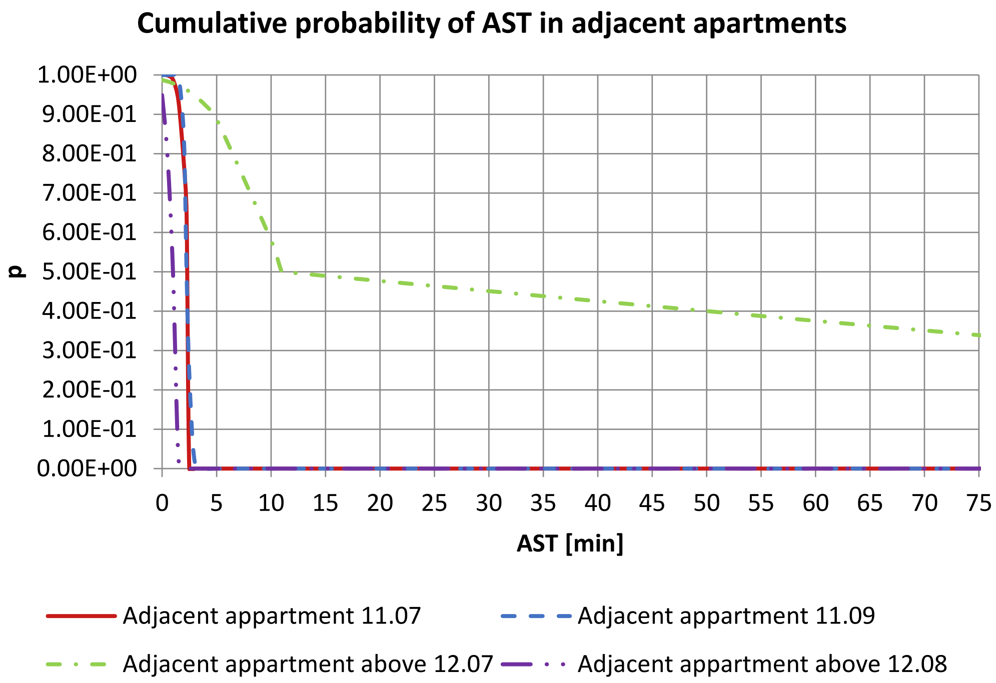

Figure 5-8. Cumulative probability of ASET in adjacent compartments.

The effect of the automatic suppression system and the pressurization system on the smoke propagation towards the adjacent compartments has been analyzed. An overview of the effect of a suppression system and or a pressurization system are shown in Table 5-4 and in Figure 5-9. Applying a suppression system and/or a pressurization system in the building has almost no effect on the ASET of the adjacent compartments on the same floor or on the compartment above. However, it does have a large effect on the adjacent compartment above. In the situation without an automatic suppression system and without a pressurization system the ASET in that compartment is 38.75 minutes, which is an improvement of approximately 350% in comparison to the standard situation. The effect of only applying an automatic suppression system or only a pressurization system is not significant for smoke propagation towards the adjacent compartments.

Table 5-4. Average AST overview of the effect of a suppression system and a pressurization system on the adjacent compartments.

Average AST overview of the adjacent compartments				
Compartment	**ASET variation depended on building services [min]**			
	Suppression + pressurization	**Suppression**	**Pressurization**	**Neither**
Adjacent compartment 11.07	2.50	2.25	2.75	2.75
Adjacent compartment 11.09	2.25	2.25	2.75	2.75
Adjacent compartment above 12.07	11.00	11.50	13.50	38.75
Compartment above 12.08	1.00	1.00	1.50	1.25

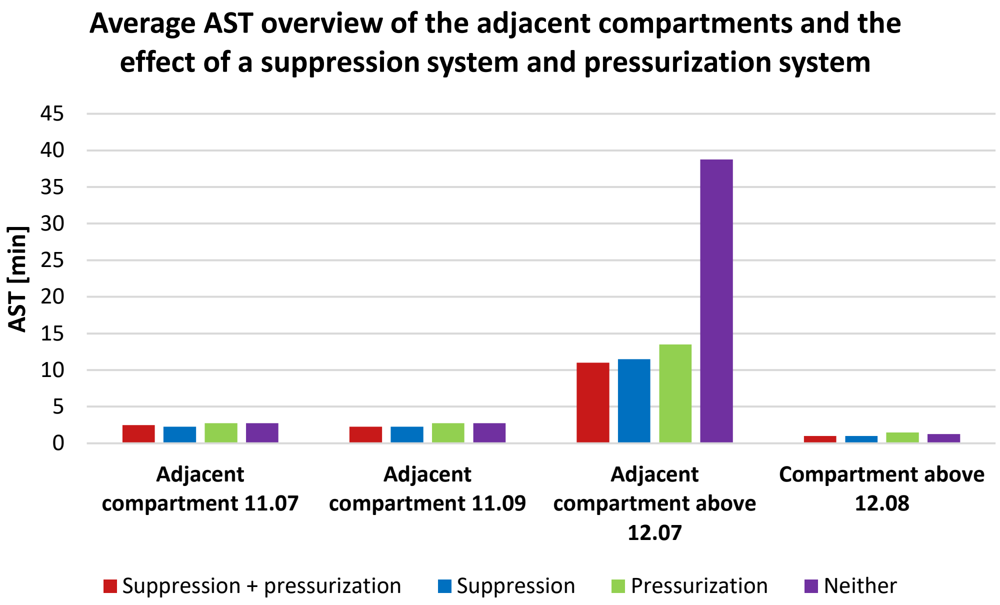

Figure 5-9. Average AST overview and the effect of a suppression system and a pressurization system on the adjacent compartment.

Evaluation

Based on the results of the spread of fire and smoke in the low-rise reference building, the spread of smoke is more important for personal safety than the spread of fire. The results of the simulations show that the spread of smoke is significantly faster than the spread of fire.

A full evacuation concept using stairs only is the standard for low-rise residential reference buildings. Based on the results of smoke spread towards adjacent compartments the reliability at 5 minutes is almost 0%. With an average AST of 2.75 minutes in the adjacent compartments and with an average of 1.5 minutes in the compartment above, the spread of smoke is very fast.

A full evacuation concept using stairs only is has been analyzed for the super-tall residential building. The reliability of the adjacent compartments at 5 minutes almost 0%, just as in the low-rise residential reference building. With an average AST of 2.25 and 2.50 minutes in the adjacent compartments and with an average of 1.5 minutes in the compartment above, the spread of smoke is even faster than in the low-rise residential reference building. The spread of smoke has been affected by the application of a suppression system and a pressurization system. The suppression system lowers the heat release rate of the fire but increases the production of smoke and toxic gasses. An increased production of smoke and the pressurization system installed in the escape routes increases the spread of smoke towards the adjacent compartments. By applying an automatic suppression system more smoke propagates towards adjacent compartments because there is no flash over. Applying only the automatic suppression system or the pressurization system or applying neither of the systems does not effect the AST of the adjacent compartments.

A full evacuation concept using stairs only is not recommended in super-tall buildings and other evacuation concepts such as a stay-in-place concept or a concept with refugee floors is more likely to be used. In case of a stay in place concept the reliability of the adjacent compartments and the compartments above at 60 or 90 minutes is 0% and should therefor be improved. When an evacuation concept with refugee floors is used, it is likely that the compartment above is not used as a refugee floor, but the adjacent compartment above could be used. The reliability of the adjacent compartment above is 35% at

60 minutes and 30 % at 90 minutes. The reliability of the adjacent compartment above would have to be improved when an evacuation concept using refugee floors is used in a super-tall residential building. The AST of the adjacent compartments does not change significantly when applying only one of the systems or neither of the systems. Applying neither of the systems does affect the AST of the adjacent compartment above positively. Increasing the AST form 11 minutes to 38.75 minutes.

The effect of wind on the building has not been considered. Wind pressure on the façade of a super-tall building can increase with the height of the building. The pressure created by the wind can influence the spread of fire and smoke by adding oxygen to the fire compartment through the equivalent surface area.

5.3.4 Conservation of load bearing structure

The conservation of the building can be calculated according to the Eurocode. The consequence classes stated in the Eurocode correspond with the use and the height of the building. For the low-rise reference building study, consequence class 2 (CC2) is used in order to calculate the failure probability and the reliability of the structural safety of the building. For the super-tall study, consequence class 3 (CC3) is used in order to calculate the cumulative probability and the reliability of the structural safety of the building. Consequence Class 3 is used for high-rise buildings taller than 70 m as defined in the BBL. In this calculation the usage area of the building, the design lifetime and the ignition probability are used to calculate the probability of fire and the reliability.

The cumulative probability calculated using the Eurocode needs to be compared with the sensitivity analyses based on a natural fire scenario. By varying each stochastic boundary condition, a standard deviation for each stochastic boundary condition can be determined. By combining the standard deviations, a standard deviation for the standard fire curve can be calculated. This standard deviation is used to calculate the reliability and the failure probability for that specific situation.

Low-rise residential reference building

In the low-rise residential reference building the cumulative probability calculated with consequence class 2 (CC2) of the Eurocode is shown in Table 5-5. With a sensitivity analysis the reliability of the load bearing structure has been determined based on the stochastic variables, as shown in section 2.3. the results of the sensitivity analysis are shown in Appendix 10. Probabilistic approach low-rise residential reference building. The available safe time for which the load bearing structure needs to be available is 120 minutes according to the BBL.

Table 5-5. Reliability of a low-rise building with a residential function calculated according to Eurocode NEN-EN 1990-2002.

Building area [m^2]	17,590
Design lifetime [yr.]	50
Ignition probability [1/m^2/1yr]	2.00E-07
Ignition probability [1/m^2/50yr]	1.00E-05 (during design lifetime)

Probability of fire p(fi)	1.76E-01 (during design lifetime)

EUROCODE	p(f)	p(f|fi)	beta(f|fi)
CC1: beta(f) > 3.3	4.83E-04	2.75E-03	2.78
CC2: beta(f) > 3.8	7.23E-05	4.11E-04	**3.35**
CC3: beta(f) > 4.3	8.54E-06	4.85E-05	3.90

The reliability index calculated using the Eurocode for a low-rise residential building with consequence class 2 is 3.35. the results of the sensitivity analysis shows that the reliability index at 120 minutes, as required by the BBL, is 3.845. Figure 5-10 shows that the cumulative probability of conservation of the building in case of fire with a 120 minutes fire resistant building structure is 100%. The reliability of a 120 minute fire resistant building structure for a low-rise building is 100%.

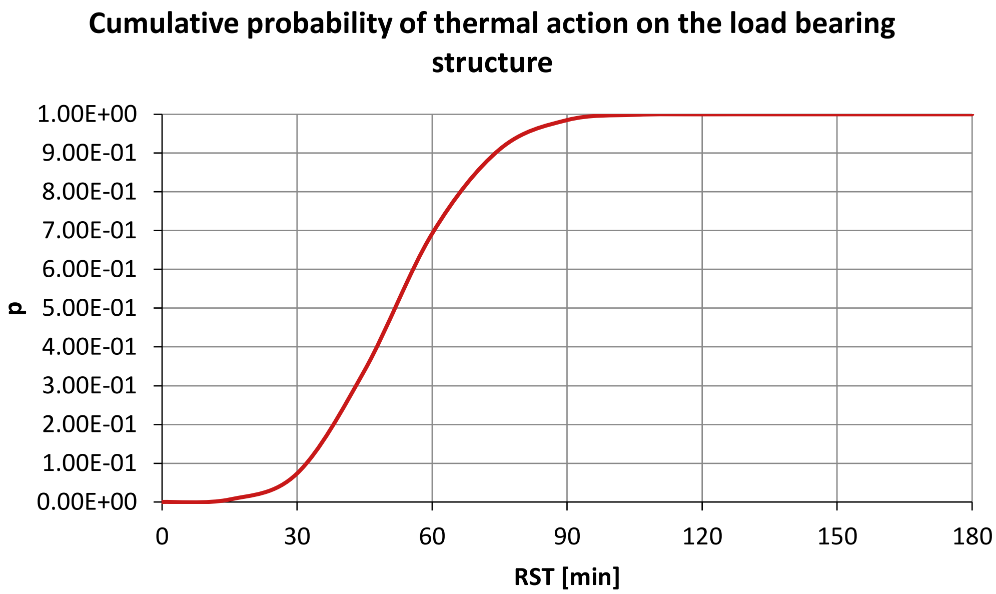

Figure 5-10. Cumulative probability of the thermal action on the load bearing structure.

Super-tall residential building

In the super-tall residential building the cumulative probability calculated with consequence class 3 (CC3) of the Eurocode is shown in Table 5-6. With a sensitivity analysis the reliability of the load bearing structure has been determined based on the stochastic variables, as shown in section 2.3. the results of the sensitivity analysis are shown in Appendix 12. Probabilistic approach super-tall residential building.

Table 5-6. Reliability of a building with a residential function calculated according to Eurocode NEN-EN 1990-2002.

Building area [m²]	140,577
Design lifetime [yr.]	100
Ignition probability [1/m²/1yr]	2.00E-07
Ignition probability [1/m²/100yr]	2.00E-05 (during design lifetime)

Probability of fire p(fi)	2.81E+00 (during design lifetime)

EUROCODE	**p(f)**	**p(f|fi)**	**beta(f|fi)**
CC1: beta(f) > 3.3	4.83E-04	1.72E-04	3.58
CC2: beta(f) > 3.8	7.23E-05	2.57E-05	4.05
CC3: beta(f) > 4.3	8.54E-06	3.04E-06	**4.52**

The reliability index calculated using the Eurocode for a super-tall residential building with consequence class 3 is 4.52. With the performed sensitivity analysis the corresponding fire resistance of the load bearing structure can be determined. At 135 minutes the reliability index is 4.681, which would be sufficient for a building with consequence class 3. A fire resistance of 135 minutes is only 15 minutes longer than the 120 minutes set as a requirement in the BBL for the conservation of the building. The cumulative probability as shown in Figure 5-10, is the same for the low-rise residential reference building as for the super-tall residential building because the fire compartmentations in both buildings are the same. Figure 5-10 shows that the cumulative probability of the conservation of the load bearing structure in case of fire with a 135 minutes fire resistant building structure is 100%. The reliability of a 135 minute fire resistant building structure for a super-tall residential building is 100%

Evaluation
For the low-rise residential reference building the load bearing elements should at least have a fire resistance of 120 minutes according to the BBL. According to the Eurocode the reliability index of consequence class 2 for the low-rise residential reference building is 3.35. This results in a fire resistance of 120 minutes for the load bearing structure according to the sensitivity analysis. The reliability of a 120 minutes fire resistant load bearing structure is 100% for the low-rise residential reference building.

In order to get the same level of fire safety in the super-tall residential building, a consequence class CC3 is required according to the Eurocode. The reliability index for the super-tall residential reference building is 4.52. This results in a fire resistance of 135 minutes for the load bearing structure when comparing the results of the sensitivity analysis and the Eurocode. This is an increase in fire resistance of 15 minutes for the building structure. The reliability of a 135 minutes fire resistant load bearing structure is 100% for the super-tall residential building.

Consequence class 3 of the Eurocode is based on an evacuation concept using full evacuation, as mentioned before full evacuation in a super-tall building is not recommended and concepts as the stay-in-place concept or an evacuation concept with refugee floors are more likely to be used. In these evacuation concepts building occupant do not evacuate the building and therefor consequence class 3 might not be sufficient anymore. A new consequence class could might be needed for those evacuation concepts in super-tall building or a safety factor could be applied. The safety factor should take into account the factor by which the lifecycle of the building has been increased and twice the factor by which the building area has been increased, since these factors increase the probability of fire ignition. The factor by which the building area has been increase should be taken into account twice. The reason for this is increase in the probability of fire and the increased in the effect of the fire. This would result in an reliability index of 5.46 and a fire resistance of 150 minutes.

5.3.5 Conservation of the escape routes
Conservation of the escape routes is based on building characteristic and is done by using fire resistant and smoke resistant compartments in the building. Fire resistance of the compartmentation is expressed in minutes. According to the BBL the fire resistance of the compartmentation needs to be 30 minutes towards escape routes. The smoke resistance of the compartmentation is express is the classes Ra or R200. The smoke classes are expressed as internal airtightness in the simulations and have an equivalent surface are through which smoke and air propagates.

The conservation of the escape routes is analyzed by performing an ASET-RSET analysis. The results of the sensitivity analyses are average values with standard deviations. Based on the average values and standard deviations the reliability of the conservation of the escape routes with cumulative probabilities is given.

Low-rise residential building
The spread of fire and smoke as mentioned in paragraph 5.3.3 also affects the conservation of the escape routes. Fire resistant wall of 60 minutes have a 31% chance to fail in the scenario of the low-rise residential reference building, as mentioned in paragraph 5.3.3.1. The required safe egress time (RSET) of a total evacuation of the low-rise residential reference building is calculated based on the SPFE handbook of fire protection engineering [21], as shown in equation (1).

$$RSET = t_d + t_n + t_{p\text{-}e} + t_e \qquad (1)$$

Where:

- t_d is the time from fire ignition to detection (detection phase)
- t_n is the time from detection to notification of the occupants of a fire emergency (notification phase)
- $t_{p\text{-}e}$ is the time from notification until evacuation commences (pre-evacuation phase)
- t_e is the time from the start of purposive evacuation movement until safety is reached (evacuation phase)

The REST of the low-rise residential reference building in this research is calculated based in the following times:

- $t_d + t_n$ = 10 to 20 seconds (RTI 0.5 / 5 $(m.s)^{0.5}$ [97]
- $t_{p\text{-}e}$ = 10 minutes (600 seconds) according to NTA 4614-2 [60].
- t_e = 30 seconds per floor + 30 seconds on the floor = 13 * 0.5 + 0.5 = 7 minutes

RSET = 0.5 + 10 + 7 = 17.5 minutes

The average values and the standard deviations of Available Safe Egress Time (ASET) for the escape routes based on smoke propagation towards the escape routes are shown in Table 5-7.

Table 5-7. Average ASET in the escape routes of the low-rise building.

		ASET [min]	
Escape route	**floor**	**average**	**SD**
Adjacent corridor	11	18.0	-24.3
	12	75.0[3]	-84.4
Stairway lobby	11	75.0[3]	-69.5
	12	75.0[3]	n.a.
Stairway	1	75.0[3]	n.a.
	2	75.0[3]	n.a.

The requires safe egress time (RSET) is 17.5 minutes as calculated above. The cumulative probability of the conservation of the escape routes on the 11th and the 12th floor based on smoke propagation is shown in Figure 5-11, Figure 5-12 and Figure 5-13. The x-axis shows the available safe egress time (ASET) in minutes and the y-axis shows the cumulative probability. As mentioned in section 4.4, the limit for the visibility is 5.0 m, which is an optical density of 0.2 m^{-1}. A P of 1 on the y-axis in the graphs is a cumulative probability of 100%, a P of 0 on the y-axis is a cumulative probability of 0%. A longer ASET on the x-axis results in a smaller failure probability of the escape routes. The results of the sensitivity analyses are shown in Appendix 10. Probabilistic approach low-rise residential reference building.

[3] Simulation time for the low-rise residential building is 75 minutes.

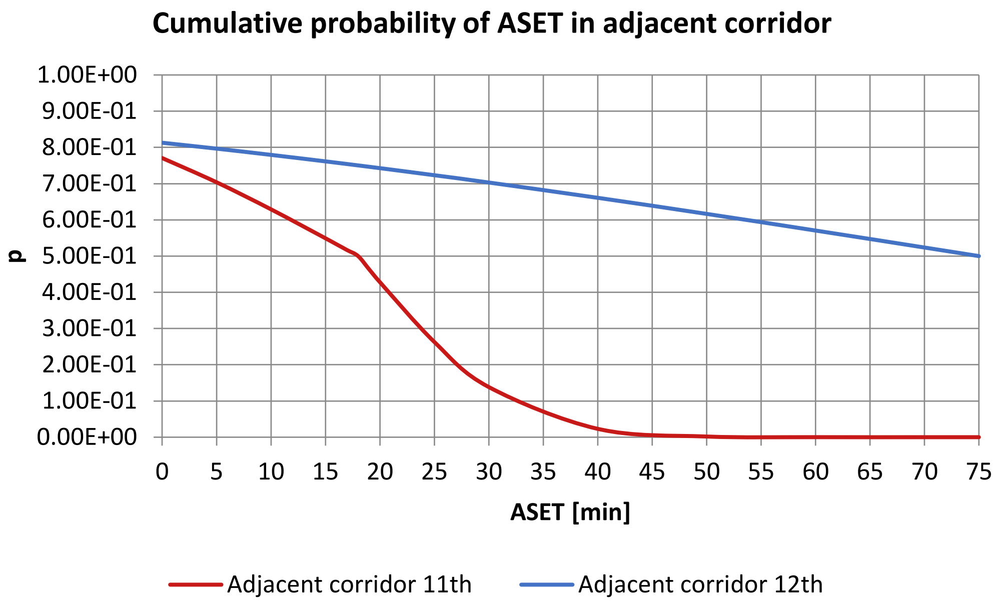

Figure 5-11. Cumulative probability of ASET in the adjacent corridor.

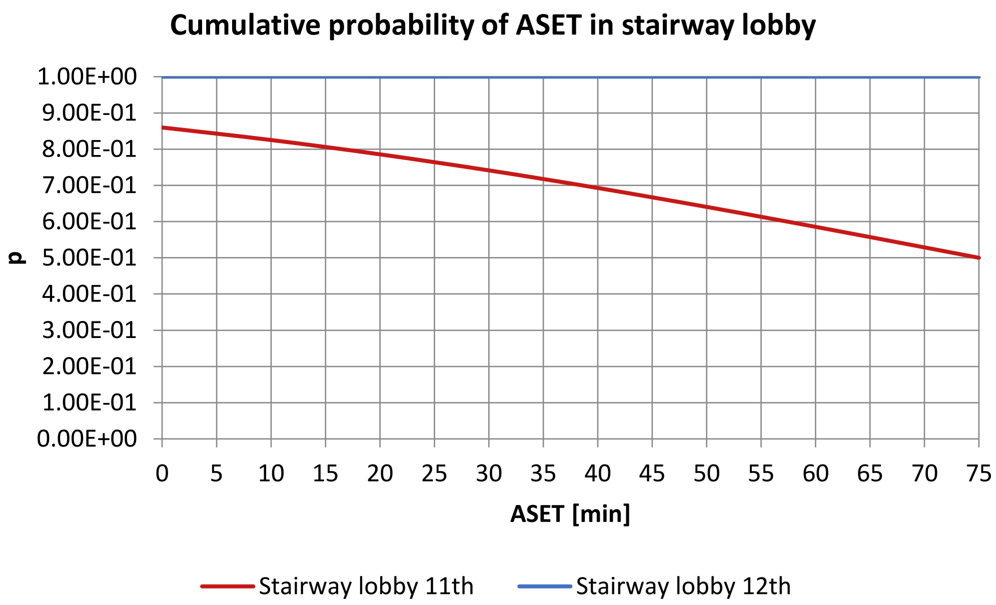

Figure 5-12. Cumulative probability of ASET in stairway lobby.

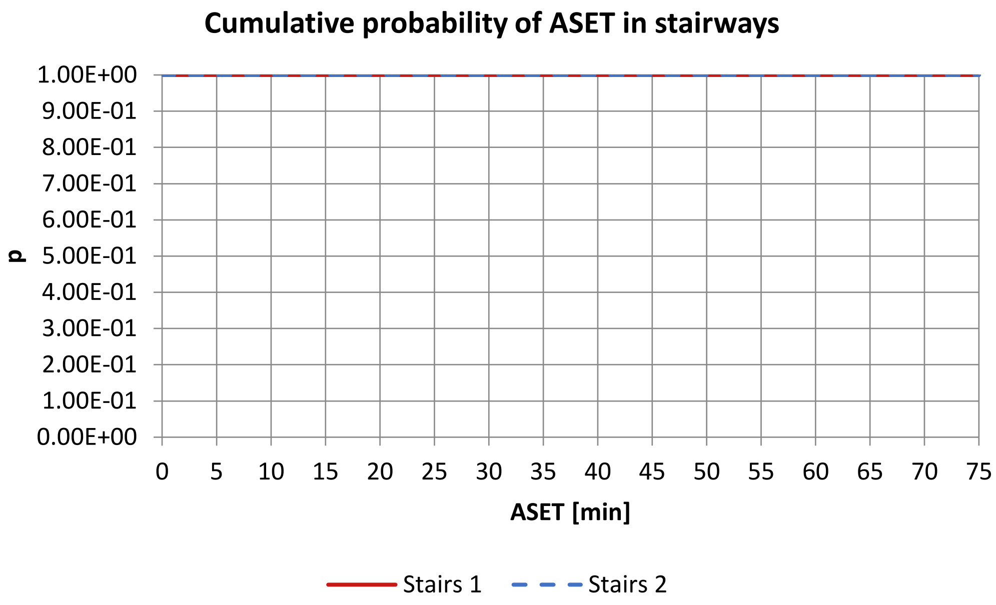

Figure 5-13. Cumulative probability of ASET in stairway.

The reliability of the evacuation concept in the low-rise residential reference building is defined as the probability that the available safe egress time (ASET) is longer than the required safe egress time (RSET): P(ASET>RSET). The reliability of the escape routes in the evacuation concept are shown in Table 5-8.

Table 5-8. Reliability of the evacuation concept of the low-rise residential reference building.

		P(ASET>RSET)
Escape route	**floor**	**Reliability**
Adjacent corridor	11	0.51
	12	0.75
Stairway lobby	11	0.80
	12	1.00
Stairway	1	1.00
	2	1.00

Super-tall residential building

The spread of fire and smoke as mentioned in paragraph 5.3.3 also affect the conservation of the escape routes. Fire resistant wall of 60 minutes have a 31% chance to fail in the scenario of the super-tall residential building, as mentioned in paragraph 5.3.3.1. The required egress time (RSET) of a total evacuation of the super-tall residential building is calculated based on the SPFE handbook of fire protection engineering [21], as shown in equation (2).

$$RSET = t_d + t_n + t_{p\text{-}e} + t_e \qquad (2)$$

Where:

- t_d is the time from fire ignition to detection (detection phase)
- t_n is the time from detection to notification of the occupants of a fire emergency (notification phase)
- $t_{p\text{-}e}$ is the time from notification until evacuation commences (pre-evacuation phase)

- t_e is the time from the start of purposive evacuation movement until safety is reached (evacuation phase)

The REST of the super-tall residential building in this research is calculated based in the following times:

- td + tn = 3,5 minutes (188 seconds = 3 minutes and 8 seconds) according to Appendix 4. Sprinkler activation DETACT.
- t_{p-e} = 10 minutes (600 seconds) according to NTA 4614-2 [60].
- t_e = 30 seconds per floor + 30 seconds on the floor = 130 * 0.5 + 0.5 = 65.5 minutes compensation for every 50 meters (1 minute per 50 meter) = 400 / 50 = 8 minutes

RSET = 3.5 + 10 + (65.5 + 8) = 87 minutes

The average values and the standard deviations of Available Safe Egress Time (ASET) for the escape routes based on smoke propagation towards the escape routes are shown in Table 5-9.

Table 5-9. ASET in the escape routes of the super-tall building.

		ASET [min]
Escape route	**Floor**	**Average**
Adjacent corridor	10	120.0[4]
	11	120.0[4, 5]
	12	120.0[4]
Stairway lobby	10	120.0[4]
	11	120.0[4]
	12	120.0[4]
Stairway	1	120.0[4]
	2	120.0[4]

The requires safe egress time (RSET) is 87 minutes as calculated above. The available safe egress time in the escape routes of the super-tall residential building is at least 120 minutes, since that is the maximum simulation time. The results of the sensitivity analyses are shown in Appendix 12. Probabilistic approach super-tall residential building. The reliability of the evacuation concept for the super-tall building is defined as the probability that the available safe egress time (ASET) is longer than the required safe egress time (RSET): P(ASET>RSET). The reliability of the escape routes of an evacuation concept in the super-tall residential building are shown in Table 5-10.

Table 5-10. Reliability of the evacuation concept of the super-tall residential building.

		P(ASET>RSET)
Escape route	**Floor**	**Reliability**
Adjacent corridor	10	1.00
	11	1.00[5]
	12	1.00
Stairway lobby	10	1.00
	11	1.00
	12	1.00
Stairway	1	1.00
	2	1.00

[4] Simulation time for the super-tall residential building is 120 minutes.
[5] A small peak in optical density exceeds the limit of 0.20 m-1 for a short period of time. The peak continues for 150 seconds from 120 seconds to 270 seconds, with the maximum after 180 seconds when the door closes.

The effect of the automatic suppression system and the pressurization system on the smoke propagation towards the adjacent corridors have been analyzed. An overview of the effect of an automatic suppression system and or a pressurization system are shown in Table 5-11 and in Figure 5-14. Applying an automatic suppression system and/or a pressurization system in the building has almost no effect on the ASET of the adjacent corridors on floor 10 and 12. However it does have a large effect on the adjacent corridor on floor 11, the floor of the fire. In the situation with an automatic suppression system and without a pressurization system the average ASET in that compartment is 9.75 minutes, which is a decrease in ASET of approximately 92% in comparison to the standard situation with a suppression system and a pressurization system. The effect of applying neither an automatic suppression system nor a pressurization system is a decrease of the ASET by approximately 85%.

Table 5-11. Average ASET overview and the effect of a suppression system and pressurization system on the adjacent corridor.

Average ASET overview of the adjacent corridor				
Compartment	**ASET variation depended on building services [min]**			
	Suppression + pressurization	**Suppression**	**Pressurization**	**Neither**
Adjacent corridor floor 10	120.00[6]	120.00[6]	120.00[6]	120.00[6]
Adjacent corridor floor 11	120.00[6]	9.75	120.00[6]	18.50
Adjacent corridor floor 12	120.00[6]	120.00[6]	120.00[6]	120.00[6]

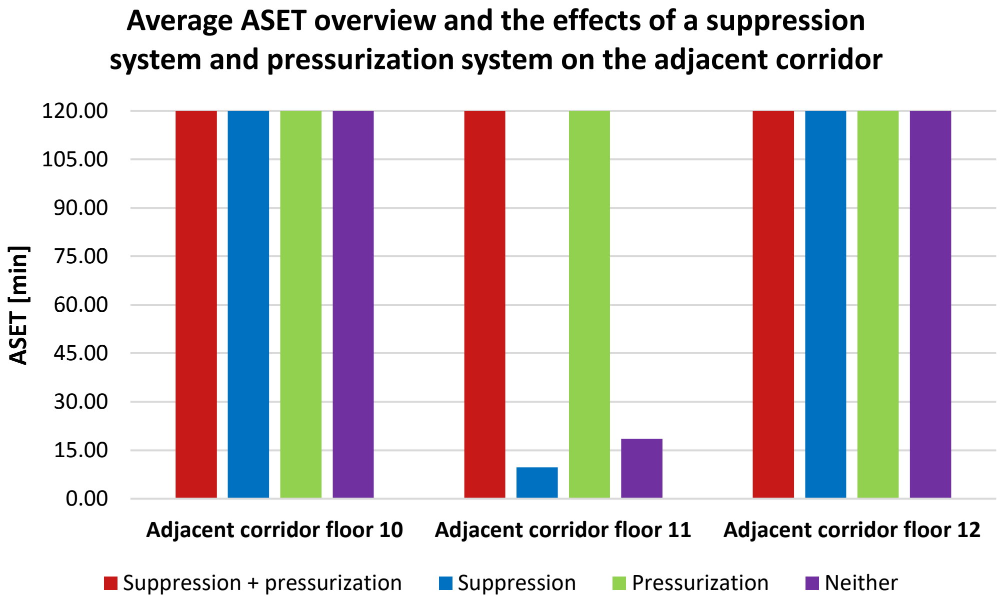

Figure 5-14. Average ASET overview and the effect of a suppression system and pressurization system on the adjacent corridor.

The effect of the automatic suppression system and the pressurization system on the smoke propagation towards the adjacent corridors has been analyzed. An overview of the effect of an automatic suppression system and or a pressurization system are shown in Table 5-12 and in Figure 5-15. Applying an automatic suppression system and/or a pressurization system in the building has no effect on the ASET of the

[6] Simulation time for the super-tall residential building is 120 minutes.

stairway lobby and the stairways. In all the situations the ASET in the stairway lobby and in the stairway is at least 120 minutes.

Table 5-12. Average ASET overview and the effect of a suppression system and pressurization system on the stairway lobby and stairway.

Average ASET overview of the stairway lobby and stairway				
Compartment	**ASET variation depended on building services [min]**			
	Suppression + pressurization	**Suppression**	**Pressurization**	**Neither**
Stairway lobby floor 10	120.00[7]	120.00[7]	120.00[7]	120.00[7]
Stairway lobby floor 11	120.00[7]	120.00[7]	120.00[7]	120.00[7]
Stairway lobby floor 12	120.00[7]	120.00[7]	120.00[7]	120.00[7]
Stairway 1	120.00[7]	120.00[7]	120.00[7]	120.00[7]
Stairway 2	120.00[7]	120.00[7]	120.00[7]	120.00[7]

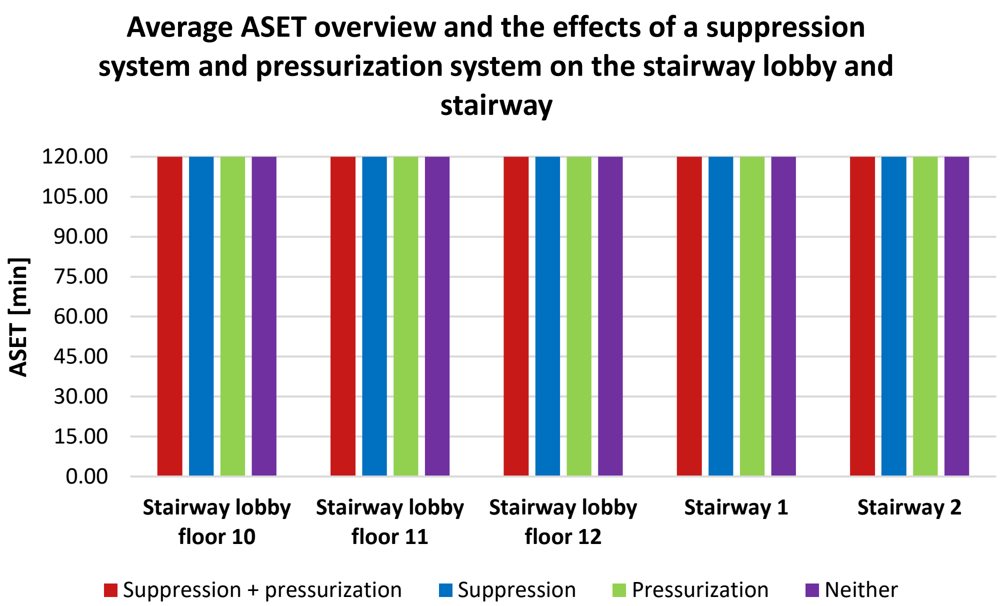

Figure 5-15. ASET overview and the effect of a suppression system and pressurization system on the stairway lobby and stairway.

<u>Elevators as escape route</u>

Depending on the chosen evacuation concept for the super-tall building the elevator may also be used as escape route. The average values and the standard deviations of available safe egress time (ASET) for the elevator lobby and elevator shafts based on smoke propagation towards the escape routes are shown in Table 5-13.

[7] Simulation time for the super-tall residential building is 120 minutes.

Table 5-13. Average ASET in the elevator lobby and elevator shafts.

		ASET [min]
	floor	**average**
Elevator lobby	10	120.00[8]
	11	120.00[8]
	12	120.00[8]
Elevator	1	120.00[8]
	2	120.00[8]

The available safe egress time in the escape routes of the super-tall residential building is at least 120 minutes, since that is the maximum simulation time. The results of the sensitivity analyses are shown in Appendix 12. Probabilistic approach super-tall residential building. The reliability of the elevator lobbies on floor 10, 11 and 12 and of the elevator shafts is 100%, as shown in Table 5-14.

Table 5-14. Reliability of the elevator lobbies and elevators of the super-tall residential building.

		P(ASET>RSET)
	floor	**Reliability**
Elevator lobby	10	1.00
	11	1.00[5]
	12	1.00
Elevator	1	1.00
	2	1.00

The effect of the automatic suppression system and the pressurization system on the smoke propagation towards the elevator lobbies and elevator shafts have been analyzed. An overview of the effect of a suppression system and or a pressurization system are shown in Table 5-15 and in Figure 5-16. Applying a suppression system and/or a pressurization system in the building has no effect on the ASET of the elevator lobbies on floor 10 and 12. However it does have a large effect on the elevator lobby on floor 11, the floor of the fire. In the situation with an automatic suppression system and without a pressurization system the ASET in that compartment is 23 minutes, which is a decrease in ASET of approximately 81% in comparison to the standard situation with a suppression system and a pressurization system. The effect of applying neither an automatic suppression system nor a pressurization system results in a decrease in ASET of approximately 78%. Just as for the elevator lobby on the 11th floor, the elevator shafts are affected by only using an automatic suppression system. The ASET in the elevator shafts is 42 minutes, which is a decrease in ASET of approximately 65% in comparison to the standard situation with an automatic suppression system and a pressurization system. The effect of applying neither an automatic suppression system nor a pressurization system results in a decrease in ASET of approximately 73%.

[8] Simulation time for the super-tall residential building is 120 minutes.

Table 5-15. Average ASET overview and the effect of a suppression system and pressurization system on the elevator lobbies and elevators.

Average ASET overview of the elevator lobbies and elevators				
Compartment	**ASET variation depended on building services [min]**			
	Suppression + pressurization	**Suppression**	**Pressurization**	**Neither**
Elevator Lobby floor 10	120.0[9]	120.0[9]	120.0[9]	120.0[9]
Elevator Lobby floor 11	120.0[9]	23.0	120.0[9]	27.0
Elevator Lobby floor 12	120.0[9]	120.0[9]	120.0[9]	120.0[9]
Elevator 1	120.0[9]	42.0	120.0[9]	35.25
Elevator 2	120.0[9]	42.0	120.0[9]	35.25

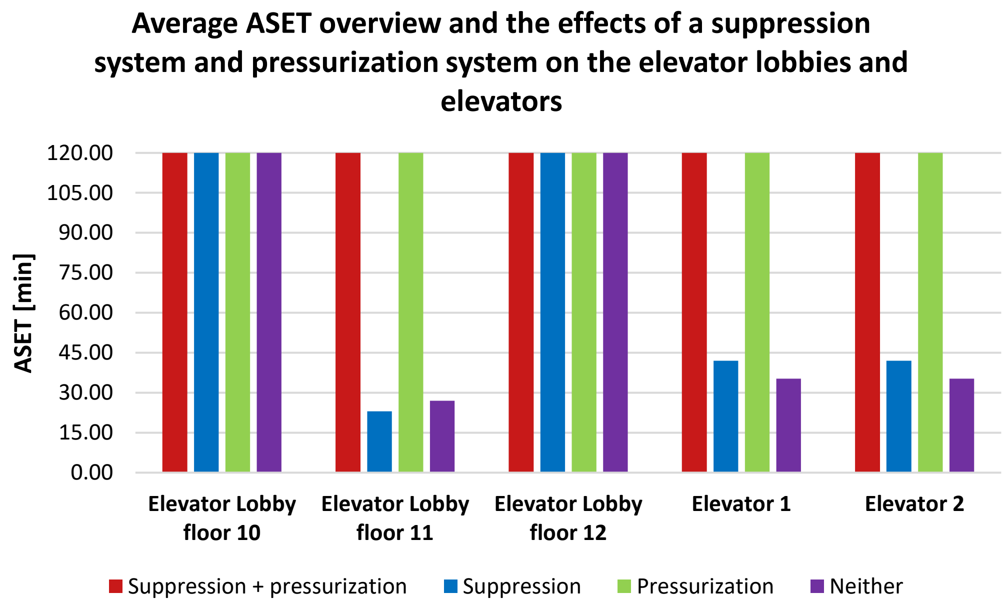

Figure 5-16. Average ASET overview and the effect of a suppression system and pressurization system on the elevator lobbies and elevators.

Evaluation

Conservation of the escape routes has been assessed based on a full evacuation concept using stairs only, which has been applied to both the low-rise residential reference building and the super-tall residential building in this research. ASET-RSET analyses have been made for both buildings based on the ASET obtained from the sensitivity analyses and the RSET which has been based on the SPFE handbook of fire protection engineering [21].

The required safe egress time (RSET) of the low-rise residential reference building would be 17.5 minutes based on the requirements for evacuation set in the BBL. The available safe egress time (ASET) in the adjacent corridor is 18 minutes. The available safe egress time in the other escape routes (the corridor above, the stairway lobbies on floor 11 and 12 and the stairways) is at least 75 minutes (which is the maximum simulation time for the low-rese residential building). The reliability of these escape routes at 17.5 minutes is 51% for the adjacent corridor, 75% for the corridor above, 80% for the stairway lobby on floor 11 and 100% for the stairway lobby on floor 12 and stairways 1 and 2.

[9] Simulation time for the super-tall residential building is 120 minutes.

The required safe egress time (RSET) of the super-tall residential building would be 87 minutes based on the requirements for evacuation set in the BBL. The available safe egress time in all the escape routes (the adjacent corridor, the corridors above and below, the stairway lobbies on floor 10, 11 and 12 and the stairways) is at least 120 minutes (which is the maximum simulation time for the low-rese residential building). The reliability of these escape routes at 87 minutes is 100% for the adjacent corridor, the corridor above, the stairway lobby on floor 11 and 12 and stairways 1 and 2. In the super-tall residential building the required safe egress time is longer than the available safe egress time (RSET < ASET). This means that during the full fire scenario building occupants will be present in the building.

For other evacuation concept such a full evacuation with refugee floors using stairs and elevators as shuttle, the same ASET-RSET analysis can be made. As mentioned above in the discussion section of limiting the spread of smoke the adjacent compartment above could be used as refugee floor. The reliability of this compartment is 24% at 120 minutes. In order to be able to use the compartment as a refugee floor/escape route the reliability of the compartment should at least be the same of as the reliability of the escape routes in an full evacuation scenario. The reliability of that compartment could be improved by applying a pressurization system or by using a partially opened façade, for instance 50% open. The effect of these solutions and the reliability of these solutions can be calculated with a sensitivity analysis.

The effect of the automatic suppression system and the pressurization system in the escape routes has been assessed in the super-tall residential building. Only applying the automatic suppression system affects the average ASET in the adjacent corridor, reducing the ASET from 120 minutes to 9.75 minutes, the other escape routes (adjacent corridors above and below, the stairway lobbies on floor 10, 11 and 12 and the stairways) are not affected by removing the pressurization system. By applying an automatic suppression system the development of smoke is increased and the windows in the façade do not shatter, so that more smoke remains in the building than when the windows shatter and the smoke can also partly escape. Only applying the pressurization system does not affect the average ASET in the escape routes, the average ASET in the escape routes remains 120 minutes. Applying neither an automatic suppression system and a pressurization system affects the average ASET in the adjacent corridor, reducing the ASET from 120 minutes to 18.5 minutes, the other escape routes (adjacent corridors above and below, the stairway lobbies on floor 10, 11 and 12 and the stairways) are not affected.

As mentioned in the previous paragraphs, the elevator lobbies and elevator shafts could also be used as escape routes for instance in an evacuation concept using refugee floor, where the elevators could be used as shuttles. The available safe egress time in all the elevator lobbies on floor 10, 11 and 12 and in the elevator shafts is at least 120 minutes (which is the maximum simulation time for the low-rese residential building). The reliability of these escape routes at 87 minutes is 100% for elevator lobbies on floor 10, 11 and 12 and in the elevator shafts. The effect of the automatic suppression system and the pressurization system on the average ASET of the elevator lobbies and elevator shafts has been assessed in the super-tall residential building. Only applying the automatic suppression system affects the average ASET in the elevator lobby on floor 11, reducing the ASET from 120 minutes to 23 minutes and affects the average ASET in the elevator shafts, reducing the ASET from 120 minutes to 42 minutes. The elevator lobbies on floor 10 and 12 are not affected by removing the pressurization system. Only applying the pressurization system does not affect the average ASET in the escape routes, the average ASET in the elevator lobbies and elevator shafts remains 120 minutes. Applying neither an automatic suppression system and a pressurization system affects the average ASET in the affects the average ASET in the elevator lobby on floor 11, reducing the ASET from 120 minutes to 27 minutes and affects the average ASET in the elevator shafts, reducing the ASET from 120 minutes to 35.25 minutes. In an evacuation concept that uses the elevators, the elevator lobbies and elevator shafts should be protected by a pressurization system just as the stairway lobbies and stairway shafts.

6. Discussion

The results of the low-rise residential reference building and of the super-tall residential building have already been discussed and can be found in section 5.3. In this chapter the limitations of this research, possible future studies based on this research and recommendations based on this research are described.

6.1 Limitations

This research focused on the fire safety engineering of super-tall buildings between 200 and 400 meters in the Netherlands. Building regulations allow buildings up to 200 meters and regulations for higher buildings have not yet been formulated. This research focuses on buildings in the Netherlands and uses the Dutch building code BBL (Besluit Bouwwerken Leefomgeving), but the method is not specifically for buildings in the Netherlands or for the Dutch building code. Because it is a quantitative assessment of fire safety of super-tall buildings with a probabilistic analysis and does not focus on the local standards, the method can also be applied internationally. A quantitative assessment with a probabilistic analysis has been mentioned multiple times in the literature, however the way to perform a quantitative assessment with a probabilistic analysis for fire safety is not explained in the literature.

The quantitative assessment with a probabilistic analysis is a performance based approach, which is always project specific. This is one of the limitations of this research. For other super-tall buildings with a different layout the conclusion may be different, especially the exact reliability or failure probability of the separate risk subsystems. In this research the case only illustrates the process, methodology and simulations needed for a performance based approach. The conclusions mentioned in this research are not generic conclusions for super-tall residential buildings.

The spread of fire and smoke has been investigated in this research, however the spread of fire and smoke via the facades was not part of this research. After the fire in the Grenfell tower an inquiry has been set up in order to evaluate the fire safety of Dutch building facades. Based on the fire and the inquiry the standard for fire propagation, the NEN 6068, will be complemented with a new method to analyze fire propagation via the façade. Based on the adjustment/complementation of the NEN 6068 and the inquiry into the fire safety of facades in the Netherlands, the subject of facades can be a graduation subject on its own. For this research the façade, the following principle for the façade has been used: the façade should not shortcut the fire compartmentation; the façade should at least have the same resistance to fire as the compartment walls and the façade should not have ignition sources.

Smoke propagation in the low-rise residential reference building and in the super-tall residential building has been investigated by simulating a fire in a model. This model did not have the full size of the buildings, since this would result in very long computational times, with the available computational power. The models used in this research are 3 or 4 levels tall instead of the 13 or 130 levels of the buildings. By modeling the full building, the results of the smoke propagation might have been affected by the elevator shafts. For the effect of the automatic suppression system and the pressurization system on the smoke propagation towards the escape routes the stairways and elevator shafts have been modelled with a height of 100 meters. The results of a shaft modeled as 12 meter tall or 100 meters tall do not differ much and therefor the difference in results is not significant.

This research is limited to a residential function in super-tall buildings. In super-tall buildings more functions are possible than just a residential function, for instance an office function and a hotel function or a combination of these 2 or 3 functions. The building use and the functions linked to the use can affect the fire safety in a building and have different results. Besides the fact that different building functions have different levels of fire safety, the building method used for these functions differs in The Netherlands. Where a residential function almost always uses structural walls and floor for the load bearing elements, office functions or hotel functions mostly use structural columns and beams for the load bearing elements.

Fire safety during construction as mentioned in the SBRCURnet publications has not been investigated in this research. However, fire safety during construction is a point of interest since not all building services might be operational during construction.

The sensitivity analyses are based on an estimate of the standard deviations. With a smaller uncertainty in the standard deviation, the uncertainty of the result will also be smaller. The standard deviations used are based on previously published reports by Van Herpen et al. [30] and the NIPV [92]. However, the standard deviations used can be further investigated because more research needs to be done into fuel characteristics, internal airtightness and human behavior, since the models of the low-rise residential reference building and the super-tall residential building are most dependent on these parameters.

6.2 Future studies

The acquired knowledge of fire safety of a super-tall residential building, assessed with a quantitative assessment with a probabilistic analysis, can be used in the design of super-tall buildings in The Netherlands. The method used shows that it is possible to calculate the fire safety level of a super-tall residential building, based on a low-rise residential reference building. The fire safety level of other building functions or a combination of building functions has not been investigated in this research and needs to be studied in future research.

Future research should also focus on the evacuation concepts used in super-tall buildings. In this research a full evacuation concept using stairs only has been investigated. The results show that in a super-tall building in which a suppression system and pressurization system has been applied, the evacuation time is longer than the fire scenario. Therefor other evacuation concepts could be of better use in super-tall buildings. In order to investigate the effect of other evacuation concepts, improvements can be made on the model used to assess the smoke propagation in the building. When assessing the fire safety level of other evacuation concepts, the same method used in this research can be used.

The effect of not applying a pressurization system in the stairway lobby as active preventive measure is unexpected. Based on the results of the ASET in the vertical escape routes the application of a pressurization system is not necessary. However further research should be conducted in order to further substantiate this conclusion.

Besides future research of building functions and evacuation concepts, the effect of the façade on fire and smoke propagation can be studied in future research. The effect of the façade and wind on the façade in combination with the external airtightness and façade connections in regard to fire and smoke propagation in super-tall buildings is not yet studies as the effect of wind on the fire is not part of the directed standards.

TU/e

6.3 Recommendations

Based on this research some recommendations for super-tall (residential) buildings in The Netherlands can be made, regarding the building method and the evacuation concept.

The building construction method in The Netherlands differs for buildings with a residential function and an office or hotel function. However, the assumed internal airtightness would be the same for all three building functions and building construction methods. Based on fire propagation the fire resistance of the walls and floors are project specific and need to be evaluated per case.

As mentioned in paragraph 3.1 the probability of fire ignition in the Eurocode differs from the probability of fire ignition based on Dutch statistics. The difference in the probability of fire between the Eurocode and the statistics might be explained by the fact that the probability of fire according to the Eurocode is for low-rise buildings and the probability of fire according to the Dutch statistics is for a residential building, low-rise and high-rise. The difference in probability of fire could also be explained based on the difference in time. The statistics in the Handbook are based on a period between 1970 and 1990. An increase in electrical appliances, PV-panels and other similar equipment may have caused an increase in the probability of fire. I would recommend to investigate the difference in probabilities and based on that adjust the probability of fire ignition if needed.

Based on the performed simulations and calculations for the AS(E)T and RS(E)T, a full evacuation using stairs only and a stay-in-place concept is not recommended in a super-tall building. The RSET of a full evacuation using stairs may take longer than the fire scenario, while the ASET of a stay-in-place concept is too short. Based on these findings I would recommend a hybrid evacuation concept, where refugee floors are used. The simulations show that a pressurization system can be used to keep the escape routes free of smoke. The refugee floor is part of the escape route and should also be kept free of smoke, either by opening the façade or by applying a pressurization system. The refugee floor can also be kept free of smoke by creating enough space between the fire and the refugee floor, for instance by not using a refugee floor directly above a fire. Based on results of the simulation the refugee floor should be split up in multiple sections so that in case of a fire burning directly under the refugee floor, the section above the fire would not be used as a safe haven. In this evacuation concept the elevators should be used to evacuate less self-reliant building occupant to the refugee floors. The elevators can also be used as shuttles from the refugee floors to ground level when the fire fighters deem a full evacuation necessary.

In order to make a quantitative assessment with a probabilistic analysis more widely accepted in the field of fire safety engineering in the Netherlands and in Europe I would recommend to add this method of fire safety engineering to a standard or international standard, in which the amount of stochastic boundary conditions and the average values and variations of those average values of the stochastic boundary conditions are set. In this way more fire safety engineers could use this method of fire safety engineering. Because a quantitative assessment with a probabilistic analysis is a specific form of fire safety engineering I would recommend that the ire safety engineers is a skilled fire safety engineer. The skilled fire safety engineer and the company/organization the engineer works for needs to be certified, just as is the case for the EP-engineers who are certified and work according tot the BRL 9500.

Based on the performed simulations and the results of these simulations the effect of an automatic suppression system and a pressurization system on the smoke propagation towards the escape routes is limited. The optical density in the escape routes does not exceed the limit when the escape routes are separated from the corridor with a lobby. Therefor I would recommend to further investigate the effect and the efficiency of a pressurization system in the escape routes. For super-tall buildings I would recommend to use sprinkler systems because a repressive action from fire and rescue services from the outside the building is almost impossible at greater heights.

7. Conclusion

During this graduation project, the application of a quantitative assessment of fire safety with a probabilistic analysis, has been studied. A literature review and multiple simulations have been performed. A main research question has been formulated, which is divided into two research questions and 5 sub research questions. These research questions will be answered here. The conclusions drawn in this research, which are based on the low-rise residential reference building and the super-tall residential building, are project specific and are therefore not generally applicable to all low-rise (residential buildings) and all super-tall (residential) buildings.

Sub-questions

a. What is the fire safety level of residential low-rise buildings in the Netherlands?

The fire safety level of residential low-rise buildings in the Netherlands is project specific. Not every low-rise building is the same. Because the buildings differ in height and size, the requirements set by the BBL are different. The fire safety level of a low-rise building is not determined in the building code. The building code only provides a set of regulations without defining the acceptable failure risk. The acceptable failure risk is project specific in all risk subsystems, because a performance based approach is project specific. The failure risks are generic applicable depending on the evacuation concept only. The fire safety level of a residential low-rise building can be defined based on the two main public objectives of the building code and based on the risk subsystems that are connected to those two main public objectives.

<u>Main public objectives</u>
The fire safety level of the two main public objectives of the Dutch national building code for a low-rise residential building in the Netherlands can not be defined for all the low-rise residential buildings because the fire safety level is project specific. Therefor the conclusion stated below is project specific.

Personal safety
The level of fire safety of building occupants in the low-rise residential reference building designed according to the requirements set in the BBL is sufficient enough to secure a RSET<ASET for a full evacuation using stairs only. The required safe egress time in the low-rise residential reference building is 17.5 minutes. The available safe egress time is 18 minutes in the adjacent corridor and at least 75[10] minutes in the other escape routes.
Personal safety of fire and rescue services such as fire fighters is not part of public law and has therefor been left out of the quantitative assessment for fire safety. However if the level of fire safety of fire and rescue services needs to be quantified, a quantitative assessment with probabilistic analysis can be used.

Protection of neighboring plots and adjacent buildings
Neighboring plots and adjacent buildings are threatened by a flashover in a compartment fire and by the collapse of a building. The threat of fire spread due to flashover to neighboring plots has not been analyzed in this research. The neighboring plots and adjacent buildings are protected from a building collapse in case of fire by ensuring that the load bearing structure of the building is conserved for at least the length of the fire scenario. Based on the simulations of the low-rise residential reference building the reliability of the load bearing structure at 120 minutes is 100%. Therefore damage of neighboring plots and adjacent buildings based on the collapse of the building is most unlikely.

[10] 75 minutes is the maximum simulation time of the low-rise residential reference building.

Risk subsystems

The fire safety level of the risk subsystems in the Dutch national building cannot be defined for all the low-rise residential buildings, because the fire safety level of the risk subsystems is project specific. The fire safety level of the risk subsystems of the low-rise residential reference building used in this study are presented below.

Limiting the probability of fire ignition

The probability of fire ignition depends on the floor area of the building and the life cycle of the building. Therefor the smaller the building the smaller the probability of fire in that building and/or the shorter the lifetime of the building the smaller the probability of fire in that building. The level of fire safety per m^2 per year however is the same in all low-rise residential buildings: 1.00E-05 /m^2/year. Because low-rise residential buildings are smaller than 70 meters and has more than 4 floors, the building has a reliability class RC2/ a consequence class CC2. The reliability index for consequence class 2 is 3.8, which considers the accepted or assumed statistical variability of resistances and load effects and modeling uncertainties. The probability of fire for the low-rise residential reference building is 1.76E-01.

Limiting the development of fire and smoke

The fire safety level as set in the BBL in order to limit the development of fire and smoke need to be applied in low-rise residential buildings. These requirements have also been used in the simulation of the low-rise residential reference building. A compartment fire in the low-rise residential reference building can develop to a heat release rate of 10,954 kW. Other options to limit the development of fire and smoke such are a suppression system are not applied in the low-rise residential reference building. Applying a suppression system would limit the development of fire but would increase the development of smoke.

Limiting the spread of fire and smoke

In the low-rise residential reference building the spread of smoke is more important for personal safety than the spread of fire.

Limiting the spread of fire

The natural fire in the low-rise residential building has an equivalent fire duration of 51 minutes standard fire curve. Therefor the available safe time of the separation constructions has been set to 60 minutes. The reliability of the 60 minute fire resistant separation constructions is 69%.

Limiting the spread of smoke

A full evacuation concept using stairs only is the standard for low-rise residential reference buildings. Based on the results of smoke spread towards adjacent compartments the reliability at 5 minutes is almost 0%. With an average AST of 2.75 minutes in the adjacent compartments and with an average of 1.5 minutes in the compartment above, the spread of smoke is very fast. The spread of smoke towards the adjacent compartments does not affect an evacuation concept with full evacuation using stairs only. However, for other evacuation concepts such as a stay-in-place concept, the smoke resistance of the walls and/or floor would not suffice for an ASET required in a stay-in-place concept.

Conservation of the load bearing structure

According to the BBL the fire resistance of the load bearing structure of the low-rise residential reference building should at least be 120 minutes. The low-rise residential reference building is classified as a building with consequence class 2 in the Eurocode. According to the Eurocode the reliability index of consequence class 2 for the low-rise residential reference building is 3.35. This results in a fire resistance of 120 minutes for the load bearing structure according to the sensitivity analysis. The reliability of a 120 minutes fire resistant load bearing structure is 100% for the low-rise residential reference building.

Conservation of the escape routes
In order to conservate the escape routes, the RSET should be shorter than the ASET. A full evacuation concept using stairs only is the standard for low-rise residential building, which results in a required safe egress time of 17.5 minutes. The available safe egress time (ASET) in the adjacent corridor is 18 minutes. The available safe egress time in the other escape routes is at least 75[11] minutes. The reliability of these escape routes at 17.5 minutes is 51% for the adjacent corridor, 75% for the corridor above, 80% for the stairway lobby on floor 11 and 100% for the stairway lobby on floor 12 and stairways 1 and 2.

b. How does the framework of a probabilistic approach in a quantitative assessment look like?

As mentioned before a probabilistic approach is project specific. The framework used in a probabilistic approach should be general applicable for all buildings and should therefore not be project specific. The Dutch National building Code 'Besluit Bouwwerken Leefomgeving' BBL is divided into risk subsystems. These risk subsystems can be used to define the level of fire safety of low-rise buildings as well as the level of fire safety of super-tall buildings, based on the assessment: AST > RST (available safe time needs to exceed the required safe time).

c. What should be the level of fire safety of a super-tall residential building between 200 and 400 meters in the Netherlands?

The fire safety level of super-tall residential buildings between 200 and 400 meters is just as for the low-rise residential buildings project specific. In order to determine the fire safety level of a super-tall residential building a quantitative assessment with a probabilistic analyses has been carried out. The layout of the super-tall residential building is the same as the layout of the low-rise residential reference building. The fire safety level of the super-tall residential building used in this research is shown in the answers of the sub questions below.

The fire safety level of the super-tall residential building between 200 and 400 meters is project specific and therefor depends on the size of the building and the evacuation concept used in the building. In this research a total evacuation using stairs only has been assessed, but other evacuation concepts could have different results for the fire safety level of the building. Therefor there is no general fire safety level of residential super-tall buildings.

<u>Main public objectives</u>
The fire safety level of the two main public objectives of the super-tall residential building are project specific. Therefor the conclusion stated below is project specific.

Personal safety
The level of fire safety of building occupants in super-tall residential buildings designed with the requirements set in the SBRCURnet publication differ from the level of fire safety of building occupants in low-rise residential buildings. The RSET in the super-tall residential building for a full evacuation using stairs only is 87 minutes. Which is 36 minutes longer than the fire scenario. The ASET in the escape routes of the super-tall residential is 120 minutes when an automatic suppression system and a pressurization system are installed.
Because personal safety of fire and rescue services has not been assessed for the low-rise residential reference building, it has also not been assessed for the super-tall residential building.

Protection of neighboring plots and adjacent building

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[11] 75 minutes is the maximum simulation time for the low-rise residential building

Neighboring plots and adjacent buildings are threatened just the same for the low rise residential building: by a flashover in a compartment fire and by the collapse of a building. The threat of fire spread due to flashover to neighboring plots has not been analyzed in this research because of the distance between two high-rise buildings. The neighboring plots and adjacent buildings are protected from a building collapse in case of fire by ensuring that the available safe time of load bearing structure of the building is longer than the required safe time. The load bearing structure has been analyzed based o consequence class 3 of the Eurocode. Based on the results of this analysis, the load bearing structure of the super-tall residential building should be at least 135 minutes. The reliability of the load bearing structure at 135 minutes is 100%.

<u>Risk subsystems</u>

The fire safety level of the risk subsystems in all super-tall residential buildings cannot be defined, because the fire safety level of the risk subsystems is project specific. The fire safety level of the risk subsystems of the super-tall residential building used in this study are presented below, the automatic suppression system and the pressurization system are set as a condition for the conclusions.

Limiting the probability of fire ignition

The probability of fire ignition depends on the floor area of the building and the life cycle of the building, making it project specific. When comparing a super-tall residential building and a low-rise residential building, the life cycle of the building doubles from 50 years for a low-rise residential building, to 100 year for a super-tall residential building. By doubling the life cycle of a building, the probability of fire is also doubled from 1.00E-05 /m^2/year to 2.00E-05 /m^2/year. Because super-tall residential buildings are taller than 70 meters, the building has a reliability class RC3/ a consequence class CC3. The reliability index for consequence class 3 is 4.3, which considers the accepted or assumed statistical variability of resistances and load effects and modeling uncertainties. The probability of fire for the super-tall residential building is 2.81E00.

Limiting the development of fire and smoke

In order to limit the development of fire and smoke in a super-tall residential building, an automatic suppression system has been applied. In this research the application of an automatic suppression system in the super-tall residential building limits the development of the fire by 97% from 10,954 kW in the reference situation to 360 kW in the sprinklered super-tall situation. However, by applying a suppression system more smoke is developed.

Limiting the spread of fire and smoke

In the super-tall residential building the spread of smoke is more important for personal safety than the spread of fire.

<u>Limiting the spread of fire</u>

The natural fire in the super-tall residential building has an equivalent fire duration of 51 minutes standard fire curve. Therefor the available safe time of the separation constructions has been set to 60 minutes. The reliability of the 60 minute fire resistant separation constructions is 69%. The spread of fire is also limited by the application of an automatic suppression system. However this is an redundant system and the separation constructions should still function if the suppression system fails.

<u>Limiting the spread of smoke</u>

A full evacuation concept using stairs only is the standard for low-rise buildings, but not for super-tall buildings. In this research a full evacuation using stairs only has been applied to the super-tall residential building, limiting the spread of smoke has been based on this evacuation concept. Based on the results of smoke spread towards adjacent compartments the reliability at 5 minutes is almost 0%. With an average AST of 2.25 minutes in the adjacent compartments and with an average of 1.5 minutes in the compartment above, the spread of smoke is very fast. The spread of smoke towards the adjacent compartments does not affect an evacuation concept with full evacuation using stairs only.

Conservation of the load bearing structure
The fire resistance of the load bearing structure of the super-tall residential building has been assessed based on a quantitative assessment with a probabilistic analysis. The super-tall residential building is classified as a building with consequence class 3 in the Eurocode. According to the Eurocode the reliability index of consequence class 2 for the low-rise residential reference building is 4.52. This results in a fire resistance of 135 minutes for the load bearing structure in consequence class 3, according to the sensitivity analysis. The reliability of a 135 minutes fire resistant load bearing structure is 100% for the low-rise residential reference building.

Conservation of the escape routes
In order to conservate the escape routes, the RSET should be shorter than the ASET. Applying the same evacuation concept in a low-rise residential building as in a super-tall residential building is not likely. The evacuation time of a super-tall building is significantly longer than in a low-rise building. A full evacuation using stair only is therefore not the most suitable evacuation concept. However, by applying a suppression system in the compartments and a pressurization system in the stairway lobbies, the escape roots are safe to use during the evacuation. A full evacuation concept using stairs only in the super-tall residential building results in a required safe egress time of 87 minutes. The available safe egress time (ASET) in the escape routes is at least 120[12] minutes. The reliability of these escape routes at 87 minutes is 100%.

d. *What should the evacuation concept for a super-tall residential building between 200 and 400 meters in the Netherlands look like?*

Based on the simulations performed in this research a full evacuation using stairs takes longer than the burning time of a natural fire in an apartment (87 minutes > 51 minutes). Therefor the evacuation concept used in super-tall buildings should not only be an evacuation using stairs. Based on the results limiting the spread of smoke towards adjacent compartments is not enough in order to apply a stay-in-place concept. therefor a hybrid concept using refugee floors might be the best solution for super-tall buildings. In this hybrid evacuation concept building occupants evacuate inside the building to refugee floors, that can be kept smoke free by opening the facades, by using a pressurization system or by creating enough distance between the fire and a refugee floor. The main way of evacuating towards the refugee floors are the stairs, elevators can be used for less self-reliant building occupant or as shuttles between refugee floors and the ground floor.

e. *To what extend does an automatic suppression system and a pressurization system guarantee personal safety of building occupants in super-tall residential buildings between 200 and 400 meters?*

An automatic suppression system and a pressurization system are mandatory in tall buildings between 70 and 200 meters in The Netherlands. The active fire safety measures are additional to the preventive fire safety measures. In this research the effect of those building systems on the available safe time has been assessed in the super-tall building. Based on the results of the simulations the effect of an automatic suppression system on the horizontal escape route are minimal. The effect of the pressurization system on the horizontal escape route on the fire floor is significant. Without the pressurization system in the horizontal escape route on the fire floor the ASET would decrease with 85% in comparison to a situation with a pressurization system. The effect of an automatic suppression system and a pressurization system on the ASET in the vertical escape routes however is minimal, based on the simulations using elevator shafts and staircases with a height of 100 meters. Removing either or both the automatic suppression

[12] 120 minutes is the maximum simulation time for the low-rise residential building

system or the pressurization system does not affect the ASET in the vertical escape routes in this design. The use of a stairway lobby is critical for this effect. In this design the elevator lobby is not protected by an additional lobby (or smoke lock) and as a result of that the effect of removing the pressurization system is significant on the elevator lobby of the fire floor. By removing the suppression system the ASET in the elevator lobby on the fire floor is decreased with 81%. To conclude this research question, a pressurization system is not needed in the super-tall residential building in order to escape in a horizontal direction, the ASET without a pressurization system is longer than the RSET in the horizontal direction. Therefor the pressurization system is a redundant system, the ASET in the horizontal escape route is improved. If for some reason the pressurization system does not work, the ASET in the horizonal and vertical escape routes is still long enough for a safe escape. The automatic suppression system however is needed for limiting the development of fire, limiting the spread of fire and for the conservation of the load bearing structure.

Research questions

I. *Which framework could be used for a probabilistic approach in a quantitative assessment of fire safety of super-tall residential buildings?*

Because a probabilistic approach is always project specific, the framework used for a probabilistic approach of fire safety should be general applicable for all building functions. Because there are no building regulations for super-tall buildings the framework should be based on the building code for low-rise buildings.
The risk-subsystems used in the Dutch National building code 'Besluit Bouwwerken Leefomgeving' (BBL) could be used as a framework for a probabilistic approach of fire safety in the Netherlands. The risk-subsystems used in the BBL are used to substantiate the two main public objectives of the building code: public safety and protection of neighboring plots and adjacent buildings.

II. *How can the level personal safety for building occupants be guaranteed in super-tall residential buildings?*

As mentioned in the previous research question a probabilistic approach is always project specific. Therefore the personal safety level of building occupant in super-tall residential building is project specific. The level of personal safety depends on the evacuation concept used in the super-tall building. However for all evacuation concepts the AS(E)T should be longer than the RS(E)T.

Main research question

What does the framework of a probabilistic analysis in a quantitative assessment of fire safety for super-tall residential buildings between 200 and 400 meters in the Netherlands look like and how do you guarantee a level of personal safety for the building occupants comparable to the Dutch national Building Code?

Super-tall residential buildings between 200 and 400 meters are not build yet in the Netherlands and the legislation for super-tall buildings has not been written. In order to guarantee the level of personal safety in case of fire in a super-tall building a probabilistic approach to fire safety can be used. This probabilistic approach is based on the framework use in the Dutch building code BBL, the risk-subsystems. By using the risk-subsystems as a framework the personal safety in case of fire and the fire safety level of super-tall buildings can be assessed so that the level of personal safety and fire safety is at least the same as in low-rise buildings.

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9. Appendix

9.1 Appendix 1. Directed NEN and NEN-EN standards in the BBL

Multiple NEN and NEN-EN standards can/need to be used in order to design and build a safe building. The following standards are controlled in paragraph 4.2.2:

a. NEN-EN 1990
b. NEN-EN 1992
c. NEN-EN 1993
d. NEN-EN 1994
e. NEN-EN 1995
f. NEN-EN 1996
g. NEN-EN 1999
h. NEN 6069

The following standards are controlled in paragraph 4.2.6. 4.2.7. 4.2.8. 4.2.9. 4.2.10. 4.2.11 and 4.2.12:

a. NEN-EN 13501-1
b. NEN-EN 13501-6
c. NEN 6061
d. NEN 6062
e. NEN 6063
f. NEN 6060
g. NEN6068
h. NEN 6075
i. NEN 6079
j. NEN 6090

The following standards are controlled in paragraph 4.7.6. 4.7.7 and 4.7.8:

a. NEN-EN 179
b. NEN-EN 1125
c. NEN-EN 1838
d. NEN 1594
e. NEN 2575
f. NEN 3011
g. NEN 6068
h. NEN 6088

The following standards are controlled in paragraph 6.2.1 and 6.2.2:

a. NEN 3011
b. NEN 6060
c. NEN 6061
d. NEN 6064
e. NEN 6065
f. NEN 6079
g. NEN-EN 13501-1

9.2 Appendix 2. Evacuation concepts of the SBRCURnet publication

Concept A

Evacuation concept A assumes a standard evacuation according to the BBL. In a standard evacuation the building occupants need to evacuate the building within 30 minutes after the ignition of the fire. The regulations assumes that the fire is discovered and reported within 15 minutes after ignition and that the escape staircase is used for a maximum of 15 minutes. When a stairway lobby is used the escape staircase can be used for 20 minutes. With the use of a quick discovery system the time in which the fire is discovered and reported is shortened from 15 to 7 minutes. decreasing the evacuation time with 7 minutes.

Concept B

Evacuation concept B assumes an extended evacuation in which the building occupants need to evacuate the building within 60 minutes after the ignition of the fire. The regulations assumes that the fire is discovered and reported within 15 minutes after ignition and that the escape staircase is used for a maximum of 45 minutes. When a stairway lobby is used the escape staircase can be used for 50 minutes. With the use of a quick discovery system the time in which the fire is discovered and reported is shortened from 15 to 7 minutes. decreasing the evacuation time with 7 minutes.

Concept C

Evacuation concept C is an evacuation concept using phased evacuation. In case of fire the building occupants in the endangered zone will be evacuated. The endangered zone consists of four levels: the fire floor. two floors above the fire and a floor below the fire. The building occupants on the other floors will only be evacuated if the fire department deems it necessary. The time in which the fire department needs to decide about the total evacuation of the building is 30 minutes. leaving 30 minutes for the other building occupant to evacuate the building.

Table 9-1. Overview of evacuation time of concepts A. B and C of the SBRCURnet publication.

Evacuation concept	Staircase type	Quick response alarm	Escape time (min)
A	Normal	No	30
		Yes	23
	With stairway lobby	No	35
		Yes	28
	Safety staircase	No	45
		Yes	38
B	Normal	No	60
		Yes	53
	With stairway lobby	No	65
		Yes	58
	Safety staircase	No	75
		Yes	68
C	Normal	No	30
		Yes	38
	With stairway lobby	No	23
		Yes	28
	Safety staircase	No	45
		yes	38

Concept D
Evacuation concept D assumes a partial evacuation of the building. Partial evacuation is not a conventional evacuation strategy in The Netherlands and is not elaborated in the publication. It is explicitly noted that partial evacuation might be necessary in super-tall buildings and needs to be project specific [5].

9.3 Appendix 3. Computational models

OZone

Building characteristics and fire characteristics in a natural fire concept are used in the program Ozone V.3.0.4, in accordance with NEN 6055. All risk and multiplication factors in OZone are set to 1. In this way the simulation model provides pure physical results.

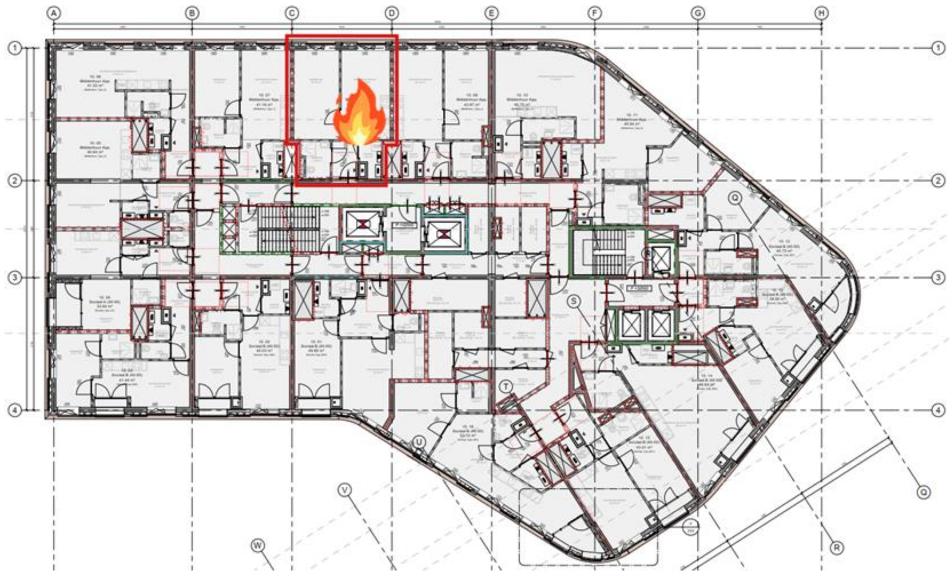


Figure 9-1. Geometry of the 10^{th} -13^{th} floor, and the compartments used in the Ozone calculations.

For the OZone calculations materials of the separation constructions are specified in Table 9-2. Table 9-3 specifies the openings used in the OZone model for the compartment.

Table 9-2. Material characteristics for the Ozone compartment model, according to the Eurocode.

Partition	Material	Thermal conductivity [W/m*K]	Thickness [mm]	Density [kg/m^3]	Specific heat [J/kg*K]	Emissivity [-]
Floor	Concrete	1.6	370	2300	1000	0.8
Ceiling	Concrete	1.6	370	2300	1000	0.8
Wall 1[13]	Concrete	1.6	250	2300	1000	0.8
	Glass wool / rock wool	0.037	150	60	1030	0,8
	Normal bricks	0.7	90	1600	840	0.8
Wall 2, 3, 4	Concrete	1.6	250	2300	1000	0.8

Table 9-3. Opening characteristics for the Ozone compartment model.

Opening	Sill height [m]	Soffit height [m]	Width [m]	Variation	Adiabatic
Window 1	0.6/1.0	2.6	variable[14]	Constant	No

CFAST

In the CFAST models the same fire characteristics are used as in the OZone models. Building characteristics such as material properties and size are also the same for the CFAST and OZone model. The windows in

[13] Wall 1 has windows to the outside.

[14] The width of the window is depending on the worst-case scenario: a fuel-controlled post flashover fire with oxygen mass = 0.0

the CFAST models are modelled as designed by the architect as seen in Appendix 6. Architectural drawing of the Brinktoren, floor 11.

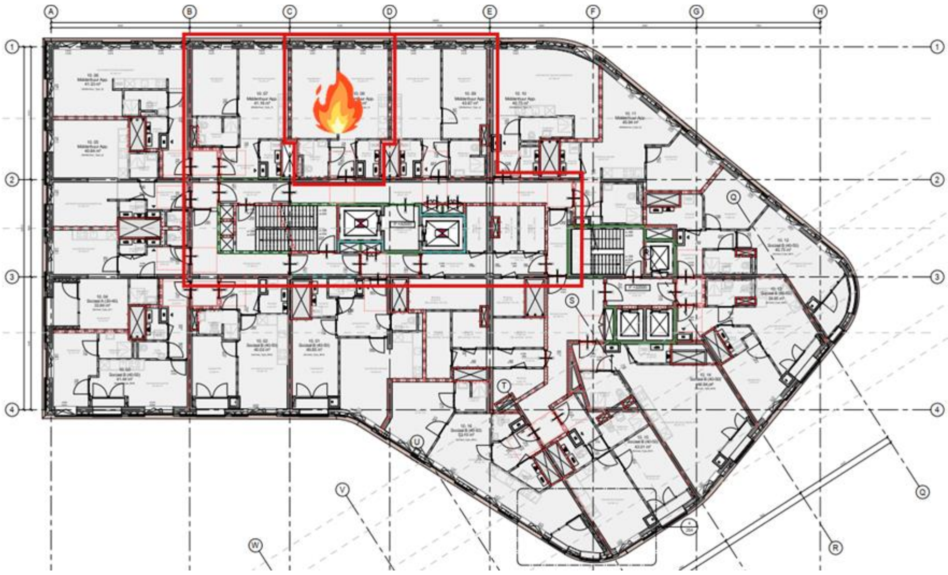


Figure 9-2. Geometry of the 10th – 13th floor, and the lay-out for the CFAST calculations.

For the CFAST calculations materials of the separation constructions are specified in Table 9-4.

Table 9-4. Material characteristics for the CFAST model, according to the Eurocode.

Partition	Material	Thermal conductivity [kW/m*K]	Thickness [mm]	Density [kg/m³]	Specific heat [J/kg*K]	Emissivity [-]
Floor	Concrete	0.0016	90	2300	1000	0.8
Ceiling	Concrete	0.0016	280	2300	1000	0.8
Wall	Concrete	0.0016	250	2300	1000	0.8

Airtightness

Airtightness is the volume flow through a separation construction of a building, measured at a pressure difference of 10 Pa. the airtightness is calculated with equation (3).

$$Q_{v;10} = C * \Delta P^n \quad (3)$$

Where:

- $Q_{v;10}$ is the volumetric leakage airflow rate at 10 Pa expressed in m^3/h
- C is the air leakage coefficient expressed in $m^3/h*Pa^{-n}$
- ΔP is the pressure difference across the building expressed in Pa
- n is the airflow exponent (0.5 ≤ n ≤ 1.0)[15]

The NEN 2687 knows two levels of airtightness, the third level of airtightness is based on the passive house principle. The levels of airtightness are shown in Table 9-5.

[15] The airflow exponent n is 0,5 for large openings and 1.0 for perfect laminar flows. The airflow exponent is between 0.7 and 0.8 for flows through separation constructions in buildings, in CFAST the airflow exponent needs to be filled in as 0.5. For different airflow exponents the air leakage coefficient needs to be adjusted in CFAST.

Table 9-5. Level of airtightness according to NEN 2687.

Class	Qualification	$Q_{v;10}$ ($dm^3/s*m^2$)
1	Basic	<1.0
2	Good	0.4 – 0.6
3	Excellent	< 0.15

The minimum airtightness of a residential building according to the national building code is a $Q_{v;10}$ of 0.2 m^3/s (200 dm^3/s) [98]. The $Q_{v:10}$ of 0.2 m^3/s is for a building with a volume of 500 m^3. This is a $Q_{v;10}$ of 1.08 $dm^3/s*m^2$ for an apartment of 43.82 m^2. Comparing it to the classification of an energy efficient building which has a $Q_{v;10}$ of 0.4-0.6 $dm^3/s*m^2$, the requirements of the National Building Code are approximately a basic level. For these simulations the airtightness of the building will differ for each scenario. The basic $Q_{v;10}$ will be 0.45 $dm^3/s*m^2$ for the internal and external separation construction. The $Q_{v;10}$ value corresponds with the national building code and is used for almost energy neutral buildings, BENG in the Dutch regulations. The $Q_{v;10}$ value used in this project are shown in Table 9-6.

Table 9-6. Airtightness of the building.

	Qualification	$Q_{v;10}$ ($dm^3/s*m^2$)
Internal	Good	0.45
external	Good	0.45

In order to calculate the equivalent surface area equation (4) has been used:

$$A_{netto} = \frac{C}{8,33} \cdot (\Delta P)^{(n-0.5)} \qquad (4)$$

Where:

- A is the equivalent surface area expressed in dm^2
- C is the air leakage coefficient expressed in $m^3/h*Pa^{-n}$
- P is the pressure expressed in Pa
- n is the flow exponent

When using formula 2 for the equivalent surface area for air leakages, the equivalent surface area depends on the pressure difference between indoor and outdoor. The equivalent surface area is calculated for a reference pressure difference of 10 Pa. This means that for pressure differences <10 Pa the equivalent surface area is overestimated and for pressure difference >10 Pa the equivalent surface area is underestimated. This is the result of a flow exponent of n>0.5.

The equivalent surface area is defined for each air leakage path. Table 9-7 shows the average factor and the standard deviation of that factor for the equivalent surface area. The equivalent surface area of the compartments is shown in Table 9-10.

Table 9-7. Stochastic boundary conditions used in the sensitivity analysis for spread of fire and conservation of the escape routes.

	Average	Variation	Standard deviation
External airtightness multiplier	1	0.7	0.7
		-0.7	0.7
Internal airtightness multiplier	1	1.5	1.5
		-0.5	-0.5

Vents

The equivalent surface area calculated based on the assumptions made for the airtightness need to be included in the model. The equivalent surface area is included in the model by creating small openings in the compartment. These small openings or small vents need to be applied over the entire height of the compartment. By applying the vents over the entire height, the fire behavior is affected as little as possible. The vent measurements used in the simulation are shown in a table for each scenario. Doors and windows will be opened and closed in the simulations, Table 9-8 and Table 9-9 show the specifics regarding the doors and windows in the fire compartment. shows the specifics for the doors and windows in the simulation used in the probabilistic approach.

Table 9-8. Specifics of the doors and windows.

Opening	From compartment	Towards compartment	Width [m]	Height [m]	Opening [s]	Closing [s]	Percentage of opening [%]
Door	Compartment 11.08	Adjacent corridor	1.26	2.4	120	140	100
Windows	Compartment 11.08	Outside	1.75	2.17	300[16]	-	10

Table 9-9. Specifics of the doors in the CFAST simulations.

SENSITIVITY ANALYSIS		Deterministic	Sensitivity analysis		
Stochastic boundary conditions		**average x**	**variation V**	**st. deviation s**	**new value x + dx**
Time door opens	s	120	1.50	180.00	300.00
			-0.50	-60.00	60.00
Time door closes	s	20	2.00	40.00	60.00
			-0.50	-10.00	10.00

The mechanical ventilation in the apartments has been neglected for the simulations of this project based on a worst case approach. The capacity of an individual mechanical ventilation system has a small influence on the fire scenario, smoke production and the smoke spread. The only effect it can have is positive since it extracts smoke from the fire compartment.

Figure 9-3 shows all the openings in the computational model for the low-rise reference study simulations. Figure 9-4 shows all the openings in the computational model for the super-tall study simulations.

[16] After 300 s the windows in the façade will be completely open in the low-rise reference study, based on a flash over. In the super-tall building study, the windows will stay closed, due to the sprinkler activation.

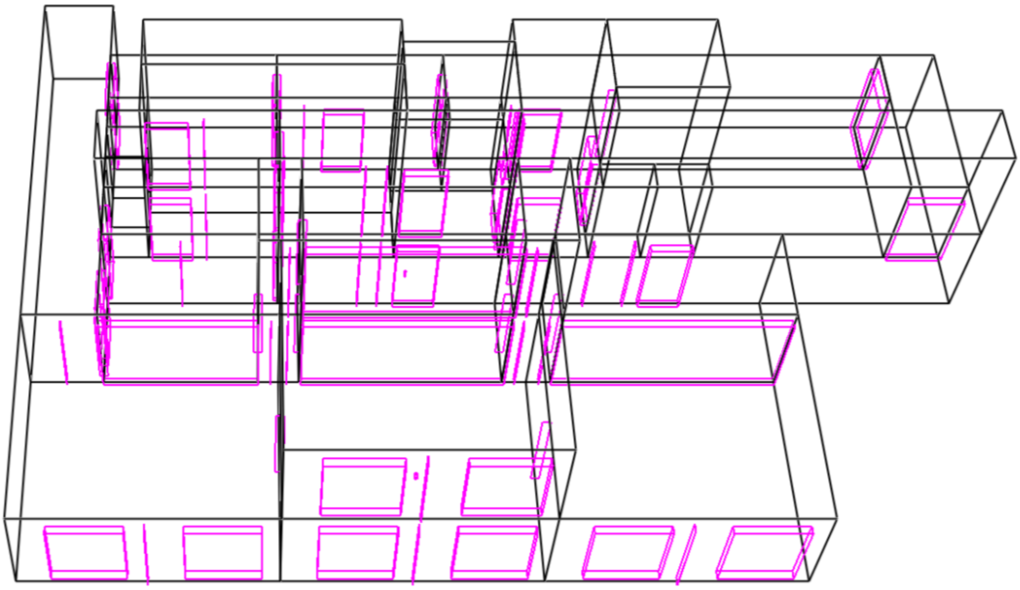


Figure 9-3. Geometry (wire model in 3D) of the low-rise reference study simulations in Smokeview.

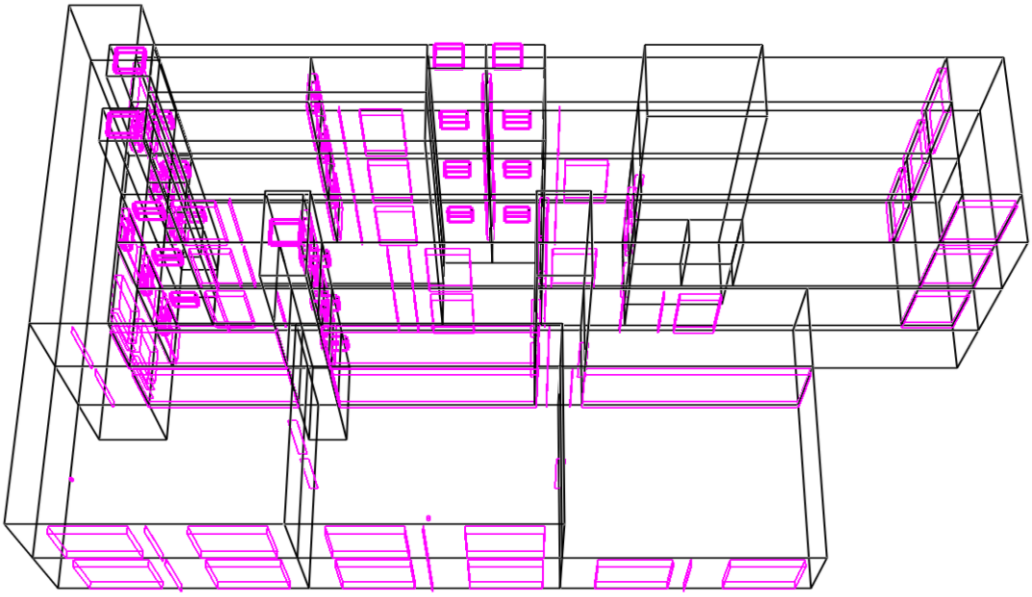


Figure 9-4. Geometry (wire model in 3D) of the super-tall study simulations in Smokeview.

Table 9-10. Equivalent surface areas of the compartments.

Separation construction	Qv;10 [dm³/s]	Qv;10 [dm³/s*m²]	$A_{equivalent}$ [dm²]	$A_{equivalent}$ [m²]	Height [m]	Vent width [m]	st. deviation +	-
11.07-1								
Façade	18.52	0.45	0.703	0.00703	2.60	0.00270	0.004597	0.000811
Floor	14.55	0.45	0.276	0.00276	-	-	0.006904	0.001381
Ceiling	14.55	0.45	0.276	0.00276	-	-	0.006904	0.001381
Separation construction 11.06 (n.a.)	14.55	0.45	0.276	0.00276	2.60	0.00106	0.002655	0.000531
Separation construction 11.08-1	14.55	0.45	0.276	0.00276	2.60	0.00106	0.002655	0.000531
Separation construction corridor 1	14.55	0.45	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Separation construction shaft 1	14.55	0.45	0.053	0.00053	2.60	0.00021	0.000514	0.000103
11.07-2								
Floor	3.97	0.45	0.075	0.00075	-	-	0.001886	0.000377
Ceiling	3.97	0.45	0.075	0.00075	-	-	0.001886	0.000377
Separation construction corridor 1	3.97	0.45	0.075	0.00075	2.60	0.00029	0.000725	0.000145
Separation construction corridor 2	3.97	0.45	0.439	0.00439	2.60	0.00169	0.004219	0.000844
Separation construction shaft 1	3.97	0.45	0.075	0.00075	2.60	0.00029	0.000725	0.000145
Door in separation construction	5.56	-	0.149	0.00149	2.60	0.00057	0.001434	0.000287
11.08-1								
Façade	19.72	0.45	0.749	0.00749	2.60	0.00288	0.004895	0.000864
Floor	14.45	0.45	0.274	0.00274	-	-	0.006857	0.001371
Ceiling	14.45	0.45	0.274	0.00274	-	-	0.006857	0.001371
Separation construction 11.07-1	14.45	0.45	0.274	0.00274	2.60	0.00105	0.002637	0.000527
Separation construction 11.09-1	14.45	0.45	0.274	0.00274	2.60	0.00105	0.002637	0.000527
Separation construction shaft 1	14.45	0.45	0.057	0.00057	2.60	0.00022	0.000543	0.000109
Separation construction shaft 2	14.45	0.45	0.070	0.00070	2.60	0.00027	0.000672	0.000134

Separation construction	Qv;10 [dm³/s]	Qv;10 [dm³/s*m²]	$A_{equivalent}$ [dm²]	$A_{equivalent}$ [m²]	Height [m]	Vent width [m]	st. deviation +	st. deviation -
11.08-2								
Floor	5.27	0.45	0.100	0.00100	-	-	0.002501	0.0005
Ceiling	5.27	0.45	0.100	0.00100	-	-	0.002501	0.0005
Separation construction shaft 1	5.27	0.45	0.100	0.00100	2.60	0.00038	0.000962	0.000192
Separation construction corridor 3	5.27	0.45	0.467	0.00467	2.60	0.00180	0.004491	0.000898
Separation construction shaft 2	5.27	0.45	0.100	0.00100	2.60	0.00038	0.000962	0.000192
Door in separation construction	5.56	-	0.149	0.00149	2.60	0.00057	0.001434	0.000287

11.09-1								
Façade	19.65	0.45	0.746	0.00746	2.60000	0.00287	0.004878	0.000861
Floor	14.24	0.45	0.270	0.00270	-	-	0.006756	0.001351
Ceiling	14.24	0.45	0.270	0.00270	-	-	0.006756	0.001351
Separation construction 11.08-1	14.24	0.45	0.270	0.00270	2.60	0.00104	0.002599	0.00052
Separation construction 11.10 (n.a.)	14.24	0.45	0.270	0.00270	2.60	0.00104	0.002599	0.00052
Separation construction shaft 2	14.24	0.45	0.071	0.00071	2.60	0.00027	0.00068	0.000136

11.09-2								
Floor	5.41	0.45	0.103	0.00103	-	-	0.002569	0.000514
Ceiling	5.41	0.45	0.103	0.00103	-	-	0.002569	0.000514
Separation construction 11.10 (n.a.)	5.41	0.45	0.103	0.00103	2.60	0.00040	0.000988	0.000198
Separation construction corridor 3	5.41	0.45	0.675	0.00675	2.60	0.00260	0.006493	0.001299
Separation construction shaft 2	5.41	0.45	0.103	0.00103	2.60	0.00040	0.000988	0.000198
Door in separation construction	5.56	-	0.149	0.00149	2.60	0.00057	0.001434	0.000287

Separation construction	Qv;10 [dm³/s]	Qv;10 [dm³/s*m²]	$A_{equivalent}$ [dm²]	$A_{equivalent}$ [m²]	Height [m]	Vent width [m]	st. deviation +	st. deviation -
12.08-1								
Façade	19.72	0.45	0.749	0.00749	2.6	0.00288	0.004895	0.000864
Floor	14.45	0.45	0.274	0.00274	-	-	0.006857	0.001371
Ceiling	14.45	0.45	0.274	0.00274	-	-	0.006857	0.001371
Separation construction shaft 1	14.45	0.45	0.057	0.00057	2.6	0.00022	0.000543	0.000109
Separation construction shaft 2	14.45	0.45	0.070	0.00070	2.6	0.00027	0.000672	0.000134

12.08-2								
Floor	5.27	0.45	0.100	0.00100	-	-	0.002501	0.0005
Ceiling	5.27	0.45	0.100	0.00100	-	-	0.002501	0.0005
Separation construction shaft 1	5.27	0.45	0.100	0.00100	2.60000	0.00038	0.000962	0.000192
Separation construction corridor 3	5.27	0.45	0.467	0.00467	2.60000	0.00180	0.004491	0.000898
Separation construction shaft 2	5.27	0.45	0.100	0.00100	2.60000	0.00038	0.000962	0.000192
Door in separation construction	5.56	-	0.149	0.00149	2.60000	0.00057	0.001434	0.000287

Corridor 1								
Door in separation construction corridor 2	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Open corridor 4	-	-	-	-	-	-	-	-

Corridor 2								
Door in separation construction corridor 1	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Door in separation construction corridor 3	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406

Corridor 3								
Door in separation construction corridor 2	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Door in separation construction 11.08-2	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Door in separation construction corridor 8	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Door in separation construction 11.09-2	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Open corridor 7	-	-	-	-	-	-	-	-

Separation construction	Qv;10 [dm³/s]	Qv;10 [dm³/s*m²]	$A_{equivalent}$ [dm²]	$A_{equivalent}$ [m²]	Height [m]	Vent width [m]	st. deviation +	st. deviation -
Corridor 6								
Door in separation construction corridor 5	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Door in separation construction corridor 8	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Open corridor 7	-	-	-	-	-	-	-	-
Corridor 7								
Open corridor 3	-	-	-	-	-	-	-	-
Open corridor 6	-	-	-	-	-	-	-	-
Corridor 8								
Door in separation construction corridor 3	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Door in separation construction corridor 6	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Stairs 1, 2								
Door in separation construction corridor 2 and 6	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406
Elevator 1, 2								
Door in separation construction corridor 10	5.56	-	0.211	0.00211	2.60	0.00081	0.002028	0.000406

9.4 Appendix 4. Sprinkler activation DETACT

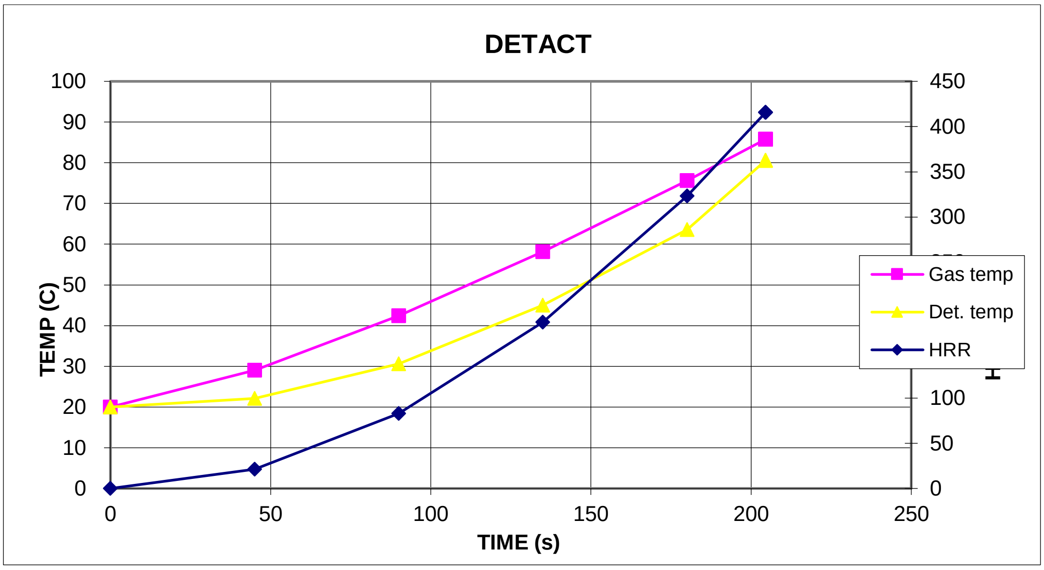
DETACT.XLS: Estimate of the response time of ceiling mounted fire detectors

INPUT PARAMETERS			CALCULATED PARAMETERS		
Calculation reset	1	0 or 1	R/H	0.8159	-
Ceiling height (H)	2.6	m	W/H	2.2692	-
Room width (W)	5.9	m	Temperature factor	0.3436	-
Radial distance (R)	2.1213	m	Velocity factor	0.237	-
Ambient temperature (To)	20	C	Calculation time (t)	192	s
Actuation temperature (Ta)	68	C	Fire HRR (Q)	433.2	kW
Rate of rise rating (ROR)	8.3	C/min	Gas temperature (Tg)	87.622	C
Response time index (RTI)	50	(m-s)1/2	Gas velocity (Ug)	1.3039	m/s
Fire growth power (n)	2	-	ROR at detector	4E-13	C/min
Fire growth coefficient (k)	0.012	kW/s^n	Detector temp (Td)	87.622	C
Fire location factor (kLF)	1	-	Detection trigger	190	1633

Representative t2 coeff.	k
Slow	0.003
Medium	0.012
Fast	0.047
Ultrafast	0.400

CALCULATION RESULTS	FT	ROR	
Transport lag time (tl)	145	15	s
Detection time (td)	**190**	1411	s
HRR at detection (Qd)	360	23891	kW
HRR w/transport lag (Ql+d)	416	24377	kW

Calculation time (s)	HRR	Gas temp	Det. temp
0	0	20	20
45	24	30	22
90	97	45	31
135	219	63	45
180	389	83	64
202	491	94	81
202	491	94	81
202	491	94	81
202	491	94	81



Design fire scenario with sprinkler activation
The design fire input for CFAST based on the DETACT calculation.

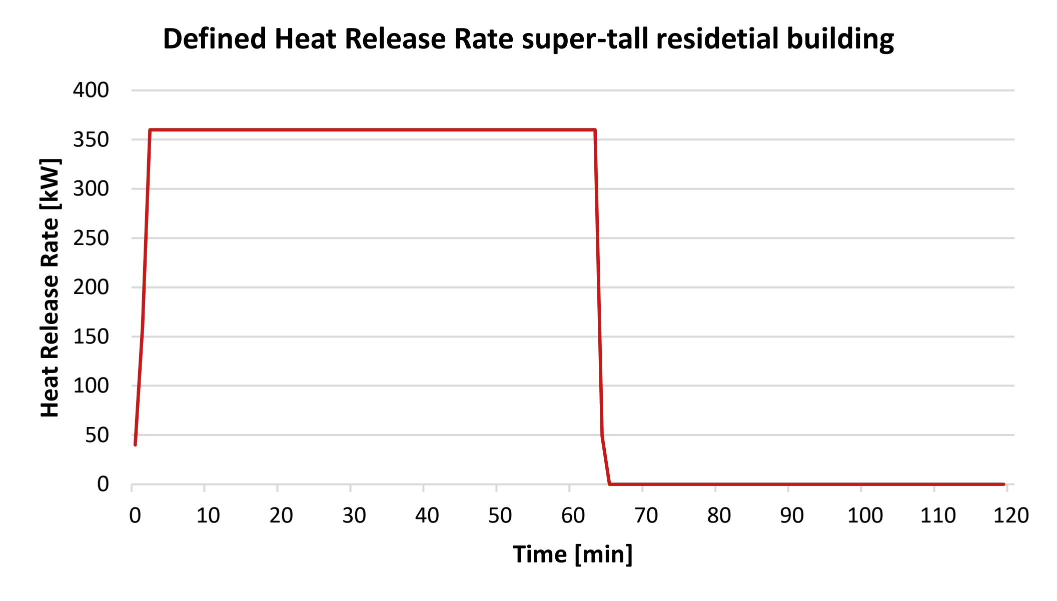


Figure 9-5. Defined Heat Release Rate in a sprinklered compartment of the super-tall residential building.

Calculated fire scenario with sprinkler activation
As a result applying an automatic suppression system the lack of oxygen in the room decreases the Heat Release Rate of the fire after 900 seconds, as shown in Figure 9-6. This scenario could also occur in a situation where the automatic suppression system completely extinguishes the fire.

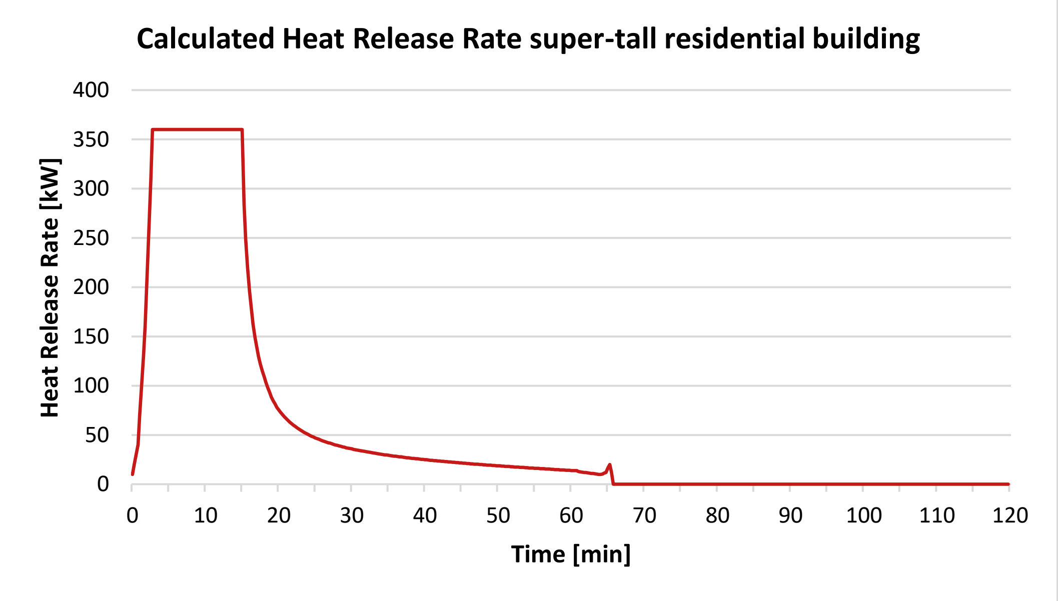
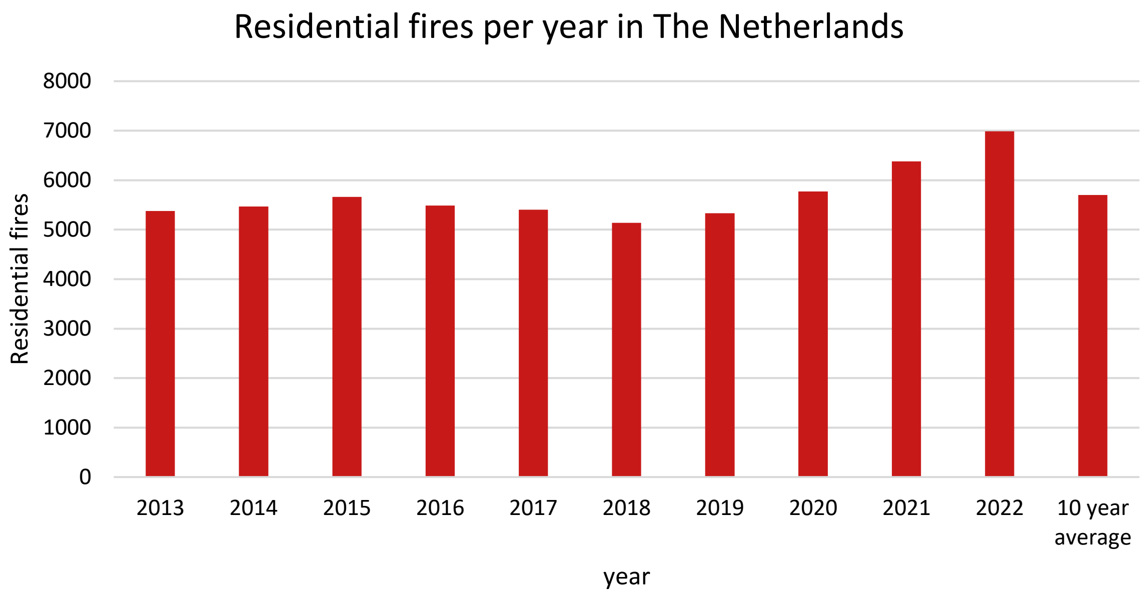


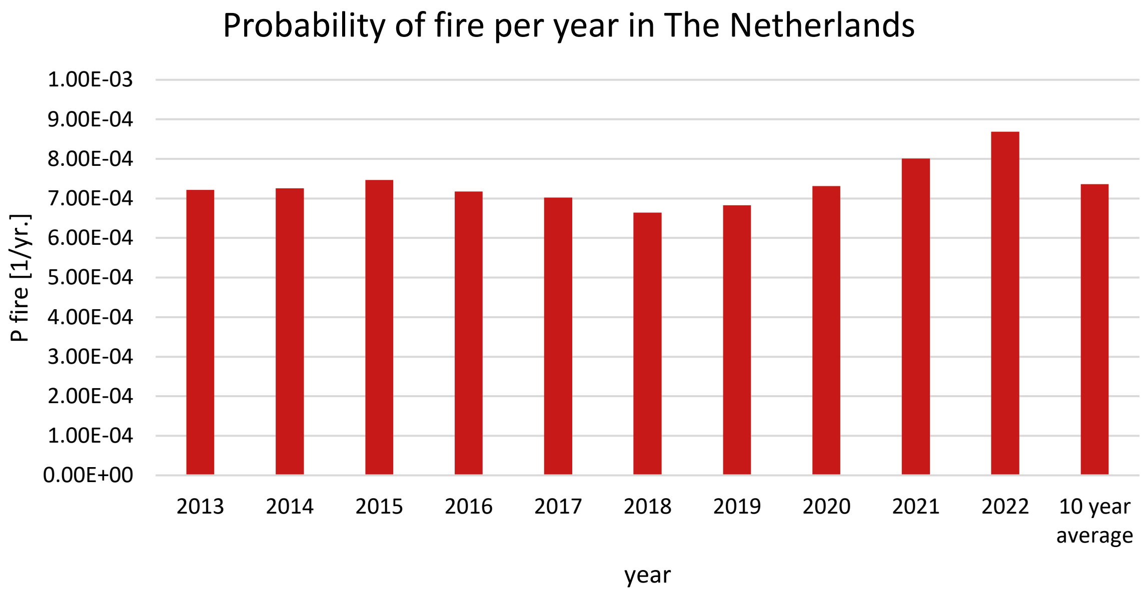
Figure 9-6. Calculated Heat Release Rate in a sprinklered compartment of the super-tall residential building.

9.5 Appendix 5. Statistics of residential fires in the Netherlands for the past 10 years

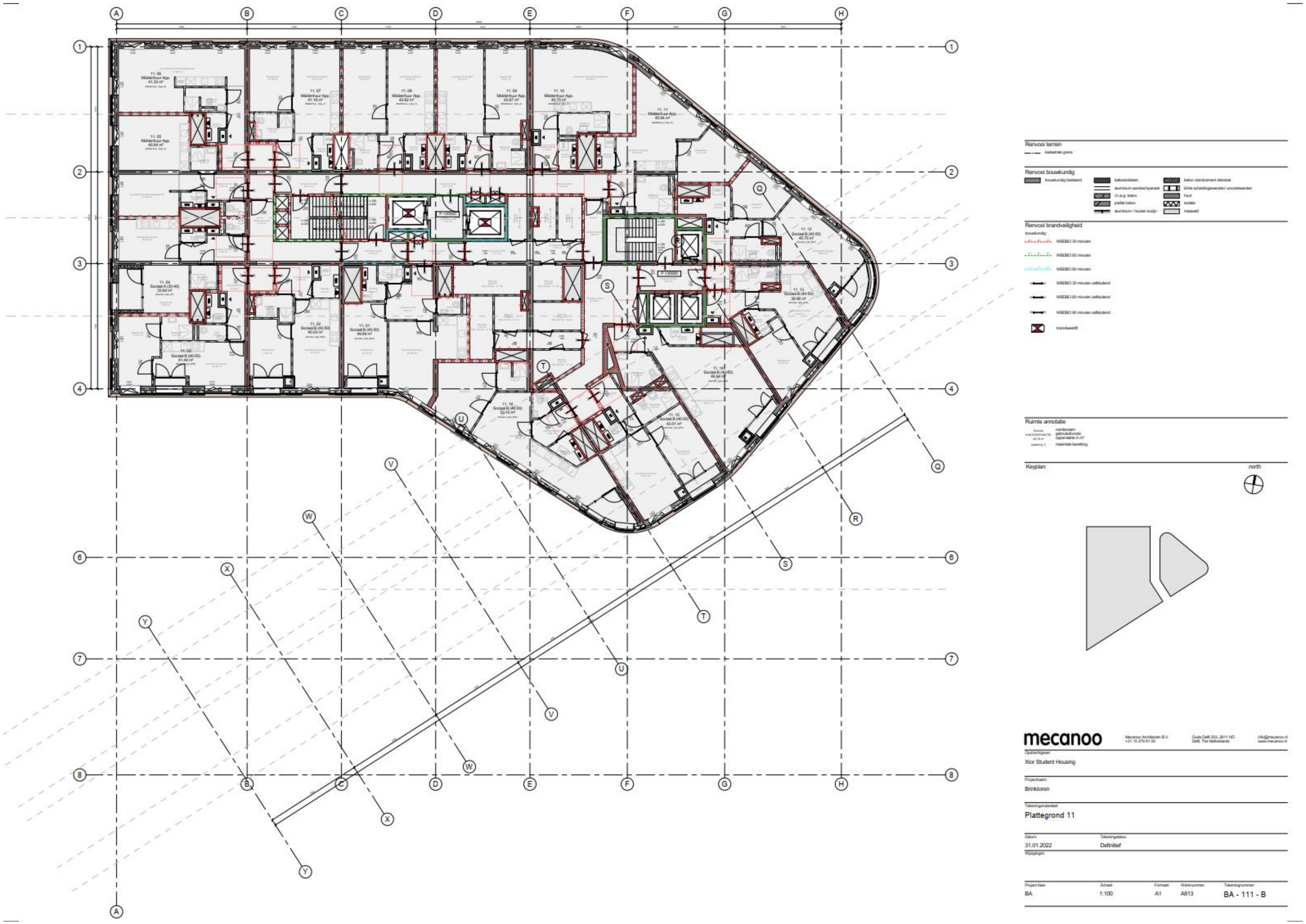
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	10 year average
Total residential fires	5375[17]	5470[17]	5665[17]	5485[17]	5400[17]**Fout! Bladwijzer niet gedefinieerd.**	5140[18]	5334[18]	5773[18]**Fout! Bladwijzer niet gedefinieerd.**	6378[18]	6990[18]**Fout! Bladwijzer niet gedefinieerd.**	5701
Total residential buildings[19]Fout! Bladwijzer niet gedefinieerd.	7.45E+06	7.54E+06	7.59E+06	7.64E+06	7.69E+06	7.74E+06	7.81E+06	7.89E+06	7.97E+06	8.05E+06	-
P fire [1/yr.]	7.22E-04	7.26E-04	7.47E-04	7.18E-04	7.03E-04	6.64E-04	6.83E-04	7.32E04	8.01E-04	8.69E-04	7.36E-04
Total residential area[19]	8.86E+08	9.04E+08	9.03E+08	9.09E+08	9.15E+08	9.21E+08	9.3E+08	9.39E+08	9.48E+08	9.65E+08	-
P fire [1/m2/yr.]	6.06E-06	6.05E-06	6.27E-06	6.03E-06	5.90E-06	5.58E-06	5.74E-06	6.15E-06	6.73E-06	7.24-E06	6.18E-06

[17] Total residential fires in the Netherlands from 2013 to 2017 [32]
[18] Total residential fires in the Netherlands from 2018 to 2022 [33]
[19] Total residential area in The Netherlands from 2013 to 2022 [99]

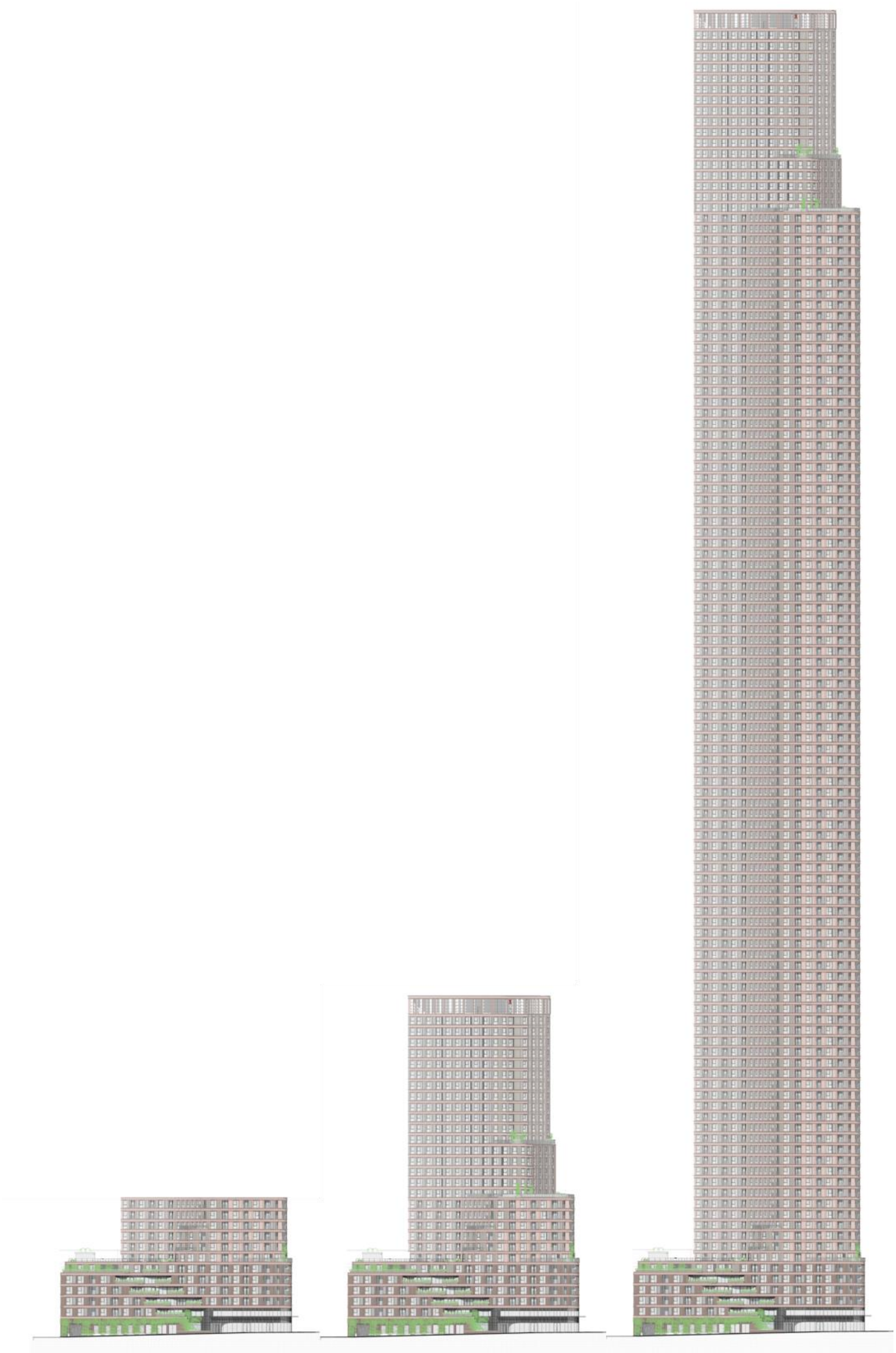

Residential fires per year in The Netherlands
8000
7000
6000
5000
4000
3000
2000
1000
0
Residential fires
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
10 year average
year


Probability of fire per year in The Netherlands
1.00E-03
9.00E-04
8.00E-04
7.00E-04
6.00E-04
5.00E-04
4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
P fire [1/yr.]
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
10 year average
year

9.6 Appendix 6. Architectural drawing of the Brinktoren, floor 11


Renvooi terrain
Renvooi bouwkundig
Renvooi brandveiligheid
Ruimte annotatie
Keyplan:
north
mecanoo
Opdrachtgever:
Xior Student Housing
Projectnaam:
Brinktoren
Tekeningonderdeel:
Plattegrond 11
Datum:
31.01.2022
Tekeningstatus:
Definitief
Wijzigingen
Project fase:
BA
Schaal:
1:100
Formaat:
A1
Werknummer:
A813
Tekeningnummer:
BA - 111 - B

9.7 Appendix 7. Comparison of the low-rise residential building, the Brinktoren and the super-tall residential building



9.8 Appendix 8. OZone input

OZone V 3.0.4 Report

ANALYSIS

Analysis Name:

File Name:C:\Users\joost\OneDrive\Bureaublad\Ozone_afstuderen\1. validation study - compartment basis.ozn

Created: 5/11/2023 at 8:46:07 PM

Strategy

Select Analysis Strategy: Combination (default)

Transition (2 Zones to 1 Zone) Criteria

Upper Layer Temperature ≥ 500 °C

Combustible in Upper Layer + U.L. Temperature ≥ Combustible Ignition Temperature = 300 °C

Interface Height ≤ 0.2 x Compartment Height

Fire Area ≥ 0.25 x Floor Area

Parameters

Openings

Radiation Through Closed Openings: 0.8

Bernoulli Coefficient: 0.7

Physical Characteristics of Compartment

Initial Temperature: 293 K

Initial Pressure: 100000 Pa

Parameters of Wall Material

Convection Coefficient at the Hot Surface: 25 W/m²K

Convection Coefficient at the Cold Surface: 9 W/m²K

Calculation Parameters

End of Calculation: 7200 sec

Time Step for Printing Results: 60 sec

Maximum Time Step for Calculation: 1 sec

Air Entrained Model:Heskestad

Temperature Dependent Openings

Temperature Dependent: 400 °C

Stepwise Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Linear Variation

Temperature	% of Total Openings
[°C]	[%]
20	10
400	50
500	100

Time Dependent Openings

Time	% of Total Openings
[sec]	[%]
0	5
1200	100

Compartment...

Compartment Geometry: Rectangular Floor

Height: 3 m

Depth: 5.895 m

Length: 7.433 m

Flat Roof

Floor

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	37	2300	1.6	1000	0.8	0.8

Ceiling

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	37	2300	1.6	1000	0.8	0.8

Wall 1

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1.6	1000	0.8	0.8
Glass wool Rock wool	15	60	0.037	1030	0.8	0.8
Normal Bricks	9	1600	0.7	840	0.8	0.8

Openings

Sill Height Hi	Soffit Height Hs	Width	Variation	Adiabatic
[m]	[m]	[m]		
1	2.6	4.58	Constant	no

Wall 2

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1.6	1000	0.8	0.8

Wall 3

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1.6	1000	0.8	0.8

Wall 4

Material	Thickness	Unit mass	Conductivity	Specific Heat	Rel Emissivity	Rel Emissivity
	[cm]	[kg/m³]	[W/mK]	[J/kgK]	Hot Surface	Rel Emissivity
Normal weight Concrete [EN1994-1-2]	25	2300	1.6	1000	0.8	0.8

TU/e

Fire...

Compartment Fire: Annex E (EN 1991-1-2)

Max Fire Area: 43.81754 m^2

Fire Elevation: 1 m

Fuel Height: 1.5 m

Occupancy	Fire Growth Rate	RHRf	Fire Load qf,k	Danger of Fire Activation
		[kW/m²]	80% Fractile [MJ/m²]	
User Defined	300	250	780	1

Active Fire Fighting Measures

Automatic Water Extinguishing System		δ_1=1
Independent Water Supplies		δ_2=1
Automatic Fire Detection by Heat		$\delta_{3,4}$=1
Automatic Fire Detection by Smoke		
Automatic Alarm Transmission to Fire Brigade		δ_5=1
Work Fire Brigade		$\delta_{6,7}$=1
Off Site Fire Brigade		
Safe Access Routes	on	δ_8=1
Staircases Under Overpressure in Fire Alarm		
Fire Fighting Devices	on	δ_9=1
Smoke Exhaust System	on	δ_{10}=1

Fire Risk Area: 12.5 m^2 $\delta_{q,1} = 1$

Danger of Fire Activation:$\delta_{q,2} = 1$

Active Measures:$\Pi\delta_{n,i} = 1$

$q_{f,d}$ = 624.0

Combustion Heat of Fuel: 17.5MJ/kg

Combustion Efficiency Factor: 0.8

Combustion Model: No combustion model

RESULTS

Fire Area: The maximum fire area (43.82m²) is greater than 25% of the floor area (43.82m²). The fire load is uniformly distributed.

Switch to one zone: Area of fire > 25.0% of floor area at time [s] 497.00

Fully engulfed fire: Temperature of zone in contact with fuel >300.0°C at time [s] 550.00

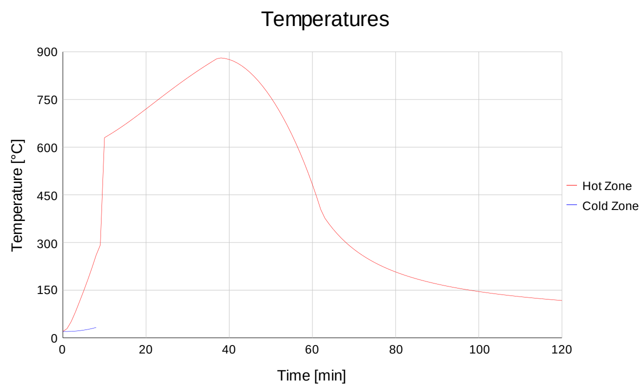


Figure 1. Hot and Cold Zone Temperature

Max: 881°C At:38 min

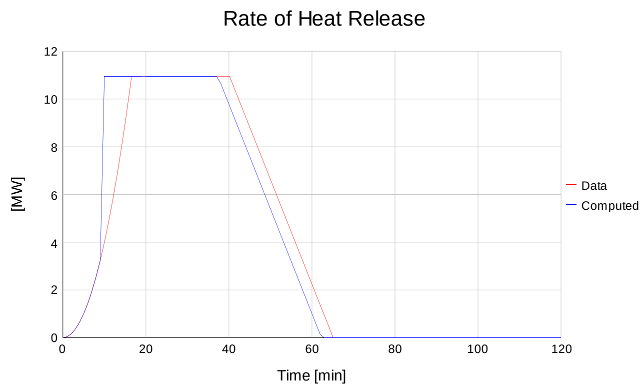


Figure 2. RHR Data and Computed

Max: 10.95MW At:10.00 min

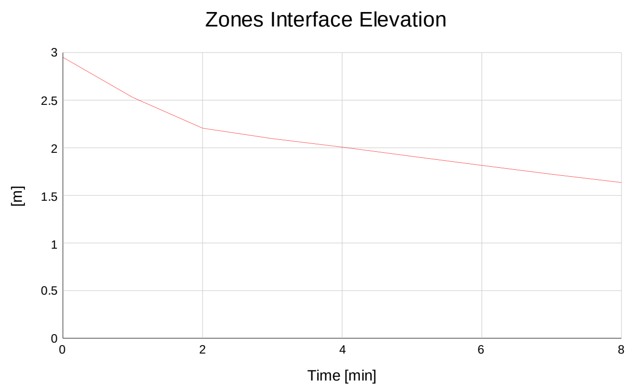


Figure 4. Zones Interface Elevation

Max: 1.64m at:8.00 min

9.9 Appendix 9. Low-rise residential reference building model, CFAST input

```
CFAST

Release Version  : CFAST 7.7.3
Revision         : CFAST7.7.4-0-g6b52d0c3
Revision Date    : Fri Jan 13 15:42:10 2023 -0500
Compilation Date : Thu 01/19/2023  11:24 AM

Data file: C:\Users\joost\OneDrive\Bureaublad\CFAST_afstuderen\CFAST-model validation - basis.in
Title: CFAST Simulation


OVERVIEW


Compartments    Doors, ...    Ceil. Vents, ...    MV Connects
-------------------------------------------------------------
  32               74            2                    0

Simulation     Output         Smokeview      Spreadsheet
Time           Interval       Interval       Interval
   (s)            (s)            (s)            (s)
--------------------------------------------------------
   4500.00          60.00          15.00          15.00


AMBIENT CONDITIONS

Interior       Interior       Exterior       Exterior
Temperature    Pressure       Temperature    Pressure
  (C)            (Pa)           (C)            (Pa)
-----------------------------------------------------
    20.          101325.          20.          101325.


THERMAL PROPERTIES

Name     Conductivity        Specific Heat       Density        Thickness     Emissivity
         (kW/(m ï¿½C))        (kJ/(m ï¿½C))        (kg/m^3)        (m)
-----------------------------------------------------------------------------------------
NM 1         1.60                800.            2.300E+03       0.250           0.800
NM 2         1.60                800.            2.300E+03       0.280           0.800
NM 3         1.50                800.            2.300E+03       9.000E-02       0.800
```

DEFAULT 0.120 900. 800. 1.200E-02 0.900

COMPARTMENTS

Compartment	Name	Width	Depth	Height	Floor Height	Ceiling Height	Shaft	Hall	Wall Leakage	Floor Leakage
		(m)	(m)	(m)	(m)	(m)			(m^2)	(m^2)
1	Comp 5 - shaf	1.00	2.45	6.00	0.00	6.00	*		0.0	0.0
2	Comp 7 - shaf	1.20	2.45	6.00	0.00	6.00	*		0.0	0.0
3	Comp 1 - 11-0	6.10	5.65	3.00	0.00	3.00			0.0	0.0
4	Comp 2 - 11-0	6.10	5.65	3.00	0.00	3.00			0.0	0.0
5	Comp 3 - 11-0	6.10	5.65	3.00	0.00	3.00			0.0	0.0
6	Comp 4 - 11-0	3.80	2.45	3.00	0.00	3.00			0.0	0.0
7	Comp 6 - 11-0	5.00	2.45	3.00	0.00	3.00			0.0	0.0
8	Comp 8 - 11-0	5.50	2.45	3.00	0.00	3.00			0.0	0.0
9	Comp 9 - gang	1.80	10.25	3.00	0.00	3.00	*		0.0	0.0
10	Comp 10 - gan	4.30	1.50	3.00	0.00	3.00	*		0.0	0.0
11	Comp 11 - gan	17.00	1.50	3.00	0.00	3.00	*		0.0	0.0
12	Comp 13 - sha	1.00	1.00	3.00	0.00	3.00	*		0.0	0.0
13	Comp 14 - sha	1.00	1.00	3.00	0.00	3.00	*		0.0	0.0
14	Comp 15 - sha	1.00	1.00	3.00	0.00	3.00	*		0.0	0.0
15	Comp 16 - sta	6.30	1.50	6.00	0.00	6.00	*		0.0	0.0
16	Comp 17 - sta	6.30	1.50	6.00	0.00	6.00	*		0.0	0.0
17	Comp 18 - gan	4.30	1.50	3.00	0.00	3.00	*		0.0	0.0
18	Comp 19 - gan	4.30	1.50	3.00	0.00	3.00	*		0.0	0.0
19	Comp 20 - gan	11.30	1.50	3.00	0.00	3.00	*		0.0	0.0
20	Comp 22 - gan	1.40	4.50	3.00	0.00	3.00	*		0.0	0.0
21	Comp 23 - lif	2.70	2.25	6.00	0.00	6.00	*		0.0	0.0
22	Comp 24 - sha	1.35	0.75	3.00	0.00	3.00	*		0.0	0.0
23	Comp 25 - sha	1.35	0.75	3.00	0.00	3.00	*		0.0	0.0
24	Comp 26 - gan	2.30	3.00	3.00	0.00	3.00	*		0.0	0.0
25	Comp 27 - sha	1.35	0.75	3.00	0.00	3.00	*		0.0	0.0
26	Comp 28 - sha	1.35	0.75	3.00	0.00	3.00	*		0.0	0.0
27	Comp 29 - lif	2.70	2.25	6.00	0.00	6.00	*		0.0	0.0
28	Comp 30 - 12-	6.10	5.65	3.00	3.00	6.00			0.0	0.0
29	Comp 32 - 12-	5.00	2.45	3.00	3.00	6.00			0.0	0.0
30	Comp 34 - gan	4.30	1.50	3.00	3.00	6.00	*		0.0	0.0
31	Comp 35 - gan	17.00	1.50	3.00	3.00	6.00	*		0.0	0.0
32	Comp 45 - gan	2.30	3.00	3.00	3.00	6.00	*		0.0	0.0

COMPARTMENT MATERIALS

Compartment	Name	Surface	Layer	Conductivity (kW/(m C))	Specific Heat (kJ/(m C))	Density (kg/m^3)	Thickness (m)	Emissivity	Material
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
3	Comp 1 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
4	Comp 2 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
5	Comp 3 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
6	Comp 4 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
7	Comp 6 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
8	Comp 8 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
9	Comp 9 - gang	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
10	Comp 10 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
11	Comp 11 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
17	Comp 18 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1

18	Comp 19 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
19	Comp 20 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
20	Comp 22 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
24	Comp 26 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
28	Comp 30 - 12-	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
29	Comp 32 - 12-	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
30	Comp 34 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
31	Comp 35 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
32	Comp 45 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1

VENT CONNECTIONS

Wall Vents (Doors, Windows, ...)

```
From           To             Vent      Width     Sill      Soffit    Open/Close  Trigger             Initial    Initial
Final       Final
Compartment    Compartment    Number              Height    Height    Type        Value     Target    Time       Fraction   Time
Fraction
```

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                                            (m)          (m)          (m)          (m)          (C/W/m^2)                (s)                        (s)
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Comp 1 - 11-07 Outside          1          1.75         0.31         2.48         Time                                 0.00         0.01      7200.00
0.01
Comp 1 - 11-07 Outside          2          1.75         0.31         2.48         Time                                 0.00         0.01      7200.00
0.01
Comp 2 - 11-08 Outside          3          1.75         0.31         2.48         RAMP # 1
Comp 2 - 11-08 Outside          4          1.75         0.31         2.48         RAMP # 2
Comp 3 - 11-09 Outside          5          1.75         0.31         2.48         Time                                 0.00         0.01      7200.00
0.01
Comp 3 - 11-09 Outside          6          1.75         0.31         2.48         Time                                 0.00         0.01      7200.00
0.01
Comp 1 - 11-07 Comp 4 - 11-07  7          3.80         0.00         2.60         RAMP # 3
Comp 2 - 11-08 Comp 6 - 11-08  8          5.00         0.00         2.60         RAMP # 4
Comp 3 - 11-09 Comp 8 - 11-09  9          5.50         0.00         2.60         RAMP # 5
Comp 4 - 11-07 Comp 9 - gang  10          1.03         0.00         2.42         RAMP # 6
Comp 6 - 11-08 Comp 11 - gang 11          1.03         0.00         2.42         RAMP # 7
Comp 8 - 11-09 Comp 11 - gang 12          1.03         0.00         2.42         RAMP # 8
Comp 9 - gang  Comp 10 - gang 13          1.14         0.00         2.42         RAMP # 9
Comp 9 - gang  Comp 18 - gang 14          1.50         0.00         2.70         Time                                 0.00         1.00      7200.00
1.00
Comp 10 - gang Comp 11 - gang 15          1.14         0.00         2.42         RAMP # 10
Comp 10 - gang Comp 16 - stai 16          1.03         0.00         2.42         RAMP # 11
Comp 18 - gang Comp 19 - gang 17          1.14         0.00         2.42         Time                                 0.00         1.00
Comp 19 - gang Comp 20 - gang 18          1.14         0.00         2.42         RAMP # 12
Comp 20 - gang Comp 22 - gang 19          1.50         0.00         2.42         Time                                 0.00         1.00      7200.00
1.00
Comp 20 - gang Comp 26 - gang 20          1.10         0.00         2.42         Time                                 0.00         1.00
Comp 11 - gang Comp 22 - gang 21          1.40         0.00         2.42         Time                                 0.00         1.00      7200.00
1.00
Comp 17 - stai Comp 19 - gang 22          1.03         0.00         2.42         RAMP # 13
Comp 11 - gang Comp 26 - gang 23          1.10         0.00         2.42         Time                                 0.00         1.00
Comp 23 - lift Comp 26 - gang 24          0.96         0.00         2.42         Time                                 0.00         1.00
Comp 26 - gang Comp 29 - lift 25          0.96         0.00         2.42         Time                                 0.00         1.00
Comp 1 - 11-07 Outside         26          0.00         0.00         2.60         Time                                 0.00         1.00      7200.00
1.00
Comp 2 - 11-08 Outside         27          0.00         0.00         2.60         Time                                 0.00         1.00      7200.00
1.00
Comp 3 - 11-09 Outside         28          0.00         0.00         2.60         Time                                 0.00         1.00      7200.00
1.00
Comp 1 - 11-07 Comp 2 - 11-08 29          0.00         0.00         2.60         Time                                 0.00         1.00      7200.00
1.00
Comp 2 - 11-08 Comp 3 - 11-09 30          0.00         0.00         2.60         Time                                 0.00         1.00      7200.00
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1.00
Comp 1 - 11-07 Comp 9 - gang 31   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 5 - shaft Comp 1 - 11-07 32   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 5 - shaft Comp 4 - 11-07 33   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 4 - 11-07 Comp 9 - gang 34   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 4 - 11-07 Comp 10 - gang 35   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 4 - 11-07 Comp 9 - gang 36   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 5 - shaft Comp 2 - 11-08 37   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 7 - shaft Comp 2 - 11-08 38   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 5 - shaft Comp 6 - 11-08 39   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 7 - shaft Comp 6 - 11-08 40   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 6 - 11-08 Comp 11 - gang 41   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 6 - 11-08 Comp 11 - gang 42   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 7 - shaft Comp 3 - 11-09 43   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 7 - shaft Comp 8 - 11-09 44   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 8 - 11-09 Comp 11 - gang 45   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 8 - 11-09 Comp 11 - gang 46   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 9 - gang Comp 10 - gang 47   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 10 - gang Comp 16 - stai 48   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 10 - gang Comp 11 - gang 49   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 11 - gang Comp 26 - gang 50   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 18 - gang Comp 19 - gang 51   0.00   0.00   2.60   Time   0.00   1.00   7200.00
1.00
Comp 17 - stai Comp 19 - gang 52   0.00   0.00   2.60   Time   0.00   1.00   7200.00

									1.00
Comp 19 - gang Comp 20 - gang	53	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 20 - gang Comp 26 - gang	54	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 23 - lift Comp 26 - gang	55	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 26 - gang Comp 29 - lift	56	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 30 - 12-0 Outside	57	1.75	0.31	2.48	Time	0.00	0.01	7200.00	0.01
Comp 30 - 12-0 Outside	58	1.75	0.31	2.48	Time	0.00	0.01	7200.00	0.01
Comp 30 - 12-0 Comp 32 - 12-0	59	5.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 32 - 12-0 Comp 35 - gang	60	1.03	0.00	2.42	RAMP # 14				
Comp 34 - gang Comp 35 - gang	61	1.14	0.00	2.42	RAMP # 15				
Comp 16 - stai Comp 34 - gang	62	1.03	3.00	5.42	RAMP # 16				
Comp 30 - 12-0 Outside	63	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 5 - shaft Comp 30 - 12-0	64	0.00	3.00	5.60	Time	0.00	1.00	7200.00	1.00
Comp 7 - shaft Comp 30 - 12-0	65	0.00	3.00	5.60	Time	0.00	1.00	7200.00	1.00
Comp 5 - shaft Comp 32 - 12-0	66	0.00	3.00	5.60	Time	0.00	1.00	7200.00	1.00
Comp 7 - shaft Comp 32 - 12-0	67	0.00	3.00	5.60	Time	0.00	1.00	7200.00	1.00
Comp 32 - 12-0 Comp 35 - gang	68	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 32 - 12-0 Comp 35 - gang	69	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 34 - gang Comp 35 - gang	70	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 16 - stai Comp 34 - gang	71	0.00	3.00	5.60	Time	0.00	1.00	7200.00	1.00
Comp 35 - gang Comp 45 - gang	72	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 23 - lift Comp 45 - gang	73	0.00	3.00	5.60	Time	0.00	1.00	7200.00	1.00
Comp 29 - lift Comp 45 - gang	74	0.00	3.00	5.60	Time	0.00	1.00	7200.00	1.00

Ceiling and Floor Vents

Top Compartment	Bottom Compartment	Vent Number	Shape	Area (m^2)	Open/Close Type	Trigger Value (C/W/m^2)	Target	Initial Time (s)	Initial Fraction	Final Time (s)	Final Fraction
Comp 30 - 12-0	Comp 2 - 11-08	1	Square	0.00	Time			0.00	1.00	0.00	1.00
Comp 32 - 12-0	Comp 6 - 11-08	2	Square	0.00	Time			0.00	1.00	0.00	1.00

There are no mechanical flow connections

VENT RAMPS

Type	From Compartment	To Compartment	Vent Number		(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)
H	Comp 2 - 11-08	Outside	1	Time	0	299	300	7200						
				Fraction	0.01	0.01	1.00	1.00						
H	Comp 2 - 11-08	Outside	2	Time	0	299	300	7200						
				Fraction	0.01	0.01	1.00	1.00						
H	Comp 1 - 11-07	Comp 4 - 11-07	3	Time	0	1	7200							
				Fraction	1.00	1.00	1.00							
H	Comp 2 - 11-08	Comp 6 - 11-08	4	Time	0	1	7200							
				Fraction	1.00	1.00	1.00							
H	Comp 3 - 11-09	Comp 8 - 11-09	5	Time	0	1	7200							
				Fraction	1.00	1.00	1.00							
H	Comp 4 - 11-07	Comp 9 - gang	6	Time	0	1019	1020	1040	1041	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 6 - 11-08	Comp 11 - gang	7	Time	0	119	120	140	141	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 8 - 11-09	Comp 11 - gang	8	Time	0	1019	1020	1040	1041	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 9 - gang	Comp 10 - gang	9	Time	0	1039	1040	1060	1061	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 10 - gang	Comp 11 - gang	10	Time	0	139	140	160	161	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 10 - gang	Comp 16 - stai	11	Time	0	159	160	180	181	1059	1060	1080	1081	7200

			Fraction	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00
0.00												
H	Comp 19 - gang	Comp 20 - gang 12	Time	0	1039	1040	1060	1061	7200			
			Fraction	0.00	0.00	1.00	1.00	0.00	0.00			
H	Comp 17 - stai	Comp 19 - gang 13	Time	0	1059	1060	1080	1081	7200			
			Fraction	0.00	0.00	1.00	1.00	0.00	0.00			
H	Comp 32 - 12-0	Comp 35 - gang 14	Time	0	1019	1020	1040	1041	7200			
			Fraction	0.00	0.00	1.00	1.00	0.00	0.00			
H	Comp 34 - gang	Comp 35 - gang 15	Time	0	1039	1040	1060	1061	7200			
			Fraction	0.00	0.00	1.00	1.00	0.00	0.00			
H	Comp 16 - stai	Comp 34 - gang 16	Time	0	1059	1060	1080	1081	7200			
			Fraction	0.00	0.00	1.00	1.00	0.00	0.00			

FIRES

Name: New Fire 1 Referenced as object # 1 Normal fire

Compartment	Fire Type	Time to Flaming	Position (x,y,z)			Relative Humidity	Lower O2 Limit	Radiative Fraction
Comp 2 - 11-08	Constrained	0.0	3.05	2.83	1.00	50.0	10.00	0.35

Chemical formula of the fuel

Carbon	Hydrogen	Oxygen	Nitrogen	Chlorine
4.000	6.000	3.000	0.000	0.000

Time (s)	Mdot (kg/s)	Hcomb (J/kg)	Qdot (W)	Zoffset (m)	Soot (kg/kg)	CO (kg/kg)	HCN (kg/kg)	HCl (kg/kg)	TS (kg/kg)
0.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
60.	2.29E-03	1.75E+07	4.00E+04	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
120.	9.14E-03	1.75E+07	1.60E+05	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
180.	2.06E-02	1.75E+07	3.60E+05	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
240.	3.66E-02	1.75E+07	6.40E+05	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
300.	5.71E-02	1.75E+07	1.00E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
360.	8.23E-02	1.75E+07	1.44E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
420.	0.11	1.75E+07	1.96E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0

480.	0.15	1.75E+07	2.56E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
540.	0.19	1.75E+07	3.24E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
600.	0.23	1.75E+07	4.00E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
660.	0.28	1.75E+07	4.84E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
720.	0.33	1.75E+07	5.76E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
780.	0.39	1.75E+07	6.76E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
840.	0.45	1.75E+07	7.84E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
900.	0.51	1.75E+07	9.00E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
960.	0.59	1.75E+07	1.02E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1020.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1080.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1140.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1200.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1260.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1320.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1380.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1440.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1500.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1560.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1620.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1680.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1740.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1800.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1860.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1920.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
1980.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2040.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2100.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2160.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2220.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2280.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2340.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2400.	0.63	1.75E+07	1.10E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2460.	0.60	1.75E+07	1.06E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2520.	0.58	1.75E+07	1.01E+07	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2580.	0.55	1.75E+07	9.70E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2640.	0.53	1.75E+07	9.27E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2700.	0.50	1.75E+07	8.83E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2760.	0.48	1.75E+07	8.39E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2820.	0.45	1.75E+07	7.95E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2880.	0.43	1.75E+07	7.51E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
2940.	0.40	1.75E+07	7.07E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3000.	0.38	1.75E+07	6.63E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3060.	0.35	1.75E+07	6.19E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0

3120.	0.33	1.75E+07	5.75E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3180.	0.30	1.75E+07	5.32E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3240.	0.28	1.75E+07	4.88E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3300.	0.25	1.75E+07	4.44E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3360.	0.23	1.75E+07	4.00E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3420.	0.20	1.75E+07	3.56E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3480.	0.18	1.75E+07	3.12E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3540.	0.15	1.75E+07	2.68E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3600.	0.13	1.75E+07	2.24E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3660.	0.10	1.75E+07	1.80E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3720.	7.81E-02	1.75E+07	1.37E+06	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3780.	5.30E-02	1.75E+07	9.27E+05	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3840.	2.79E-02	1.75E+07	4.88E+05	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3900.	2.82E-03	1.75E+07	4.94E+04	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
3960.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4020.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4080.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4140.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4200.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4260.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4320.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4380.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4440.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4500.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4560.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4620.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4680.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4740.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4800.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4860.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4920.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
4980.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5040.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5100.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5160.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5220.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5280.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5340.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5400.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5460.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5520.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5580.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5640.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5700.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0

5760.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5820.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5880.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0
5940.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0

9.10 Appendix 10. Probabilistic approach low-rise residential reference building

PROBABILISTIC CALCULATION THERMAL LOAD / THERMAL RESISTANCE
REQUIRED TIME [SFC]

RST
Case: Low-rise residential reference building
Assessment: Equivalent fire duration of a natural fire (no flaming model)

SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic	
		average x	**RST t [min]**
Rate of heat release density	kW/m^2	250	
Timeconstant for fire spread	s	300	
Fire load density	MJ/m^2	780	
Combustion efficiency factor	-	0,8	
Stoichiometric coefficient	kg/kg	1,27	
Standard fire curve SFC	60 min. SFC	60	
		RST	**51,0**

(opening factor worst case: fuel/oxygen controlled)

Sensitivity analysis			
variation V	**st. deviation s**	**new value x + dx**	**RST t [min]**
0,40	100	350	41,0
-0,30	-75	175	65,0
0,25	75	375	51,0
-0,50	-150	150	52,0
0,15	117	897	59,0
-0,15	-117	663	44,0
0,08	0,1	0,862	57,0
-0,08	-0,1	0,738	46,0
0,50	0,6	1,91	45,0
-0,25	-0,3	0,95	56,0

Probabilistic			
dt/dx	**s·dt/dx**	**$(s·dt/dx)^2$**	
-0,10	-10,00	0,00	100,00
-0,19	14,00	196,00	0,00
0,00	0,00	0,00	0,00
-0,01	1,00	1,00	0,00
0,07	8,00	64,00	0,00
0,06	-7,00	0,00	49,00
96,77	6,00	36,00	0,00
80,65	-5,00	0,00	25,00
-9,45	-6,00	0,00	36,00
-15,75	5,00	25,00	0,00
	variancy(t) =	322,000	210,000
	s(t) =	17,944	-14,491

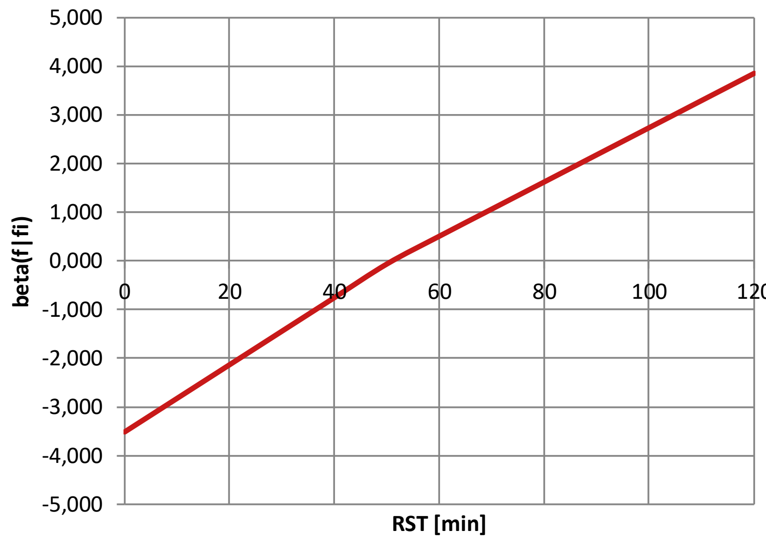
Reliability and cumulative failure probability			
t [min]	**s(t)**	**beta(f|fi)**	**p(f|fi)**
0	14,49138	-3,519	2,16E-04
10	14,49138	-2,829	2,33E-03
20	14,49138	-2,139	1,62E-02
30	14,49138	-1,449	7,36E-02
40	14,49138	-0,759	2,24E-01
50	14,49138	-0,069	4,72E-01
60	17,94436	0,502	6,92E-01
70	17,94436	1,059	8,55E-01
80	17,94436	1,616	9,47E-01
90	17,94436	2,173	9,85E-01
100	17,94436	2,731	9,97E-01
110	17,94436	3,288	9,99E-01
120	17,94436	3,845	1,00E+00

Significant event compartmentfire

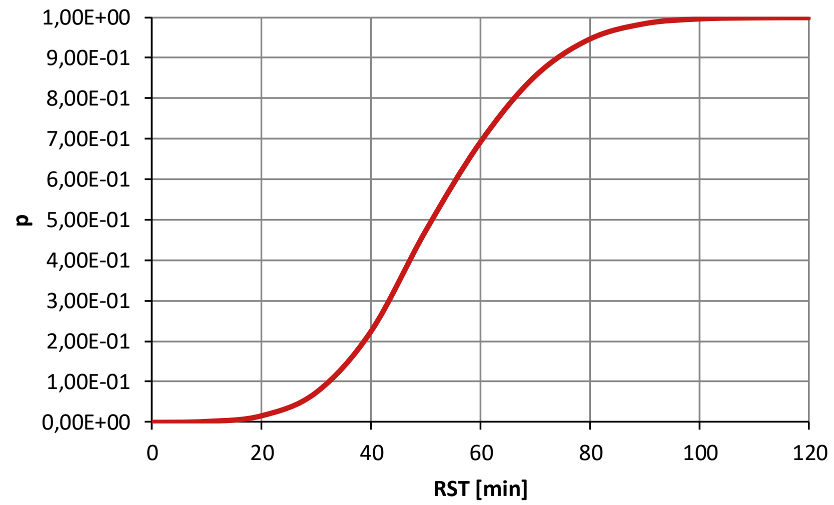
Compartment area $[m^2]$	43,82		
Design life time [yr] :	50		
Ignition probability $[1/m^2/1yr]$:	2,000E-07		
Ignition probability $[1/m^2/50yr]$:	1,00E-05	(during design lifetime)	
Probability of fire p(fi) :	4,38E-04	(during design lifetime)	

EUROCODE	p(f)	p(f|fi)	beta(f|fi)
CC1: beta(f) > 3,3	4,83E-04	1,10E+00	#GETAL!
CC2: beta(f) > 3,8	7,23E-05	1,65E-01	**0,97**
CC3: beta(f) > 4,3	8,54E-06	1,95E-02	2,06

reliability index



Cumulative probability of thermal action on compartment separation constructions



PROBABILISTIC CALCULATION THERMAL LOAD / THERMAL RESISTANCE
AVAILABLE AND REQUIRED TIME [SFC]

RST
Case: Low-rise residential building study
Assessment: Equivalent fire duration of a natural fire (no flaming model)

SENSITIVITY ANALYSIS		**Deterministic**	
Stochastic boundary conditions		**average** **x**	**RST** **t [min]**
Rate of heat release density	kW/m^2	250	
Timeconstant for fire spread	s	300	
Fire load density	MJ/m^2	780	
Combustion efficiency factor	-	0,8	
Stoichiometric coefficient	kg/kg	1,27	
Standard fire curve SFC	120 min. SFC	120	
		RST	**51,0**

(opening factor worst case: fuel/oxygen controlled)

Sensitivity analysis			
variation **V**	**st. deviation** **s**	**new value** **x + dx**	**RST** **t [min]**
0,40	100	350	41,0
-0,30	-75	175	65,0
0,25	75	375	51,0
-0,50	-150	150	52,0
0,15	117	897	59,0
-0,15	-117	663	44,0
0,08	0,1	0,862	57,0
-0,08	-0,1	0,738	46,0
0,50	0,6	1,91	45,0
-0,25	-0,3	0,95	56,0

Probabilistic			
dt/dx	**s·dt/dx**	**$(s \cdot dt/dx)^2$**	
-0,10	-10,00	0,00	100,00
-0,19	14,00	196,00	0,00
0,00	0,00	0,00	0,00
-0,01	1,00	1,00	0,00
0,07	8,00	64,00	0,00
0,06	-7,00	0,00	49,00
96,77	6,00	36,00	0,00
80,65	-5,00	0,00	25,00
-9,45	-6,00	0,00	36,00
-15,75	5,00	25,00	0,00
	variancy(t) =	322,000	210,000
	s(t) =	17,944	-14,491

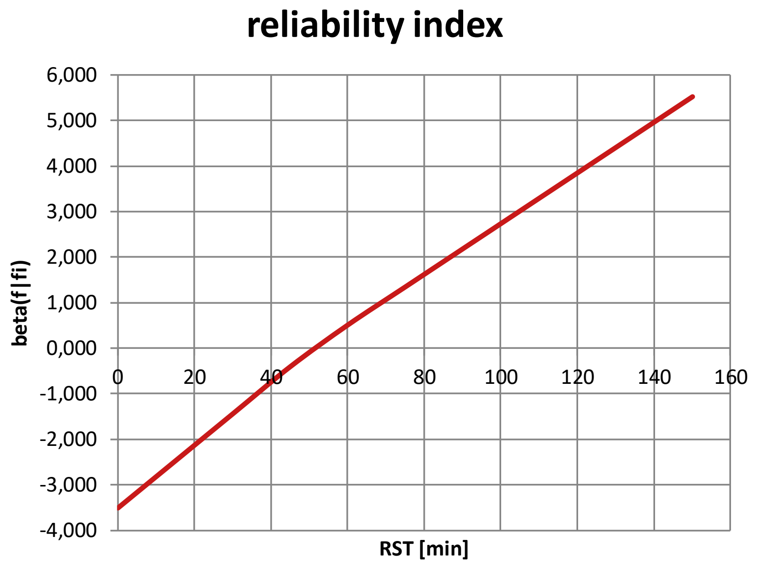
Reliability and cumulative failure probability			
t [min]	**s(t)**	**beta(f|fi)**	**p(f|fi)**
0	14,49138	-3,519	2,16E-04
15	14,49138	-2,484	6,49E-03
30	14,49138	-1,449	7,36E-02
45	14,49138	-0,414	3,39E-01
60	17,94436	0,502	6,92E-01
75	17,94436	1,337	9,09E-01
90	17,94436	2,173	9,85E-01
105	17,94436	3,009	9,99E-01
120	17,94436	**3,845**	1,00E+00
135	17,94436	4,681	1,00E+00
150	17,94436	5,517	1,00E+00
165	17,94436	6,353	1,00E+00
180	17,94436	7,189	1,00E+00

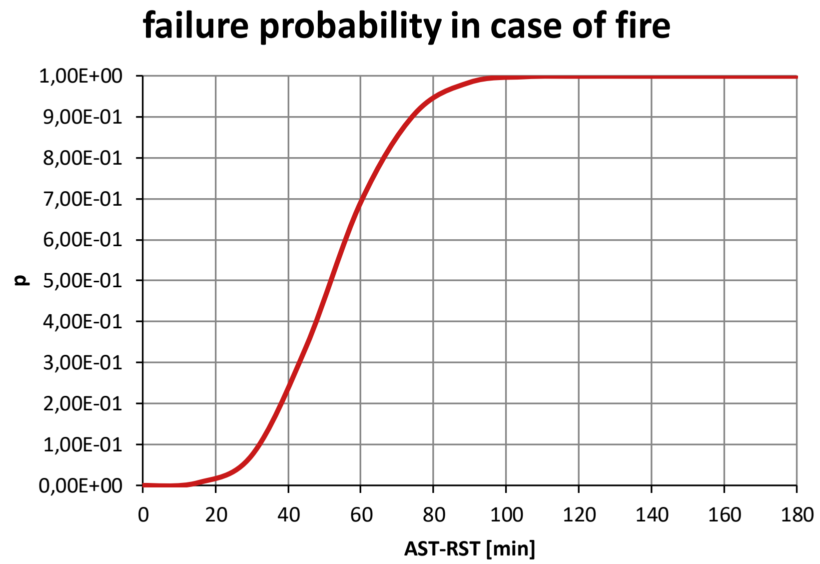
Significant event compartmentfire

Building area $[m^2]$ 17590
Design life time [yr] : 50
Ignition probability $[1/m^2/1yr]$: 2,000E-07
Ignition probability $[1/m^2/50yr]$: 1,00E-05 (during design lifetime)

Probability of fire p(fi) : 1,76E-01 (during design lifetime)

EUROCODE	**p(f)**	**p(f|fi)**	**beta(f|fi)**
CC1: beta(f) > 3,3	4,83E-04	2,75E-03	2,78
CC2: beta(f) > 3,8	7,23E-05	4,11E-04	**3,35**
CC3: beta(f) > 4,3	8,54E-06	4,85E-05	3,90

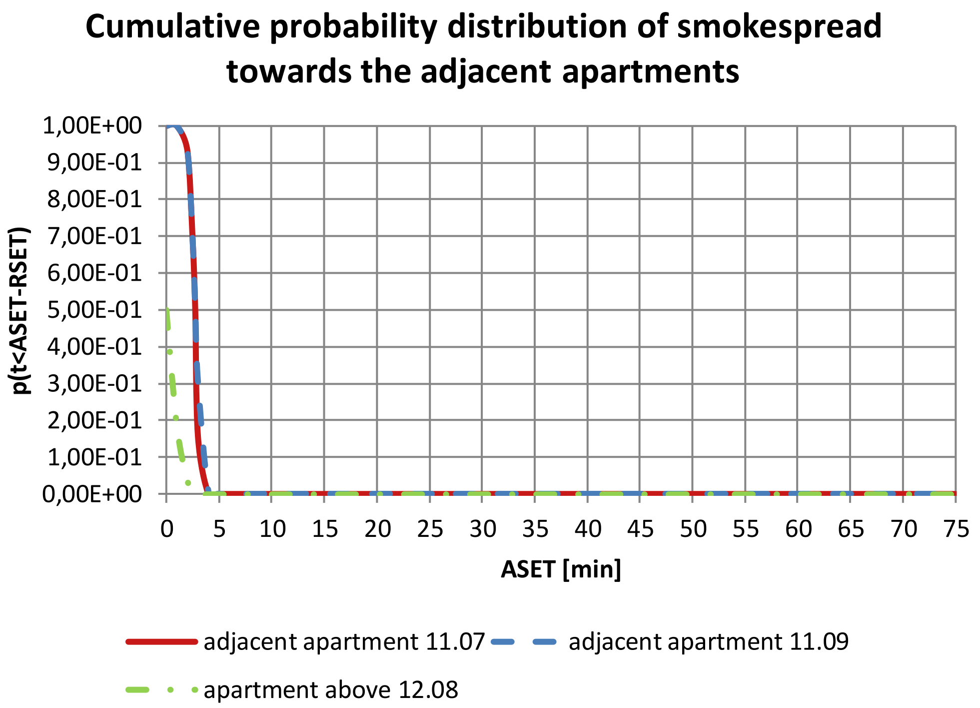




PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Overview: Apartments 11.07, 11.09 and 12.08

Reliability and failure probability			
t [min]	**adjacent apartment 11.07**	**adjacent apartment 11.09**	**apartment above 12.08**
0	1,000	1,000	5,00E-01
1	1,000	1,000	1,86E-01
2	0,933	0,933	3,68E-02
2,5	0,691	0,691	1,27E-02
2,75	0,500	0,500	9,87E-10
3	0,159	0,309	1,28E-12
4	0,000	0,006	6,22E-16
5	0,000	0,000	2,75E-89
10	0,000	0,000	0,00E+00
20	0,000	0,000	0,00E+00
30	0,000	0,000	0,00E+00
40	0,000	0,000	0,00E+00
50	0,000	0,000	0,00E+00
60	0,000	0,000	0,00E+00
70	0,000	0,000	0,00E+00
75	0,000	0,000	0,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

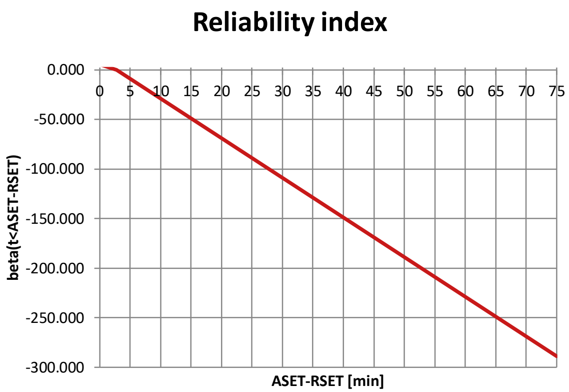
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Adjacent apartments 11.07

SENSITIVITY ANALYSIS
Stochastic boundary conditions

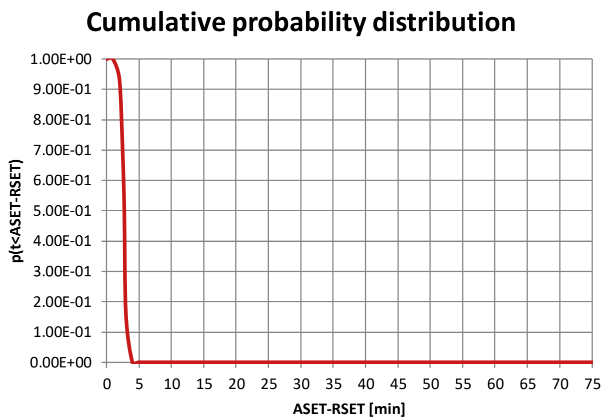
		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	2.75

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	2.75
-0.70	-0.70	0.30	2.75
1.50	1.50	2.50	2.75
-0.50	-0.50	0.50	2.75
1.50	180.00	300.00	2.75
-0.50	-60.00	60.00	2.75
2.00	40.00	60.00	2.75
-0.50	-10.00	10.00	2.75
0.50	5.00	15.00	2.75
-0.50	-5.00	5.00	2.75
1.00	1.00	2.00	2.25
-0.30	-0.30	0.70	3.00

Standard deviation			
dt/dx	s·dt/dx	$(s\cdot dt/dx)^2$	
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.50	-0.50	0.00	0.25
-0.83	0.25	0.06	0.00
	variancy(t) =	0.063	0.250
	s(t) =	0.250	-0.500



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0.50000	5.500	1.00E+00
1	0.50000	3.500	1.00E+00
2	0.50000	1.500	9.33E-01
2.5	0.50000	0.500	6.91E-01
2.75	0.25000	0.000	5.00E-01
3	0.25000	-1.000	1.59E-01
4	0.25000	-5.000	2.87E-07
5	0.25000	-9.000	1.13E-19
10	0.25000	-29.000	3.29E-185
20	0.25000	-69.000	0.00E+00
30	0.25000	-109.000	0.00E+00
40	0.25000	-149.000	0.00E+00
50	0.25000	-189.000	0.00E+00
60	0.25000	-229.000	0.00E+00
70	0.25000	-269.000	0.00E+00
75	0.25000	-289.000	0.00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

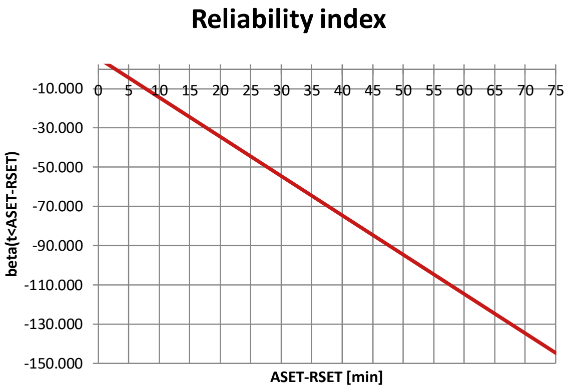
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Adjacent apartments 11.09

SENSITIVITY ANALYSIS
Stochastic boundary conditions

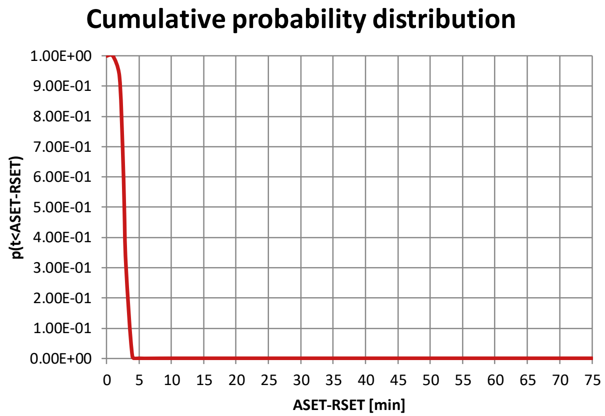
		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	**2.75**

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	2.75
-0.70	-0.70	0.30	2.75
1.50	1.50	2.50	2.75
-0.50	-0.50	0.50	3.00
1.50	180.00	300.00	2.75
-0.50	-60.00	60.00	3.00
2.00	40.00	60.00	3.00
-0.50	-10.00	10.00	2.75
0.50	5.00	15.00	2.75
-0.50	-5.00	5.00	2.75
1.00	1.00	2.00	2.25
-0.30	-0.30	0.70	3.00

Standard deviation			
dt/dx	s·dt/dx	$(s\cdot dt/dx)^2$	
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.50	0.25	0.06	0.00
0.00	0.00	0.00	0.00
0.00	0.25	0.06	0.00
0.01	0.25	0.06	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.50	-0.50	0.00	0.25
-0.83	0.25	0.06	0.00
	variancy(t) =	0.250	0.250
	s(t) =	0.500	-0.500



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0.50000	5.500	1.00E+00
1	0.50000	3.500	1.00E+00
2	0.50000	1.500	9.33E-01
2.5	0.50000	0.500	6.91E-01
2.75	0.50000	0.000	5.00E-01
3	0.50000	-0.500	3.09E-01
4	0.50000	-2.500	6.21E-03
5	0.50000	-4.500	3.40E-06
10	0.50000	-14.500	6.06E-48
20	0.50000	-34.500	4.01E-261
30	0.50000	-54.500	0.00E+00
40	0.50000	-74.500	0.00E+00
50	0.50000	-94.500	0.00E+00
60	0.50000	-114.500	0.00E+00
70	0.50000	-134.500	0.00E+00
75	0.50000	-144.500	0.00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Apartments above 12.08

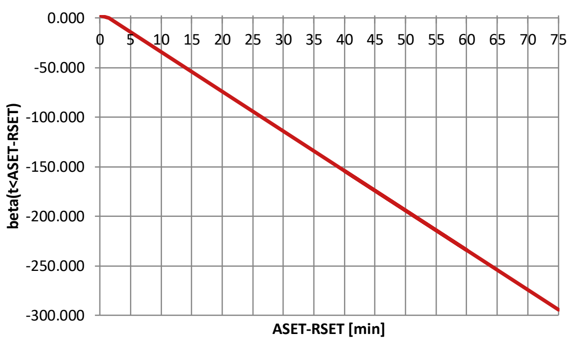
SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	1.5

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	1.50
-0.70	-0.70	0.30	1.50
1.50	1.50	2.50	1.25
-0.50	-0.50	0.50	1.50
1.50	180.00	300.00	1.50
-0.50	-60.00	60.00	1.50
2.00	40.00	60.00	1.50
-0.50	-10.00	10.00	1.50
0.50	5.00	15.00	1.50
-0.50	-5.00	5.00	1.50
1.00	1.00	2.00	1.00
-0.30	-0.30	0.70	1.75

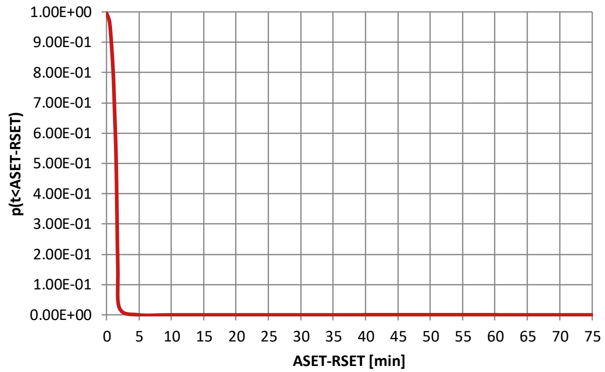
Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.17	-0.25	0.00	0.06
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.50	-0.50	0.00	0.25
-0.83	0.25	0.06	0.00
	variancy(t) =	0.063	0.313
	s(t) =	0.250	-0.559

Reliability index



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0.55902	2.683	9.96E-01
0.5	0.55902	1.789	9.63E-01
1	0.55902	0.894	8.14E-01
1.25	0.55902	0.447	6.73E-01
1.5	0.25000	0.000	5.00E-01
1.75	0.25000	-1.000	1.59E-01
2	0.25000	-2.000	2.28E-02
5	0.25000	-14.000	7.79E-45
10	0.25000	-34.000	1.11E-253
20	0.25000	-74.000	0.00E+00
60	0.25000	-234.000	0.00E+00
40	0.25000	-154.000	0.00E+00
50	0.25000	-194.000	0.00E+00
60	0.25000	-234.000	0.00E+00
70	0.25000	-274.000	0.00E+00
75	0.25000	-294.000	0.00E+00

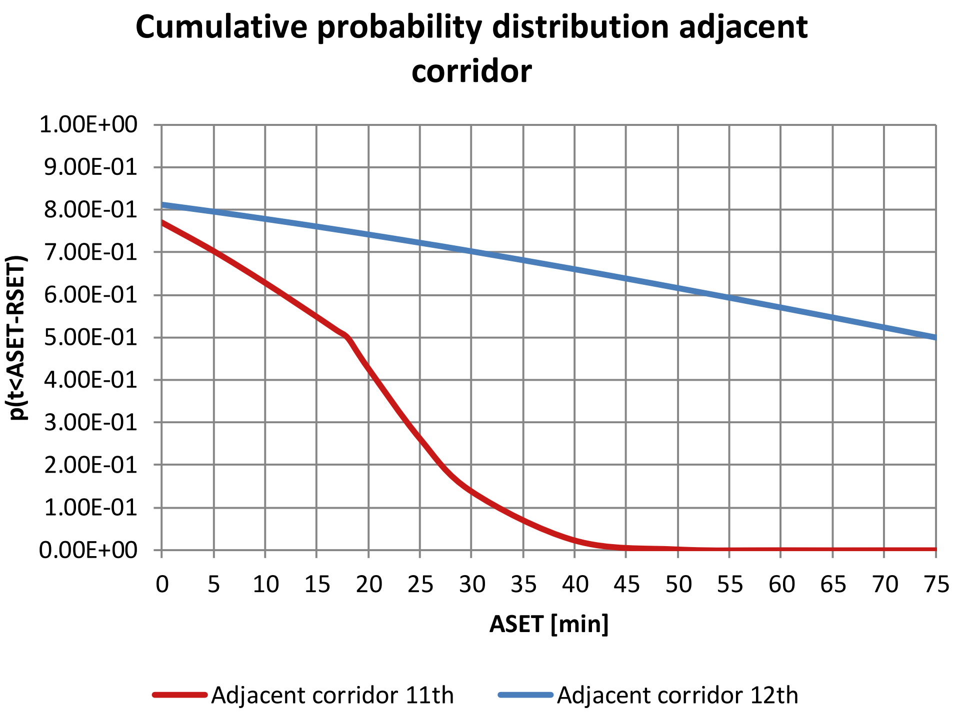
Cumulative probability distribution



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Overview: Adjacent corridors floor 11 and 12

Reliability and failure probability		
t [min]	**Adjacent corridor 11th**	**Adjacent corridor 12th**
0	0.77074	0.813
5	0.70380	0.797
10	0.62910	0.779
15	0.54916	0.761
16	0.53282	0.758
17	0.51642	0.754
18	0.50000	0.750
19	0.46389	0.747
20	0.42808	0.743
25	0.26291	0.723
30	0.13840	0.703
40	0.02309	0.661
50	0.00187	0.616
60	0.00007	0.571
70	0.00000	0.524
75	0.00000	0.500



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

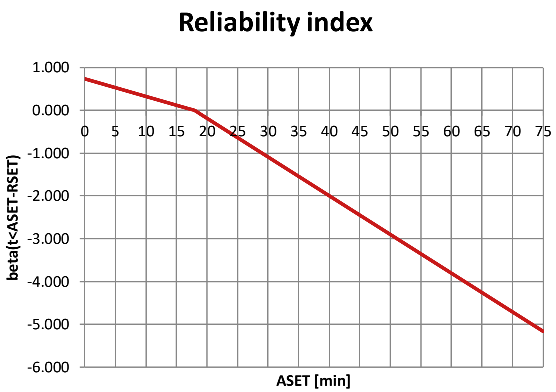
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Adjacent corridors floor 11

SENSITIVITY ANALYSIS
Stochastic boundary conditions

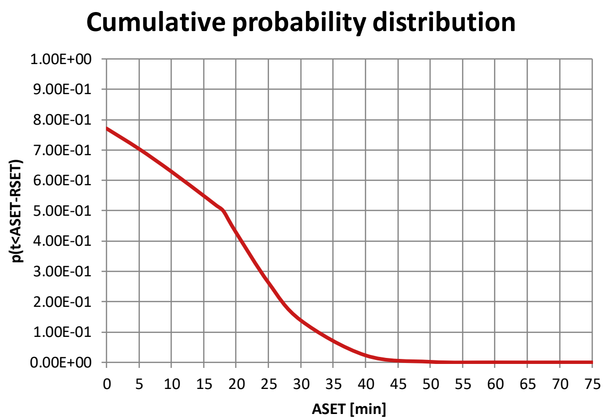
		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	18.0

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	16.50
-0.70	-0.70	0.30	18.00
1.50	1.50	2.50	12.25
-0.50	-0.50	0.50	27.50
1.50	180.00	300.00	5.25
-0.50	-60.00	60.00	19.00
2.00	40.00	60.00	3.00
-0.50	-10.00	10.00	18.50
0.50	5.00	15.00	18.00
-0.50	-5.00	5.00	18.00
1.00	1.00	2.00	5.00
-0.30	-0.30	0.70	23.50

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
-2.14	-1.50	0.00	2.25
0.00	0.00	0.00	0.00
-3.83	-5.75	0.00	33.06
-19.00	9.50	90.25	0.00
-0.07	-12.75	0.00	162.56
-0.02	1.00	1.00	0.00
-0.38	-15.00	0.00	225.00
-0.05	0.50	0.25	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-13.00	-13.00	0.00	169.00
-18.33	5.50	30.25	0.00
	variancy(t) =	121.750	589.625
	s(t) =	11.034	-24.282



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	24.28220	0.741	7.71E-01
5	24.28220	0.535	7.04E-01
10	24.28220	0.329	6.29E-01
15	24.28220	0.124	5.49E-01
16	24.28220	0.082	5.33E-01
17	24.28220	0.041	5.16E-01
18	11.03404	0.000	**5.00E-01**
19	11.03404	-0.091	4.64E-01
20	11.03404	-0.181	4.28E-01
25	11.03404	-0.634	2.63E-01
30	11.03404	-1.088	1.38E-01
40	11.03404	-1.994	2.31E-02
50	11.03404	-2.900	1.87E-03
60	11.03404	-3.806	7.05E-05
70	11.03404	-4.713	1.22E-06
75	11.03404	-5.166	1.20E-07



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

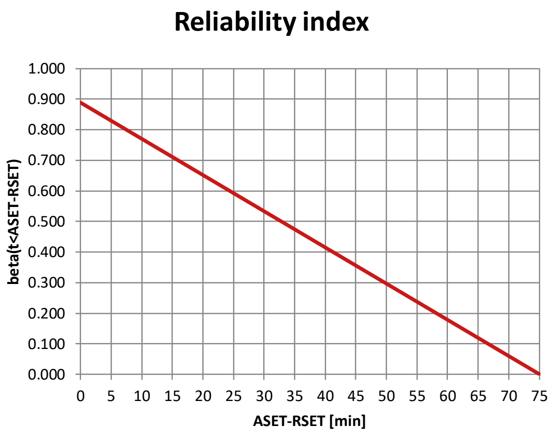
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Adjacent corridors floor 12

SENSITIVITY ANALYSIS
Stochastic boundary conditions

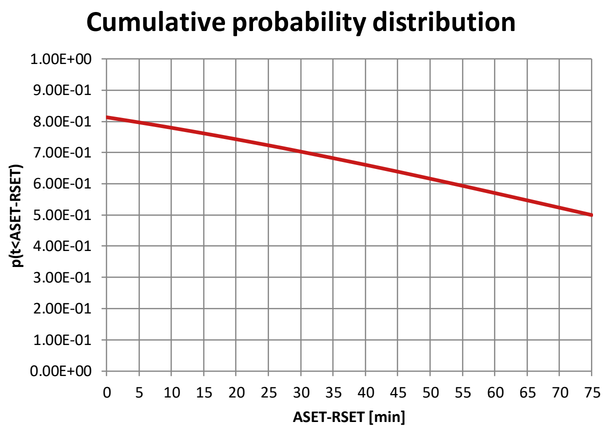
Parameter	Unit	Deterministic: average x	Deterministic: ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		**ASET**	**75.0**

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	75.00
-0.70	-0.70	0.30	53.00
1.50	1.50	2.50	31.25
-0.50	-0.50	0.50	75.00
1.50	180.00	300.00	37.25
-0.50	-60.00	60.00	54.50
2.00	40.00	60.00	49.25
-0.50	-10.00	10.00	53.75
0.50	5.00	15.00	53.00
-0.50	-5.00	5.00	53.00
1.00	1.00	2.00	40.75
-0.30	-0.30	0.70	64.75

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0.00	0.00	0.00	0.00
31.43	-22.00	0.00	484.00
-29.17	-43.75	0.00	1914.06
0.00	0.00	0.00	0.00
-0.21	-37.75	0.00	1425.06
0.34	-20.50	0.00	420.25
-0.64	-25.75	0.00	663.06
2.13	-21.25	0.00	451.56
-4.40	-22.00	0.00	484.00
4.40	-22.00	0.00	484.00
-34.25	-34.25	0.00	1173.06
34.17	-10.25	0.00	105.06
	variancy(t) =	0.000	7120.125
	s(t) =	0.000	-84.381



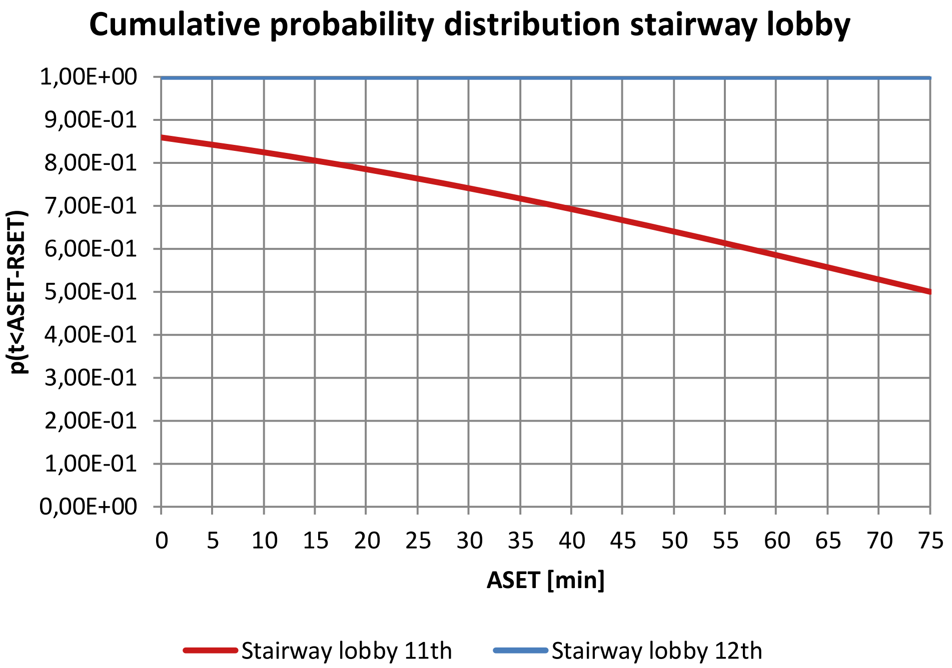
Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	84.38083	0.889	8.13E-01
5	84.38083	0.830	7.97E-01
10	84.38083	0.770	7.79E-01
15	84.38083	0.711	7.61E-01
16	84.38083	0.699	7.58E-01
17	84.38083	0.687	7.54E-01
18	84.38083	0.676	7.50E-01
19	84.38083	0.664	7.47E-01
20	84.38083	0.652	7.43E-01
25	84.38083	0.593	7.23E-01
30	84.38083	0.533	7.03E-01
40	84.38083	0.415	6.61E-01
50	84.38083	0.296	6.16E-01
60	84.38083	0.178	5.71E-01
70	84.38083	0.059	5.24E-01
75	84.38083	0.000	5.00E-01



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Overview: Stairway Lobbies floor 11 and 12

Reliability and failure probability		
t [min]	Stairway lobby 11th	Stairway lobby 12th
0	0,85974	1,000
10	0,82517	1,000
20	0,78564	1,000
30	0,74134	1,000
40	0,69273	1,000
50	0,64047	1,000
60	0,58544	1,000
70	0,52868	1,000
75	0,50000	1,000

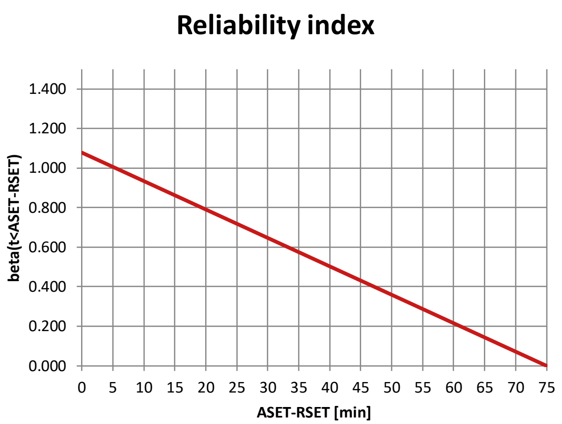


PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

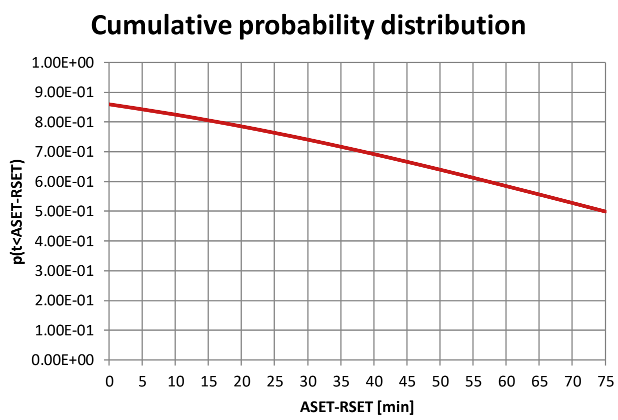
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Stairwaylobby floor 11

SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic		Probabilistic: sensitivity analysis				Standard deviation			
		average	ASET	variation	st. deviation	value	ASET	dt/dx	s·dt/dx	$(s\cdot dt/dx)^2$	
		x	t [min]	V	s	x + dx	t [min]				
External airtightness multiplier	-	1		0.70	0.70	1.70	75.00	0.00	0.00	0.00	0.00
				-0.70	-0.70	0.30	75.00	0.00	0.00	0.00	0.00
Internal airtightness multiplier	-	1		1.50	1.50	2.50	75.00	0.00	0.00	0.00	0.00
				-0.50	-0.50	0.50	75.00	0.00	0.00	0.00	0.00
Time door opens	s	120		1.50	180.00	300.00	5.50	-0.39	-69.50	0.00	4830.25
				-0.50	-60.00	60.00	75.00	0.00	0.00	0.00	0.00
Time door closes	s	20		2.00	40.00	60.00	75.00	0.00	0.00	0.00	0.00
				-0.50	-10.00	10.00	75.00	0.00	0.00	0.00	0.00
Lower oxygen limit	%	10		0.50	5.00	15.00	75.00	0.00	0.00	0.00	0.00
				-0.50	-5.00	5.00	75.00	0.00	0.00	0.00	0.00
Soot yield multiplier	-	1		1.00	1.00	2.00	75.00	0.00	0.00	0.00	0.00
				-0.30	-0.30	0.70	75.00	0.00	0.00	0.00	0.00
Acceptable conditions		ASET	75.0						variancy(t) =	0.000	4830.250
									s(t) =	0.000	-69.500



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	69.50000	1.079	8.60E-01
10	69.50000	0.935	8.25E-01
20	69.50000	0.791	7.86E-01
30	69.50000	0.647	7.41E-01
40	69.50000	0.504	6.93E-01
50	69.50000	0.360	6.40E-01
60	69.50000	0.216	5.85E-01
70	69.50000	0.072	5.29E-01
75	69.50000	0.000	5.00E-01



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Stairwaylobby floor 12

SENSITIVITY ANALYSIS

Stochastic boundary conditions		**Deterministic** average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	75,0

Probabilistic: sensitivity analysis

variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	75,00
-0,70	-0,70	0,30	75,00
1,50	1,50	2,50	75,00
-0,50	-0,50	0,50	75,00
1,50	180,00	300,00	75,00
-0,50	-60,00	60,00	75,00
2,00	40,00	60,00	75,00
-0,50	-10,00	10,00	75,00
0,50	5,00	15,00	75,00
-0,50	-5,00	5,00	75,00
1,00	1,00	2,00	75,00
-0,30	-0,30	0,70	75,00

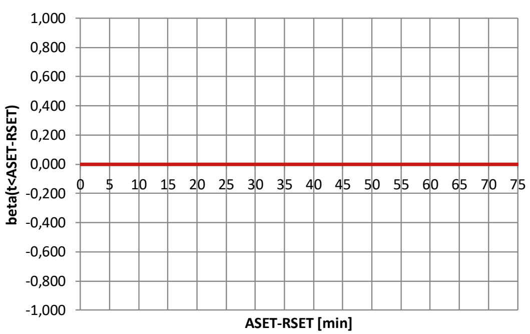
Standard deviation

dt/dx	s·dt/dx	$(s·dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000

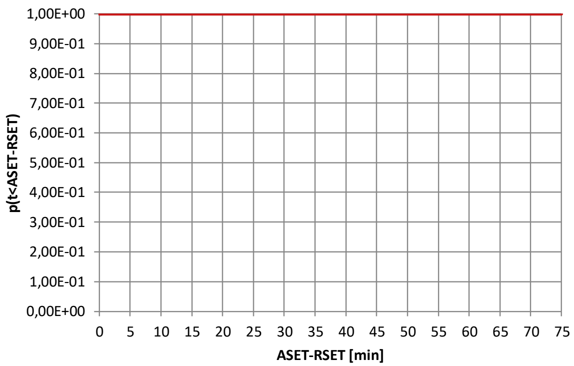
Reliability and failure probability

t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
10	0,00000	#########	1,00E+00
20	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
40	0,00000	#########	1,00E+00
50	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
70	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00

Reliability index



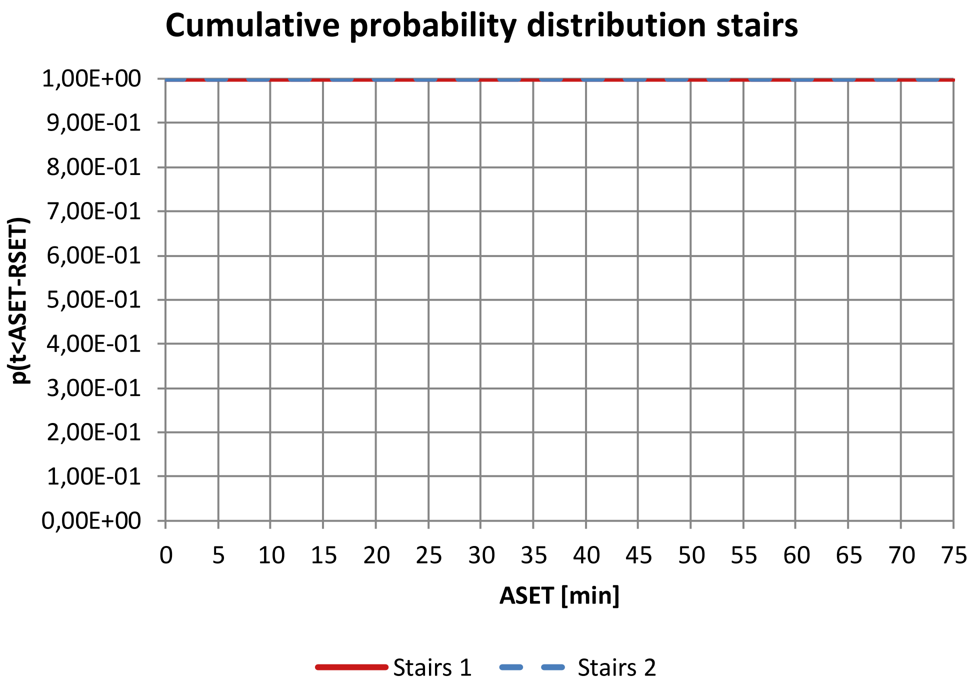
Cumulative probability distribution



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Overview: Stairway 1 and 2

Reliability and failure probability		
t [min]	**Stairs 1**	**Stairs 2**
0	1,00000	1,000
10	1,00000	1,000
20	1,00000	1,000
30	1,00000	1,000
40	1,00000	1,000
50	1,00000	1,000
60	1,00000	1,000
70	1,00000	1,000
75	1,00000	1,000



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

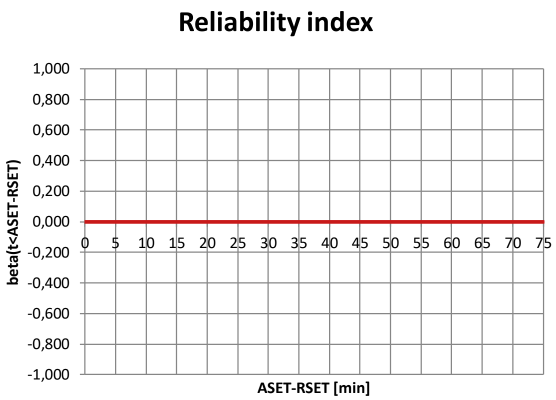
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Stairway 1

SENSITIVITY ANALYSIS
Stochastic boundary conditions

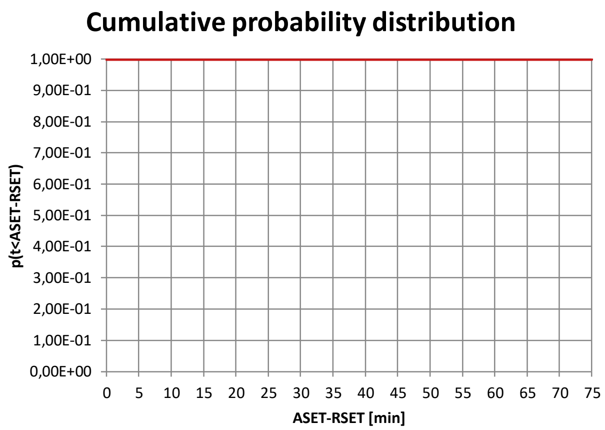
Stochastic boundary conditions	unit	Deterministic: average x	Deterministic: ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	75,0

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	75,00
-0,70	-0,70	0,30	75,00
1,50	1,50	2,50	75,00
-0,50	-0,50	0,50	75,00
1,50	180,00	300,00	75,00
-0,50	-60,00	60,00	75,00
2,00	40,00	60,00	75,00
-0,50	-10,00	10,00	75,00
0,50	5,00	15,00	75,00
-0,50	-5,00	5,00	75,00
1,00	1,00	2,00	75,00
-0,30	-0,30	0,70	75,00

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
10	0,00000	#########	1,00E+00
20	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
40	0,00000	#########	1,00E+00
50	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
70	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Stairway 2

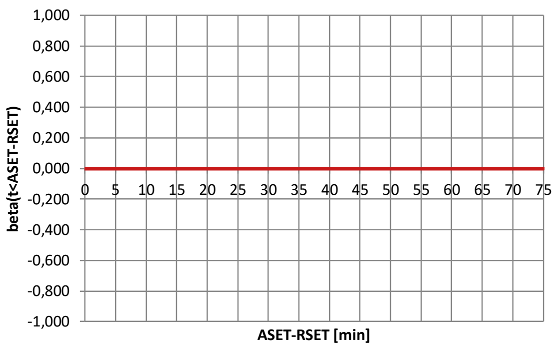
SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	75,0

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	75,00
-0,70	-0,70	0,30	75,00
1,50	1,50	2,50	75,00
-0,50	-0,50	0,50	75,00
1,50	180,00	300,00	75,00
-0,50	-60,00	60,00	75,00
2,00	40,00	60,00	75,00
-0,50	-10,00	10,00	75,00
0,50	5,00	15,00	75,00
-0,50	-5,00	5,00	75,00
1,00	1,00	2,00	75,00
-0,30	-0,30	0,70	75,00

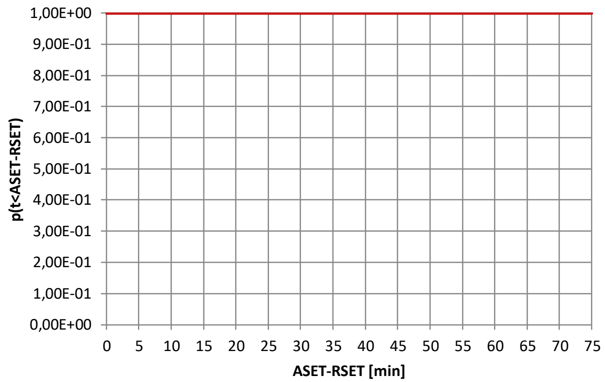
Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000

Reliability index



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
10	0,00000	#########	1,00E+00
20	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
40	0,00000	#########	1,00E+00
50	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
70	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00

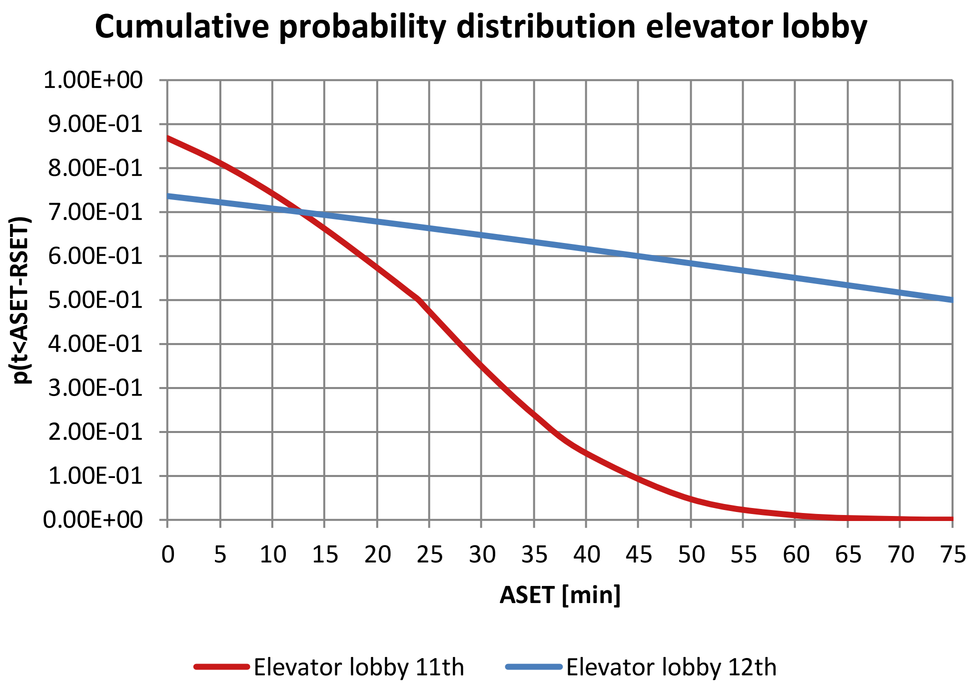
Cumulative probability distribution



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Overview: Elevator Lobbies floor 11 and 12

Reliability and failure probability		
t [min]	Elevator lobby 11th	Elevator lobby 12th
0	0.86783	0.736
5	0.81156	0.722
10	0.74252	0.707
15	0.66224	0.693
20	0.57379	0.678
23	0.51855	0.669
24	0.50000	0.666
25	0.47433	0.663
30	0.34960	0.647
35	0.23935	0.632
40	0.15142	0.616
50	0.04703	0.583
60	0.01021	0.550
70	0.00153	0.517
75	0.00051	0.500



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

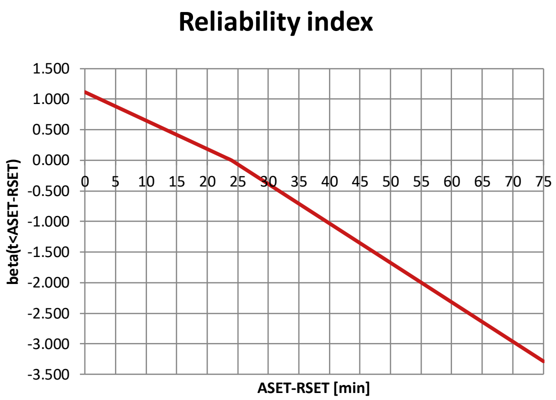
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Elevator Lobbies floor 11

SENSITIVITY ANALYSIS
Stochastic boundary conditions

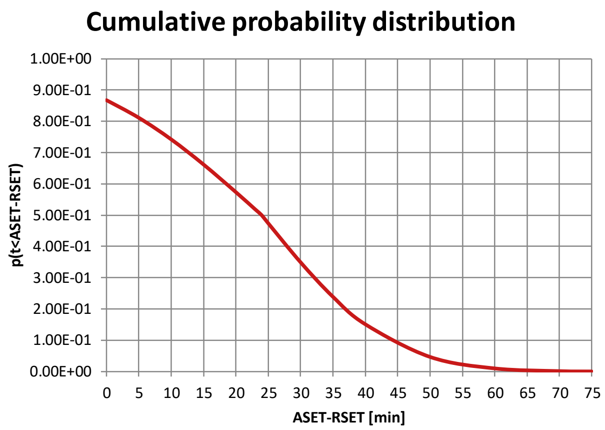
		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		**ASET**	**24.0**

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	19.75
-0.70	-0.70	0.30	25.00
1.50	1.50	2.50	16.50
-0.50	-0.50	0.50	36.75
1.50	180.00	300.00	5.50
-0.50	-60.00	60.00	26.50
2.00	40.00	60.00	21.25
-0.50	-10.00	10.00	25.50
0.50	5.00	15.00	25.00
-0.50	-5.00	5.00	25.00
1.00	1.00	2.00	16.50
-0.30	-0.30	0.70	32.25

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
-6.07	-4.25	0.00	18.06
-1.43	1.00	1.00	0.00
-5.00	-7.50	0.00	56.25
-25.50	12.75	162.56	0.00
-0.10	-18.50	0.00	342.25
-0.04	2.50	6.25	0.00
-0.07	-2.75	0.00	7.56
-0.15	1.50	2.25	0.00
0.20	1.00	1.00	0.00
-0.20	1.00	1.00	0.00
-7.50	-7.50	0.00	56.25
-27.50	8.25	68.06	0.00
	variancy(t) =	241.125	462.313
	s(t) =	15.528	-21.501



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	21.50145	1.116	8.68E-01
5	21.50145	0.884	8.12E-01
10	21.50145	0.651	7.43E-01
15	21.50145	0.419	6.62E-01
20	21.50145	0.186	5.74E-01
23	21.50145	0.047	5.19E-01
24	15.52820	0.000	**5.00E-01**
25	15.52820	-0.064	4.74E-01
30	15.52820	-0.386	3.50E-01
35	15.52820	-0.708	2.39E-01
40	15.52820	-1.030	1.51E-01
50	15.52820	-1.674	4.70E-02
60	15.52820	-2.318	1.02E-02
70	15.52820	-2.962	1.53E-03
75	15.52820	-3.284	5.11E-04

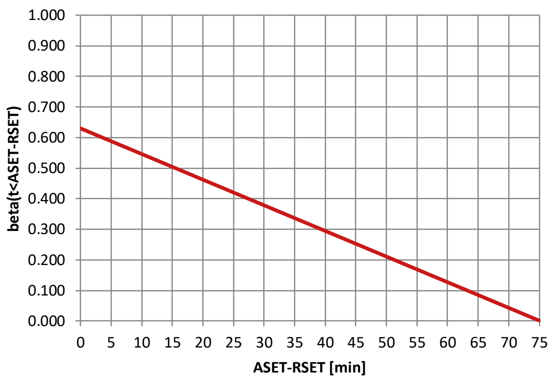


PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Elevator Lobbies floor 12

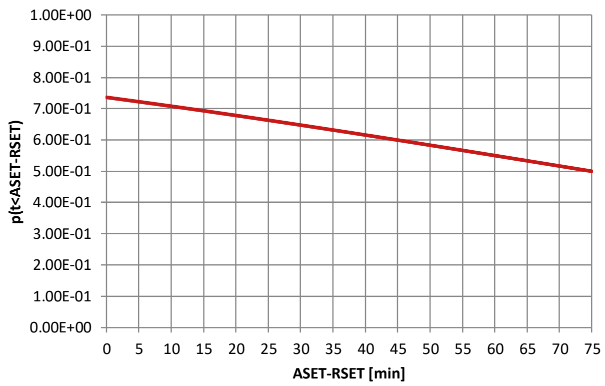
SENSITIVITY ANALYSIS		Deterministic		Probabilistic: sensitivity analysis				Standard deviation			
Stochastic boundary conditions		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]	dt/dx	s·dt/dx	(s·dt/dx)^2	
External airtightness multiplier	-	1		0.70	0.70	1.70	75.00	0.00	0.00	0.00	0.00
				-0.70	-0.70	0.30	40.50	49.29	-34.50	0.00	1190.25
Internal airtightness multiplier	-	1		1.50	1.50	2.50	25.00	-33.33	-50.00	0.00	2500.00
				-0.50	-0.50	0.50	75.00	0.00	0.00	0.00	0.00
Time door opens	s	120		1.50	180.00	300.00	22.25	-0.29	-52.75	0.00	2782.56
				-0.50	-60.00	60.00	41.75	0.55	-33.25	0.00	1105.56
Time door closes	s	20		2.00	40.00	60.00	36.50	-0.96	-38.50	0.00	1482.25
				-0.50	-10.00	10.00	41.00	3.40	-34.00	0.00	1156.00
Lower oxygen limit	%	10		0.50	5.00	15.00	40.50	-6.90	-34.50	0.00	1190.25
				-0.50	-5.00	5.00	40.50	6.90	-34.50	0.00	1190.25
Soot yield multiplier	-	1		1.00	1.00	2.00	28.75	-46.25	-46.25	0.00	2139.06
				-0.30	-0.30	0.70	50.00	83.33	-25.00	0.00	625.00
Acceptable conditions		ASET	75.0						variancy(t) =	0.000	##########
									s(t) =	0.000	-119.042

Reliability index



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	119.04175	0.630	7.36E-01
5	119.04175	0.588	7.22E-01
10	119.04175	0.546	7.07E-01
15	119.04175	0.504	6.93E-01
20	119.04175	0.462	6.78E-01
23	119.04175	0.437	6.69E-01
24	119.04175	0.428	6.66E-01
25	119.04175	0.420	6.63E-01
30	119.04175	0.378	6.47E-01
35	119.04175	0.336	6.32E-01
40	119.04175	0.294	6.16E-01
50	119.04175	0.210	5.83E-01
60	119.04175	0.126	5.50E-01
70	119.04175	0.042	5.17E-01
75	119.04175	0.000	5.00E-01

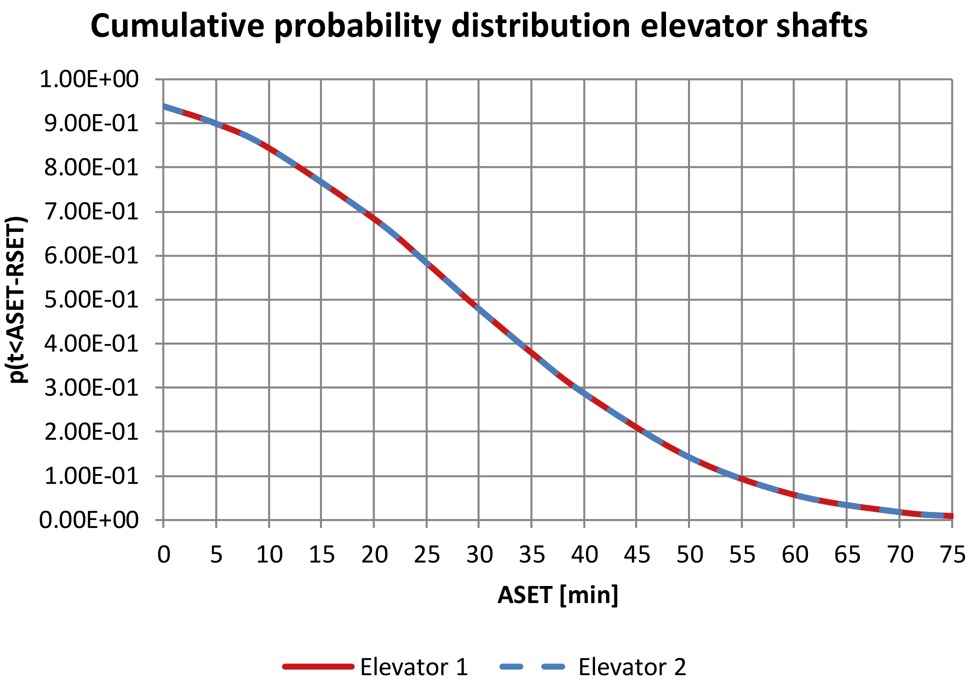
Cumulative probability distribution



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Overview: Elevator shafts

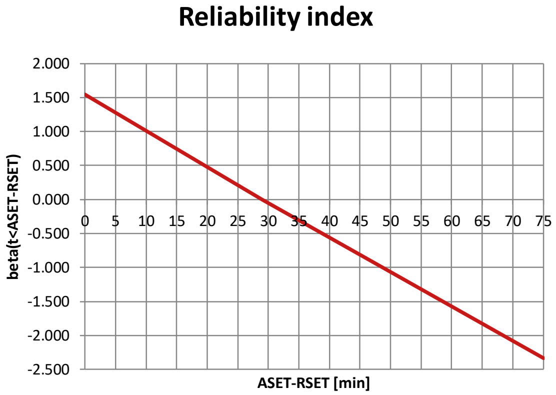
Reliability and failure probability		
t [min]	**Elevator 1**	**Elevator 2**
0	0.939	0.939
5	0.900	0.900
10	0.845	0.845
20	0.685	0.685
25	0.585	0.585
27	0.543	0.543
28	0.521	0.521
29	0.500	0.500
30	0.480	0.480
31	0.460	0.460
35	0.380	0.380
40	0.288	0.288
50	0.143	0.143
60	0.058	0.058
70	0.019	0.019
75	0.010	0.010



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

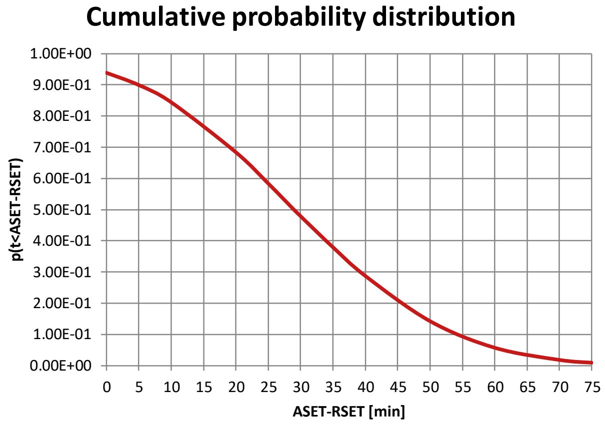
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Elevator shaft 1

SENSITIVITY ANALYSIS **Stochastic boundary conditions**		Deterministic: average x	Deterministic: ASET t [min]	Probabilistic: variation V	st. deviation s	value x + dx	ASET t [min]	Standard deviation: dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
External airtightness multiplier	-	1		0.70	0.70	1.70	75.00	65.71	46.00	2116.00	0.00
				-0.70	-0.70	0.30	32.25	-4.64	3.25	10.56	0.00
Internal airtightness multiplier	-	1		1.50	1.50	2.50	21.00	-5.33	-8.00	0.00	64.00
				-0.50	-0.50	0.50	43.00	-28.00	14.00	196.00	0.00
Time door opens	s	120		1.50	180.00	300.00	13.50	-0.09	-15.50	0.00	240.25
				-0.50	-60.00	60.00	33.75	-0.08	4.75	22.56	0.00
Time door closes	s	20		2.00	40.00	60.00	28.25	-0.02	-0.75	0.00	0.56
				-0.50	-10.00	10.00	33.00	-0.40	4.00	16.00	0.00
Lower oxygen limit	%	10		0.50	5.00	15.00	32.25	0.65	3.25	10.56	0.00
				-0.50	-5.00	5.00	32.25	-0.65	3.25	10.56	0.00
Soot yield multiplier	-	1		1.00	1.00	2.00	22.25	-6.75	-6.75	0.00	45.56
				-0.30	-0.30	0.70	40.50	-38.33	11.50	132.25	0.00
Acceptable conditions		ASET	29.0						variancy(t) =	387.938	350.375
									s(t) =	19.696	-18.718



Reliability and failure probability

t [min]	s(t)	beta(t|fi)	p(t|fi)
0	18.71831	1.549	9.39E-01
5	18.71831	1.282	9.00E-01
10	18.71831	1.015	8.45E-01
20	18.71831	0.481	6.85E-01
25	18.71831	0.214	5.85E-01
27	18.71831	0.107	5.43E-01
28	18.71831	0.053	5.21E-01
29	19.69613	0.000	5.00E-01
30	19.69613	-0.051	4.80E-01
31	19.69613	-0.102	4.60E-01
35	19.69613	-0.305	3.80E-01
40	19.69613	-0.558	2.88E-01
50	19.69613	-1.066	1.43E-01
60	19.69613	-1.574	5.78E-02
70	19.69613	-2.082	1.87E-02
75	19.69613	-2.335	9.76E-03

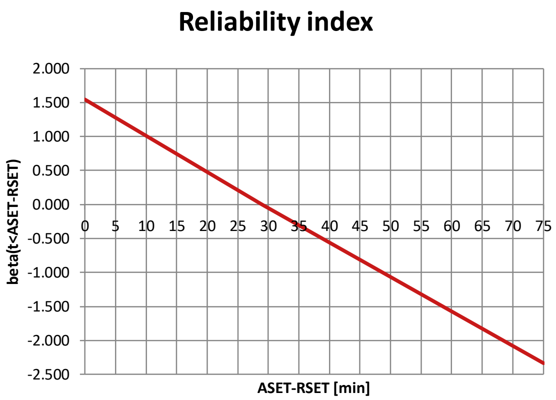


PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

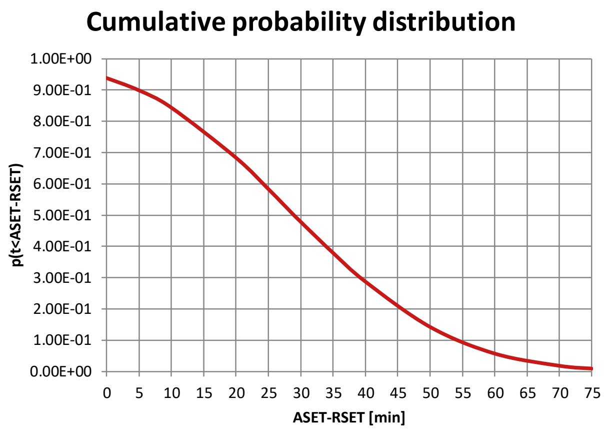
ASET
Case: Low-rise residential reference building
Assessment criterion: Optical density ULOD
Compartment: Elevator shaft 2

SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic		Probabilistic: sensitivity analysis				Standard deviation			
		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]	dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
External airtightness multiplier	-	1		0.70	0.70	1.70	75.00	65.71	46.00	2116.00	0.00
				-0.70	-0.70	0.30	32.25	-4.64	3.25	10.56	0.00
Internal airtightness multiplier	-	1		1.50	1.50	2.50	21.00	-5.33	-8.00	0.00	64.00
				-0.50	-0.50	0.50	43.00	-28.00	14.00	196.00	0.00
Time door opens	s	120		1.50	180.00	300.00	13.50	-0.09	-15.50	0.00	240.25
				-0.50	-60.00	60.00	33.75	-0.08	4.75	22.56	0.00
Time door closes	s	20		2.00	40.00	60.00	28.25	-0.02	-0.75	0.00	0.56
				-0.50	-10.00	10.00	33.00	-0.40	4.00	16.00	0.00
Lower oxygen limit	%	10		0.50	5.00	15.00	32.25	0.65	3.25	10.56	0.00
				-0.50	-5.00	5.00	32.25	-0.65	3.25	10.56	0.00
Soot yield multiplier	-	1		1.00	1.00	2.00	22.25	-6.75	-6.75	0.00	45.56
				-0.30	-0.30	0.70	40.50	-38.33	11.50	132.25	0.00
Acceptable conditions		**ASET**	**29.0**						variancy(t) =	387.938	350.375
									s(t) =	19.696	-18.718



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	18.71831	1.549	9.39E-01
5	18.71831	1.282	9.00E-01
10	18.71831	1.015	8.45E-01
20	18.71831	0.481	6.85E-01
25	18.71831	0.214	5.85E-01
27	18.71831	0.107	5.43E-01
28	18.71831	0.053	5.21E-01
29	19.69613	0.000	5.00E-01
30	19.69613	-0.051	4.80E-01
31	19.69613	-0.102	4.60E-01
35	19.69613	-0.305	3.80E-01
40	19.69613	-0.558	2.88E-01
50	19.69613	-1.066	1.43E-01
60	19.69613	-1.574	5.78E-02
70	19.69613	-2.082	1.87E-02
75	19.69613	-2.335	9.76E-03



9.11 Appendix 11. Super-tall residential building model, CFAST input

CFAST

Release Version : CFAST 7.7.3
Revision   : CFAST7.7.4-0-g6b52d0c3
Revision Date   : Fri Jan 13 15:42:10 2023 -0500
Compilation Date : Thu 01/19/2023 11:24 AM

Data file: C:\Users\joost\OneDrive\Bureaublad\CFAST_afstuderen\03 Super-tall residential building\01 Basis\1.1 basis - sprinkler en overdruk \CFAST-model case - basis.in
Title: CFAST Simulation

OVERVIEW

Compartments	Doors, ...	Ceil. Vents, ...	MV Connects
47	109	4	35

Simulation Time (s)	Output Interval (s)	Smokeview Interval (s)	Spreadsheet Interval (s)
7200.00	60.00	15.00	15.00

AMBIENT CONDITIONS

Interior Temperature (C)	Interior Pressure (Pa)	Exterior Temperature (C)	Exterior Pressure (Pa)
20.	101325.	20.	101325.

THERMAL PROPERTIES

Name	Conductivity (kW/(m ï¿½C))	Specific Heat (kJ/(m ï¿½C))	Density (kg/m^3)	Thickness (m)	Emissivity
NM 1	1.60	800.	2.300E+03	0.250	0.800
NM 2	1.60	800.	2.300E+03	0.280	0.800

NM 3	1.50	800.	2.300E+03	9.000E-02	0.800
DEFAULT	0.120	900.	800.	1.200E-02	0.900

COMPARTMENTS

Compartment	Name	Width (m)	Depth (m)	Height (m)	Floor Height (m)	Ceiling Height (m)	Shaft	Hall	Wall Leakage (m^2)	Floor Leakage (m^2)
1	Comp 5 - shaf	1.00	2.45	12.00	0.00	12.00	*		0.0	0.0
2	Comp 7 - shaf	1.20	2.45	9.00	3.00	12.00	*		0.0	0.0
3	Comp 1 - 11-0	6.10	5.65	3.00	3.00	6.00			0.0	0.0
4	Comp 2 - 11-0	6.10	5.65	3.00	3.00	6.00			0.0	0.0
5	Comp 3 - 11-0	6.10	5.65	3.00	3.00	6.00			0.0	0.0
6	Comp 4 - 11-0	3.80	2.45	3.00	3.00	6.00			0.0	0.0
7	Comp 6 - 11-0	5.00	2.45	3.00	3.00	6.00			0.0	0.0
8	Comp 8 - 11-0	5.50	2.45	3.00	3.00	6.00			0.0	0.0
9	Comp 9 - gang	1.80	10.25	3.00	3.00	6.00	*		0.0	0.0
10	Comp 10 - gan	4.30	1.50	3.00	3.00	6.00	*		0.0	0.0
11	Comp 11 - gan	17.00	1.50	3.00	3.00	6.00	*		0.0	0.0
12	Comp 13 - sha	1.00	1.00	12.00	0.00	12.00	*		0.0	0.0
13	Comp 14 - sha	1.00	1.00	3.00	3.00	6.00	*		0.0	0.0
14	Comp 15 - sha	1.00	1.00	12.00	0.00	12.00	*		0.0	0.0
15	Comp 16 - sta	6.30	1.50	12.00	0.00	12.00	*		0.0	0.0
16	Comp 17 - sta	6.30	1.50	12.00	0.00	12.00	*		0.0	0.0
17	Comp 18 - gan	4.30	1.50	3.00	3.00	6.00	*		0.0	0.0
18	Comp 19 - gan	4.30	1.50	3.00	3.00	6.00	*		0.0	0.0
19	Comp 20 - gan	11.30	1.50	3.00	3.00	6.00	*		0.0	0.0
20	Comp 22 - gan	1.40	4.50	3.00	3.00	6.00	*		0.0	0.0
21	Comp 23 - lif	2.70	2.25	12.00	0.00	12.00	*		0.0	0.0
22	Comp 24 - sha	1.35	0.75	12.00	0.00	12.00	*		0.0	0.0
23	Comp 25 - sha	1.35	0.75	12.00	0.00	12.00	*		0.0	0.0
24	Comp 26 - gan	2.30	3.00	3.00	3.00	6.00	*		0.0	0.0
25	Comp 27 - sha	1.35	0.75	3.00	3.00	6.00	*		0.0	0.0
26	Comp 28 - sha	1.35	0.75	3.00	3.00	6.00	*		0.0	0.0
27	Comp 29 - lif	2.70	2.25	12.00	0.00	12.00	*		0.0	0.0
28	Comp 30 - 12-	6.10	5.65	3.00	6.00	9.00			0.0	0.0
29	Comp 32 - 12-	5.00	2.45	3.00	6.00	9.00			0.0	0.0
30	Comp 43 - gan	1.80	10.25	3.00	6.00	9.00	*		0.0	0.0
31	Comp 34 - gan	4.30	1.50	3.00	6.00	9.00	*		0.0	0.0
32	Comp 35 - gan	17.00	1.50	3.00	6.00	9.00	*		0.0	0.0
33	Comp 44 - gan	4.30	1.50	3.00	6.00	9.00	*		0.0	0.0

34	Comp 45 - gan	4.30	1.50	3.00	6.00	9.00	*	0.0	0.0
35	Comp 47 - gan	11.30	1.50	3.00	6.00	9.00	*	0.0	0.0
36	Comp 46 - gan	1.40	4.50	3.00	6.00	9.00	*	0.0	0.0
37	Comp 45 - gan	2.30	3.00	3.00	6.00	9.00	*	0.0	0.0
38	Comp 34 - 12-	6.10	5.65	3.00	6.00	9.00		0.0	0.0
39	Comp 35 - 12-	3.80	2.45	3.00	6.00	9.00		0.0	0.0
40	Comp 36 - gan	1.80	10.25	3.00	0.00	3.00	*	0.0	0.0
41	Comp 33 - gan	4.30	1.50	3.00	0.00	3.00	*	0.0	0.0
42	Comp 37 - gan	17.00	1.50	3.00	0.00	3.00	*	0.0	0.0
43	Comp 38 - gan	4.30	1.50	3.00	0.00	3.00	*	0.0	0.0
44	Comp 39 - gan	4.30	1.50	3.00	0.00	3.00	*	0.0	0.0
45	Comp 40 - gan	11.30	1.50	3.00	0.00	3.00	*	0.0	0.0
46	Comp 41 - gan	1.40	4.50	3.00	0.00	3.00	*	0.0	0.0
47	Comp 42 - gan	2.30	3.00	3.00	0.00	3.00	*	0.0	0.0

COMPARTMENT MATERIALS

Compartment	Name	Surface	Layer	Conductivity (kW/(m C))	Specific Heat (kJ/(m C))	Density (kg/m^3)	Thickness (m)	Emissivity	Material
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
3	Comp 1 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
4	Comp 2 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
5	Comp 3 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
6	Comp 4 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
7	Comp 6 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
8	Comp 8 - 11-0	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
9	Comp 9 - gang	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3

		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
10	Comp 10 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
11	Comp 11 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
17	Comp 18 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
18	Comp 19 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
19	Comp 20 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
20	Comp 22 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
24	Comp 26 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.100	0.800	NM 1
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
28	Comp 30 - 12-	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
29	Comp 32 - 12-	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
30	Comp 43 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
31	Comp 34 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3

		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
32	Comp 35 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
33	Comp 44 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
34	Comp 45 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
35	Comp 47 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
36	Comp 46 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
37	Comp 45 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
38	Comp 34 - 12-	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
39	Comp 35 - 12-	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
40	Comp 36 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
41	Comp 33 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
42	Comp 37 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
43	Comp 38 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
44	Comp 39 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
45	Comp 40 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
46	Comp 41 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2

		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1
47	Comp 42 - gan	Ceiling	1	1.60	800.	2.300E+03	0.280	0.800	NM 2
		Floor	1	1.50	800.	2.300E+03	9.000E-02	0.800	NM 3
		Walls	1	1.60	800.	2.300E+03	0.250	0.800	NM 1

VENT CONNECTIONS

Wall Vents (Doors, Windows, ...)

From Compartment	To Compartment	Vent Number	Width	Sill Height	Soffit Height	Open/Close Type	Trigger Value	Target	Initial Time	Initial Fraction	Final Time	Final Fraction
			(m)	(m)	(m)	(m)	(C/W/m^2)		(s)		(s)	
Comp 1 - 11-07	Outside	1	1.75	0.31	2.48	Time			0.00	0.01	7200.00	0.01
Comp 1 - 11-07	Outside	2	1.75	0.31	2.48	Time			0.00	0.01	7200.00	0.01
Comp 2 - 11-08	Outside	3	1.75	0.31	2.48	RAMP # 1						
Comp 2 - 11-08	Outside	4	1.75	0.31	2.48	RAMP # 2						
Comp 3 - 11-09	Outside	5	1.75	0.31	2.48	Time			0.00	0.01	7200.00	0.01
Comp 3 - 11-09	Outside	6	1.75	0.31	2.48	Time			0.00	0.01	7200.00	0.01
Comp 1 - 11-07	Comp 4 - 11-07	7	3.80	0.00	2.60	RAMP # 3						
Comp 2 - 11-08	Comp 6 - 11-08	8	5.00	0.00	2.60	RAMP # 4						
Comp 3 - 11-09	Comp 8 - 11-09	9	5.50	0.00	2.60	RAMP # 5						
Comp 4 - 11-07	Comp 9 - gang	10	1.03	0.00	2.42	RAMP # 6						
Comp 6 - 11-08	Comp 11 - gang	11	1.03	0.00	2.42	RAMP # 7						
Comp 8 - 11-09	Comp 11 - gang	12	1.03	0.00	2.42	RAMP # 8						
Comp 9 - gang	Comp 10 - gang	13	1.14	0.00	2.42	RAMP # 9						
Comp 9 - gang	Comp 18 - gang	14	1.50	0.00	2.70	Time			0.00	1.00	7200.00	1.00
Comp 10 - gang	Comp 11 - gang	15	1.14	0.00	2.42	RAMP # 10						
Comp 10 - gang	Comp 16 - stai	16	1.03	0.00	2.42	RAMP # 11						
Comp 18 - gang	Comp 19 - gang	17	1.14	0.00	2.42	Time			0.00	1.00		
Comp 19 - gang	Comp 20 - gang	18	1.14	0.00	2.42	RAMP # 12						
Comp 20 - gang	Comp 22 - gang	19	1.50	0.00	2.42	Time			0.00	1.00	7200.00	1.00

Comp 20 - gang Comp 26 - gang	20	1.10	0.00	2.42	Time	0.00	1.00		
Comp 11 - gang Comp 22 - gang	21	1.40	0.00	2.42	Time	0.00	1.00	7200.00	1.00
Comp 17 - stai Comp 19 - gang	22	1.03	3.00	5.42	RAMP # 13				
Comp 11 - gang Comp 26 - gang	23	1.10	0.00	2.42	Time	0.00	1.00		
Comp 23 - lift Comp 26 - gang	24	0.96	3.00	5.42	Time	0.00	1.00		
Comp 26 - gang Comp 29 - lift	25	0.96	0.00	2.42	Time	0.00	1.00		
Comp 1 - 11-07 Outside	26	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 2 - 11-08 Outside	27	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 3 - 11-09 Outside	28	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 1 - 11-07 Comp 2 - 11-08	29	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 2 - 11-08 Comp 3 - 11-09	30	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 1 - 11-07 Comp 9 - gang	31	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 4 - 11-07 Comp 9 - gang	32	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 4 - 11-07 Comp 10 - gang	33	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 4 - 11-07 Comp 9 - gang	34	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 7 - shaft Comp 2 - 11-08	35	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 7 - shaft Comp 6 - 11-08	36	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 6 - 11-08 Comp 11 - gang	37	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 6 - 11-08 Comp 11 - gang	38	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 7 - shaft Comp 3 - 11-09	39	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 7 - shaft Comp 8 - 11-09	40	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 8 - 11-09 Comp 11 - gang	41	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 8 - 11-09 Comp 11 - gang	42	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 9 - gang Comp 10 - gang	43	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 10 - gang Comp 16 - stai	44	0.00	0.00	2.60	Time	0.00	1.00	7200.00	

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1.00
Comp 10 - gang Comp 11 - gang 45        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 11 - gang Comp 26 - gang 46        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 18 - gang Comp 19 - gang 47        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 17 - stai Comp 19 - gang 48        0.00        3.00        5.60        Time                                0.00        1.00      7200.00
1.00
Comp 19 - gang Comp 20 - gang 49        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 20 - gang Comp 26 - gang 50        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 23 - lift Comp 26 - gang 51        0.00        3.00        5.60        Time                                0.00        1.00      7200.00
1.00
Comp 26 - gang Comp 29 - lift 52        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 30 - 12-0 Outside        53        1.75        0.31        2.48        Time                                0.00        0.01      7200.00
0.01
Comp 30 - 12-0 Outside        54        1.75        0.31        2.48        Time                                0.00        0.01      7200.00
0.01
Comp 30 - 12-0 Comp 32 - 12-0 55        5.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 32 - 12-0 Comp 35 - gang 56        1.03        0.00        2.42        RAMP # 14
Comp 34 - gang Comp 35 - gang 57        1.14        0.00        2.42        RAMP # 15
Comp 16 - stai Comp 34 - gang 58        1.03        6.00        8.42        RAMP # 16
Comp 30 - 12-0 Outside        59        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 7 - shaft Comp 30 - 12-0 60        0.00        3.00        5.60        Time                                0.00        1.00      7200.00
1.00
Comp 7 - shaft Comp 32 - 12-0 61        0.00        3.00        5.60        Time                                0.00        1.00      7200.00
1.00
Comp 32 - 12-0 Comp 35 - gang 62        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 32 - 12-0 Comp 35 - gang 63        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 34 - gang Comp 35 - gang 64        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 16 - stai Comp 34 - gang 65        0.00        6.00        8.60        Time                                0.00        1.00      7200.00
1.00
Comp 35 - gang Comp 45 - gang 66        0.00        0.00        2.60        Time                                0.00        1.00      7200.00
1.00
Comp 23 - lift Comp 45 - gang 67        0.00        6.00        8.60        Time                                0.00        1.00      7200.00
1.00
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Comp 29 - lift Comp 45 - gang	68	0.00	6.00	8.60	Time	0.00	1.00	7200.00	1.00
Comp 34 - 12-0 Outside	69	1.75	0.31	2.48	Time	0.00	0.01	7200.00	0.01
Comp 34 - 12-0 Outside	70	1.75	0.31	2.48	Time	0.00	0.01	7200.00	0.01
Comp 34 - 12-0 Comp 35 - 12-0	71	3.80	0.00	2.60	RAMP # 17				
Comp 34 - 12-0 Outside	72	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 30 - 12-0 Comp 34 - 12-0	73	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 34 - gang Comp 35 - 12-0	74	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 36 - gang Comp 33 - gang	75	1.14	0.00	2.42	RAMP # 18				
Comp 36 - gang Comp 38 - gang	76	1.50	0.00	2.70	Time	0.00	1.00	7200.00	1.00
Comp 33 - gang Comp 37 - gang	77	1.14	0.00	2.42	RAMP # 19				
Comp 16 - stai Comp 33 - gang	78	1.03	0.00	2.42	RAMP # 20				
Comp 39 - gang Comp 40 - gang	79	1.14	0.00	2.42	RAMP # 21				
Comp 40 - gang Comp 41 - gang	80	1.50	0.00	2.42	Time	0.00	1.00	7200.00	1.00
Comp 37 - gang Comp 41 - gang	81	1.40	0.00	2.42	Time	0.00	1.00	7200.00	1.00
Comp 17 - stai Comp 39 - gang	82	1.03	0.00	2.42	RAMP # 22				
Comp 36 - gang Comp 33 - gang	83	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 16 - stai Comp 33 - gang	84	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 33 - gang Comp 37 - gang	85	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 37 - gang Comp 42 - gang	86	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 38 - gang Comp 39 - gang	87	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 17 - stai Comp 39 - gang	88	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 39 - gang Comp 40 - gang	89	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 40 - gang Comp 42 - gang	90	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 23 - lift Comp 42 - gang	91	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 29 - lift Comp 42 - gang	92	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00

Comp 43 - gang	Comp 34 - gang	93	1.14	0.00	2.42	RAMP # 23				
Comp 43 - gang	Comp 44 - gang	94	1.50	0.00	2.70	Time	0.00	1.00	7200.00	1.00
Comp 38 - gang	Comp 39 - gang	95	1.14	0.00	2.42	Time	0.00	1.00		
Comp 43 - gang	Comp 35 - 12-0	96	1.03	0.00	2.42	RAMP # 24				
Comp 44 - gang	Comp 45 - gang	97	1.14	0.00	2.42	Time	0.00	1.00		
Comp 45 - gang	Comp 47 - gang	98	1.14	0.00	2.42	RAMP # 25				
Comp 47 - gang	Comp 46 - gang	99	1.50	0.00	2.42	Time	0.00	1.00	7200.00	1.00
Comp 35 - gang	Comp 46 - gang	100	1.40	0.00	2.42	Time	0.00	1.00	7200.00	1.00
Comp 17 - stai	Comp 45 - gang	101	1.03	6.00	8.42	RAMP # 26				
Comp 43 - gang	Comp 34 - 12-0	102	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 43 - gang	Comp 35 - 12-0	103	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 43 - gang	Comp 35 - 12-0	104	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 43 - gang	Comp 34 - gang	105	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 44 - gang	Comp 45 - gang	106	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 17 - stai	Comp 45 - gang	107	0.00	6.00	8.60	Time	0.00	1.00	7200.00	1.00
Comp 45 - gang	Comp 47 - gang	108	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00
Comp 47 - gang	Comp 45 - gang	109	0.00	0.00	2.60	Time	0.00	1.00	7200.00	1.00

Ceiling and Floor Vents

Top Compartment	Bottom Compartment	Vent Number	Shape	Area (m^2)	Open/Close Type	Trigger Value (C/W/m^2)	Target	Initial Time (s)	Initial Fraction	Final Time (s)	Final Fraction
Comp 30 - 12-0	Comp 2 - 11-08	1	Square	0.00	Time			0.00	1.00	0.00	1.00
Comp 32 - 12-0	Comp 6 - 11-08	2	Square	0.00	Time			0.00	1.00	0.00	1.00
Comp 34 - 12-0	Comp 1 - 11-07	3	Square	0.00	Time			0.00	1.00	0.00	1.00
Comp 35 - 12-0	Comp 4 - 11-07	4	Square	0.00	Time			0.00	1.00	0.00	1.00

Mechanical Vents (Fans)

From Compartment	To Compartment	Fan Number	Area (m^2)	Flowrate (m^3/s)	Open/Close Type	Trigger Value (C/W/m^2)	Target	Initial Time (s)	Initial Fraction	Final Time (s)	Final Fraction
Outside	Comp 13 - shaf	1	0.42	15.00	Time			0.00	1.00	0.00	1.00
Outside	Comp 24 - shaf	2	0.42	15.00	Time			0.00	1.00	0.00	1.00
Comp 15 - shaf	Outside	3	0.42	15.00	Time			0.00	1.00	0.00	1.00
Comp 5 - shaft	Outside	4	0.42	7.50	Time			0.00	1.00	0.00	1.00
Comp 25 - shaf	Outside	5	0.42	7.50	Time			0.00	1.00	0.00	1.00
Comp 13 - shaf	Comp 33 - gang	6	0.42	5.00	Time			0.00	1.00	0.00	1.00
Comp 33 - gang	Comp 36 - gang	7	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 33 - gang	Comp 37 - gang	8	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 37 - gang	Comp 5 - shaft	9	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 36 - gang	Comp 15 - shaf	10	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 24 - shaf	Comp 39 - gang	11	0.42	5.00	Time			0.00	1.00	0.00	1.00
Comp 39 - gang	Comp 38 - gang	12	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 39 - gang	Comp 40 - gang	13	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 38 - gang	Comp 15 - shaf	14	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 40 - gang	Comp 25 - shaf	15	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 13 - shaf	Comp 10 - gang	16	0.42	5.00	Time			0.00	1.00	0.00	1.00
Comp 10 - gang	Comp 9 - gang	17	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 10 - gang	Comp 11 - gang	18	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 11 - gang	Comp 5 - shaft	19	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 9 - gang	Comp 15 - shaf	20	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 24 - shaf	Comp 19 - gang	21	0.42	5.00	Time			0.00	1.00	0.00	1.00
Comp 19 - gang	Comp 18 - gang	22	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 19 - gang	Comp 20 - gang	23	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 18 - gang	Comp 15 - shaf	24	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 20 - gang	Comp 25 - shaf	25	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 13 - shaf	Comp 34 - gang	26	0.42	5.00	Time			0.00	1.00	0.00	1.00
Comp 34 - gang	Comp 43 - gang	27	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 34 - gang	Comp 35 - gang	28	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 35 - gang	Comp 5 - shaft	29	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 43 - gang	Comp 15 - shaf	30	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 24 - shaf	Comp 45 - gang	31	0.42	5.00	Time			0.00	1.00	0.00	1.00
Comp 45 - gang	Comp 44 - gang	32	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 45 - gang	Comp 47 - gang	33	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 44 - gang	Comp 15 - shaf	34	0.42	2.50	Time			0.00	1.00	0.00	1.00
Comp 47 - gang	Comp 25 - shaf	35	0.42	2.50	Time			0.00	1.00	0.00	1.00

VENT RAMPS

Type	From Compartment	To Compartment	Vent Number		(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)
H	Comp 2 - 11-08	Outside	1	Time	0	299	300	7200						
				Fraction	0.01	0.01	0.01	0.01						
H	Comp 2 - 11-08	Outside	2	Time	0	299	300	7200						
				Fraction	0.01	0.01	0.01	0.01						
H	Comp 1 - 11-07	Comp 4 - 11-07	3	Time	0	1	7200							
				Fraction	1.00	1.00	1.00							
H	Comp 2 - 11-08	Comp 6 - 11-08	4	Time	0	1	7200							
				Fraction	1.00	1.00	1.00							
H	Comp 3 - 11-09	Comp 8 - 11-09	5	Time	0	1	7200							
				Fraction	1.00	1.00	1.00							
H	Comp 4 - 11-07	Comp 9 - gang	6	Time	0	1019	1020	1040	1041	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 6 - 11-08	Comp 11 - gang	7	Time	0	119	120	140	141	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 8 - 11-09	Comp 11 - gang	8	Time	0	1019	1020	1040	1041	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 9 - gang	Comp 10 - gang	9	Time	0	1039	1040	1060	1061	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 10 - gang	Comp 11 - gang	10	Time	0	139	140	160	161	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 10 - gang	Comp 16 - stai	11	Time	0	159	160	180	181	1059	1060	1080	1081	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 19 - gang	Comp 20 - gang	12	Time	0	1039	1040	1060	1061	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 17 - stai	Comp 19 - gang	13	Time	0	1059	1060	1080	1081	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 32 - 12-0	Comp 35 - gang	14	Time	0	1019	1020	1040	1041	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				
H	Comp 34 - gang	Comp 35 - gang	15	Time	0	1039	1040	1060	1061	7200				
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00				

H	Comp 16 - stai	Comp 34 - gang	16	Time	0	1059	1060	1080	1081	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 34 - 12-0	Comp 35 - 12-0	17	Time	0	1	7200			
				Fraction	1.00	1.00	1.00			
H	Comp 36 - gang	Comp 33 - gang	18	Time	0	1039	1040	1060	1061	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 33 - gang	Comp 37 - gang	19	Time	0	1039	1040	1060	1061	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 16 - stai	Comp 33 - gang	20	Time	0	1059	1060	1080	1081	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 39 - gang	Comp 40 - gang	21	Time	0	1039	1040	1060	1061	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 17 - stai	Comp 39 - gang	22	Time	0	1059	1060	1080	1081	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 43 - gang	Comp 34 - gang	23	Time	0	1039	1040	1060	1061	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 43 - gang	Comp 35 - 12-0	24	Time	0	1019	1020	1040	1041	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 45 - gang	Comp 47 - gang	25	Time	0	1039	1040	1060	1061	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00
H	Comp 17 - stai	Comp 45 - gang	26	Time	0	1059	1060	1080	1081	7200
				Fraction	0.00	0.00	1.00	1.00	0.00	0.00

FIRES

Name: New Fire 1   Referenced as object # 1 Normal fire

Compartment	Fire Type	Time to Flaming	Position (x,y,z)			Relative Humidity	Lower O2 Limit	Radiative Fraction
Comp 2 - 11-08	Constrained	0.0	3.05	2.83	1.00	50.0	10.00	0.35

Chemical formula of the fuel

Carbon	Hydrogen	Oxygen	Nitrogen	Chlorine
4.000	6.000	3.000	0.000	0.000

Time (s)	Mdot (kg/s)	Hcomb (J/kg)	Qdot (W)	Zoffset (m)	Soot (kg/kg)	CO (kg/kg)	HCN (kg/kg)	HCl (kg/kg)	TS (kg/kg)

0.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
60.	2.29E-03	1.75E+07	4.00E+04	1.0	5.28E-02	0.10	0.0	0.0	0.0
120.	9.14E-03	1.75E+07	1.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
180.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
240.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
300.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
360.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
420.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
480.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
540.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
600.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
660.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
720.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
780.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
840.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
900.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
960.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1020.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1080.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1140.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1200.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1260.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1320.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1380.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1440.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1500.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1560.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1620.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1680.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1740.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1800.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1860.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1920.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
1980.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2040.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2100.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2160.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2220.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2280.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2340.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2400.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2460.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2520.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2580.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0

2640.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2700.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2760.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2820.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2880.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
2940.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3000.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3060.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3120.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3180.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3240.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3300.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3360.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3420.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3480.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3540.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3600.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3660.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3720.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3780.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3840.	2.06E-02	1.75E+07	3.60E+05	1.0	5.28E-02	0.10	0.0	0.0	0.0
3900.	2.82E-03	1.75E+07	4.94E+04	1.0	5.28E-02	0.10	0.0	0.0	0.0
3960.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4020.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4080.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4140.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4200.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4260.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4320.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4380.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4440.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4500.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4560.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4620.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4680.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4740.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4800.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4860.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4920.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
4980.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5040.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5100.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5160.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5220.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0

5280.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5340.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5400.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5460.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5520.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5580.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5640.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5700.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5760.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5820.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5880.	0.0	1.75E+07	0.0	1.0	5.28E-02	0.10	0.0	0.0	0.0
5940.	0.0	1.75E+07	0.0	1.0	2.64E-02	1.04E-02	0.0	0.0	0.0

9.12 Appendix 12. Probabilistic approach super-tall residential building

PROBABILISTIC CALCULATION THERMAL LOAD / THERMAL RESISTANCE
AVAILABLE AND REQUIRED TIME [SFC]

RST
Case: Super-tall residential building study
Assessment: Equivalent fire duration of a natural fire (no flaming model)

SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic	
		average x	RST t [min]
Rate of heat release density	kW/m^2	250	
Timeconstant for fire spread	s	300	
Fire load density	MJ/m^2	780	
Combustion efficiency factor	-	0,8	
Stoichiometric coefficient	kg/kg	1,27	
Standard fire curve SFC	60 min. SFC	60	
		RST	**51,0**

(opening factor worst case: fuel/oxygen controlled)

Sensitivity analysis			
variation V	st. deviation s	new value x + dx	RST t [min]
0,40	100	350	41,0
-0,30	-75	175	65,0
0,25	75	375	51,0
-0,50	-150	150	52,0
0,15	117	897	59,0
-0,15	-117	663	44,0
0,08	0,1	0,862	57,0
-0,08	-0,1	0,738	46,0
0,50	0,6	1,91	45,0
-0,25	-0,3	0,95	56,0

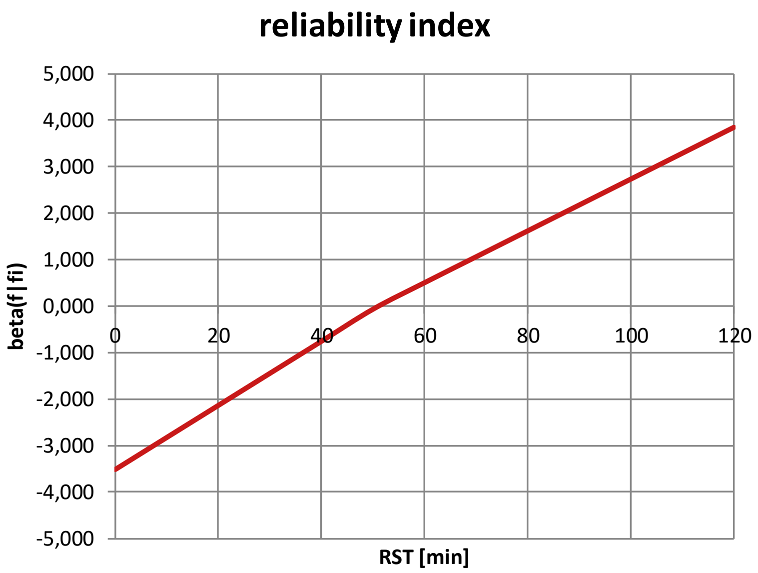
Probabilistic			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
-0,10	-10,00	0,00	100,00
-0,19	14,00	196,00	0,00
0,00	0,00	0,00	0,00
-0,01	1,00	1,00	0,00
0,07	8,00	64,00	0,00
0,06	-7,00	0,00	49,00
96,77	6,00	36,00	0,00
80,65	-5,00	0,00	25,00
-9,45	-6,00	0,00	36,00
-15,75	5,00	25,00	0,00
	variancy(t) =	322,000	210,000
	s(t) =	17,944	-14,491

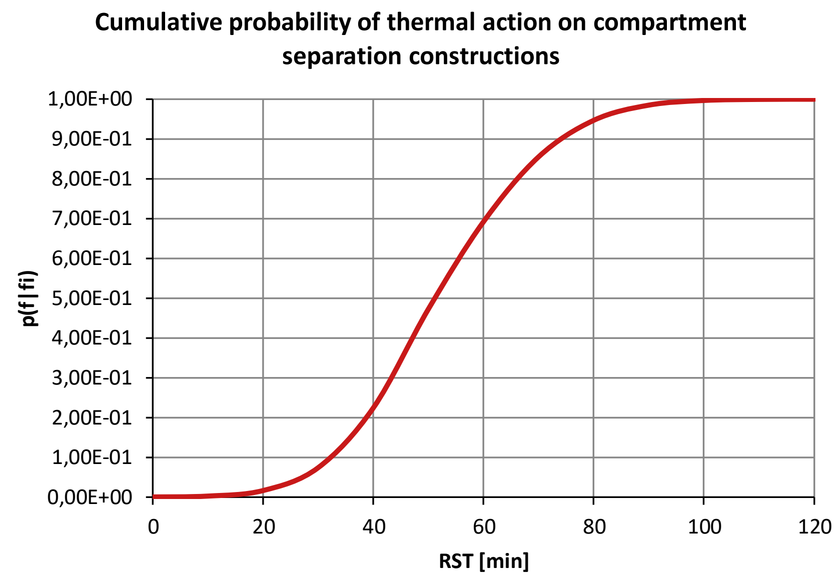
Reliability and cumulative failure probability			
t [min]	s(t)	beta(f|fi)	p(f|fi)
0	14,49138	-3,519	2,16E-04
10	14,49138	-2,829	2,33E-03
20	14,49138	-2,139	1,62E-02
30	14,49138	-1,449	7,36E-02
40	14,49138	-0,759	2,24E-01
50	14,49138	-0,069	4,72E-01
60	17,94436	0,502	6,92E-01
70	17,94436	1,059	8,55E-01
80	17,94436	1,616	9,47E-01
90	17,94436	2,173	9,85E-01
100	17,94436	2,731	9,97E-01
110	17,94436	3,288	9,99E-01
120	17,94436	3,845	1,00E+00

Significant event compartmentfire

compartment area $[m^2]$	43,82		
Design life time [yr] :	100		
Ignition probability $[1/m^2/1yr]$:	2,000E-07		
Ignition probability $[1/m^2/100yr]$:	2,00E-05	(during design lifetime)	
Probability of fire p(fi) :	8,76E-04	(during design lifetime)	

EUROCODE	p(f)	p(f|fi)	beta(f|fi)
CC1: beta(f) > 3,3	4,83E-04	5,52E-01	-0,13
CC2: beta(f) > 3,8	7,23E-05	8,26E-02	1,39
CC3: beta(f) > 4,3	8,54E-06	9,74E-03	**2,34**





PROBABILISTIC CALCULATION THERMAL LOAD / THERMAL RESISTANCE
AVAILABLE AND REQUIRED TIME [SFC]

RST
Case: Super-tall residential building study
Assessment: Equivalent fire duration of a natural fire (no flaming model)

sensitivity analysis **stochastic boundary conditions**		**deterministic** average x	RST t [min]
rate of heat release density	kW/m^2	250	
timeconstant for fire spread	s	300	
fire load density	MJ/m^2	780	
combustion efficiency factor	-	0,8	
stoichiometric coefficient	kg/kg	1,27	
standard fire curve SFC	60 min. SFC	60	
		RST	**51,0**

(opening factor worst case: fuel/oxygen controlled)

sensitivity analysis variation V	st. deviation s	new value x + dx	RST t [min]
0,40	100	350	41,0
-0,30	-75	175	65,0
0,25	75	375	51,0
-0,50	-150	150	52,0
0,15	117	897	59,0
-0,15	-117	663	44,0
0,08	0,1	0,862	57,0
-0,08	-0,1	0,738	46,0
0,50	0,6	1,91	45,0
-0,25	-0,3	0,95	56,0

probabilistic dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
-0,10	-10,00	0,00	100,00
-0,19	14,00	196,00	0,00
0,00	0,00	0,00	0,00
-0,01	1,00	1,00	0,00
0,07	8,00	64,00	0,00
0,06	-7,00	0,00	49,00
96,77	6,00	36,00	0,00
80,65	-5,00	0,00	25,00
-9,45	-6,00	0,00	36,00
-15,75	5,00	25,00	0,00
	variancy(t) =	322,000	210,000
	s(t) =	17,944	-14,491

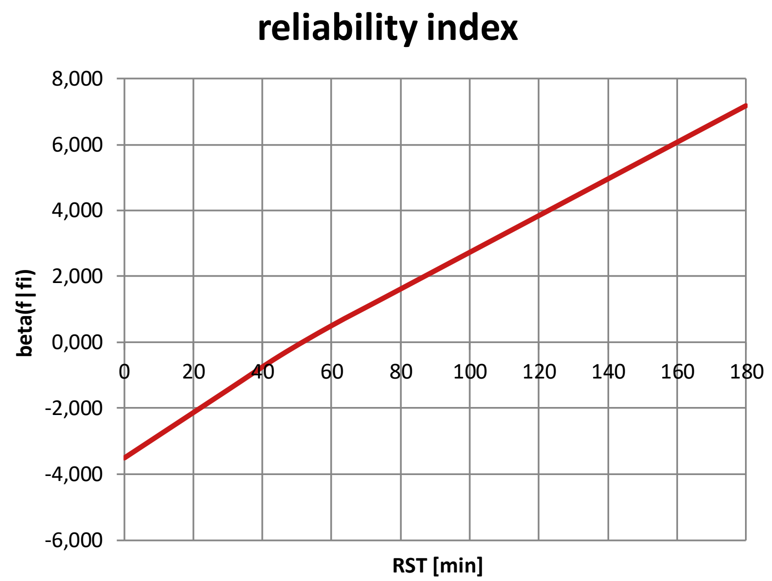
Reliability and cumulative failure probability t [min]	s(t)	beta(f|fi)	p(f|fi)
0	14,49138	-3,519	2,16E-04
15	14,49138	-2,484	6,49E-03
30	14,49138	-1,449	7,36E-02
45	14,49138	-0,414	3,39E-01
60	17,94436	0,502	6,92E-01
75	17,94436	1,337	9,09E-01
90	17,94436	2,173	9,85E-01
105	17,94436	3,009	9,99E-01
120	17,94436	3,845	1,00E+00
135	17,94436	**4,681**	1,00E+00
150	17,94436	5,517	1,00E+00
165	17,94436	6,353	1,00E+00
180	17,94436	7,189	1,00E+00

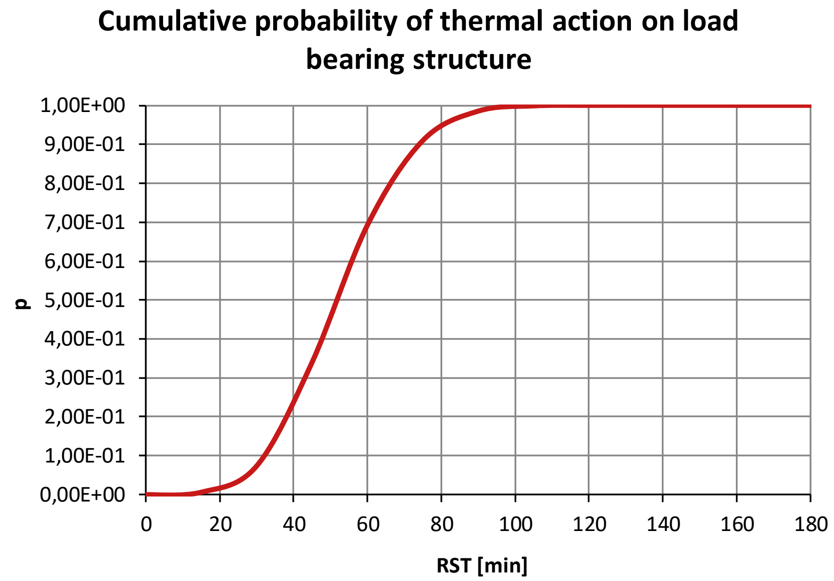
significant event compartmentfire

building area $[m^2]$ 140577
design life time [yr] : 100
ignition probability $[1/m^2/1yr]$: 2,000E-07
Ignition probability $[1/m^2/100yr]$: 2,00E-05 (during design lifetime)

probability of fire p(fi) : 2,81E+00 (during design lifetime)

EUROCODE	p(f)	p(f|fi)	beta(f|fi)
CC1: beta(f) > 3,3	4,83E-04	1,72E-04	3,58
CC2: beta(f) > 3,8	7,23E-05	2,57E-05	4,05
CC3: beta(f) > 4,3	8,54E-06	3,04E-06	**4,52**

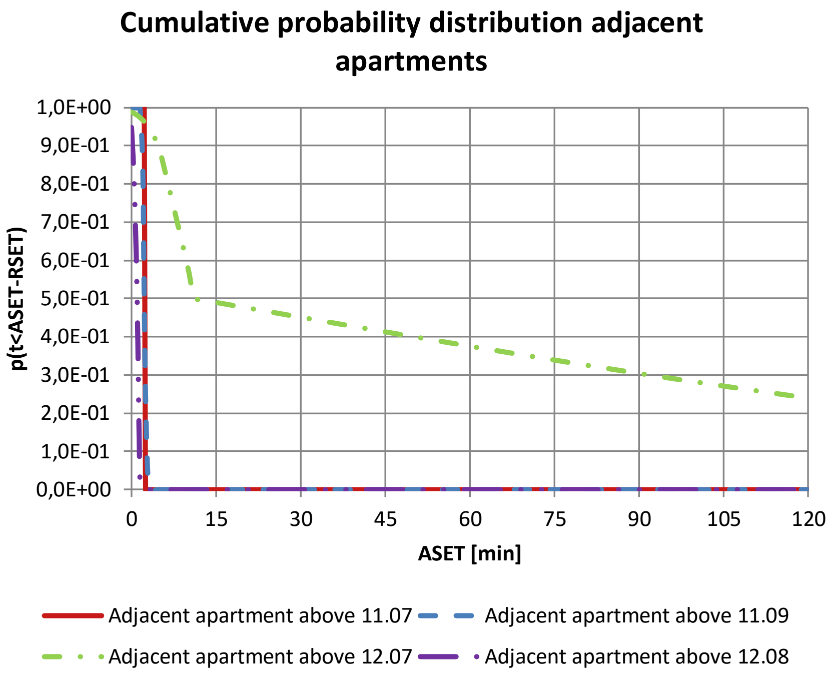




PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Overview: Apartments 11.07, 11.09, 12.07 and 12.08

Reliability and failure probability				
t [min]	Adjacent apartment above 11.07	Adjacent apartment above 11.09	Adjacent apartment above 12.07	Adjacent apartment above 12.08
0,00	1,00E+00	1,00E+00	9,87E-01	9,49E-01
0,50	1,00E+00	1,00E+00	9,84E-01	7,93E-01
1,00	1,00E+00	1,00E+00	9,79E-01	5,00E-01
1,50	1,00E+00	9,99E-01	9,73E-01	2,28E-02
2,00	1,00E+00	8,41E-01	9,66E-01	3,17E-05
2,25	1,00E+00	5,00E-01	9,62E-01	2,87E-07
2,50	###########	2,40E-01	9,58E-01	9,87E-10
3,00	###########	1,69E-02	9,48E-01	6,22E-16
4,00	###########	3,72E-07	9,22E-01	1,78E-33
5,00	###########	3,68E-15	8,88E-01	6,39E-58
10,00	###########	8,32E-107	5,80E-01	4,18E-284
11,00	###########	1,60E-135	5,00E-01	0,00E+00
12,00	###########	1,05E-167	4,97E-01	0,00E+00
15,00	###########	4,40E-285	4,90E-01	0,00E+00
30,00	###########	0,00E+00	4,51E-01	0,00E+00
45,00	###########	0,00E+00	4,13E-01	0,00E+00
60,00	###########	0,00E+00	3,75E-01	0,00E+00
75,00	###########	0,00E+00	3,39E-01	0,00E+00
90,00	###########	0,00E+00	3,04E-01	0,00E+00
105,00	###########	0,00E+00	2,71E-01	0,00E+00
120,00	###########	0,00E+00	2,40E-01	0,00E+00



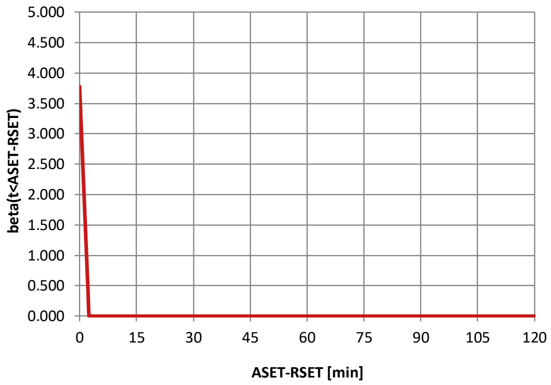
PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Adjacent apartments 11.07

SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic		Probabilistic: sensitivity analysis				Standard deviation			
		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]	dt/dx	s·dt/dx	$(s·dt/dx)^2$	
External airtightness multiplier	-	1		0.70	0.70	1.70	2.50	0.00	0.00	0.00	0.00
				-0.70	-0.70	0.30	2.25	0.36	-0.25	0.00	0.06
Internal airtightness multiplier	-	1		1.50	1.50	2.50	2.25	-0.17	-0.25	0.00	0.06
				-0.50	-0.50	0.50	2.50	0.00	0.00	0.00	0.00
Time door opens	s	120		1.50	180.00	300.00	2.25	0.00	-0.25	0.00	0.06
				-0.50	-60.00	60.00	2.25	0.00	-0.25	0.00	0.06
Time door closes	s	20		2.00	40.00	60.00	2.50	0.00	0.00	0.00	0.00
				-0.50	-10.00	10.00	2.50	0.00	0.00	0.00	0.00
Lower oxygen limit	%	10		0.50	5.00	15.00	2.50	0.00	0.00	0.00	0.00
				-0.50	-5.00	5.00	2.50	0.00	0.00	0.00	0.00
Soot yield multiplier	-	1		1.00	1.00	2.00	2.00	-0.50	-0.50	0.00	0.25
				-0.30	-0.30	0.70	2.50	0.00	0.00	0.00	0.00
Acceptable conditions		ASET	2.50						variancy(t) =	0.000	0.438
									s(t) =	0.000	-0.661

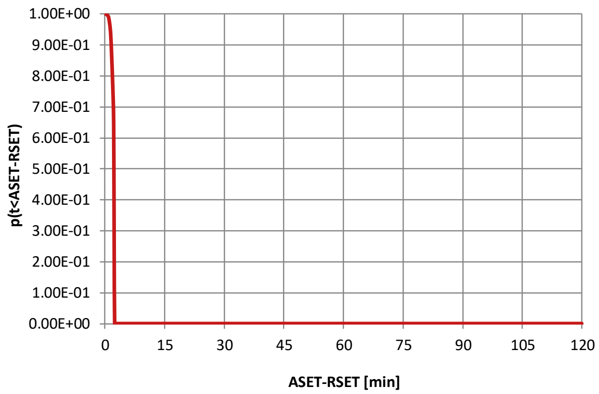
reliability index



Reliability and failure probability

t [min]	s(t)	beta(t|fi)	p(t|fi)
0.00	0.66144	3.780	1.00E+00
0.50	0.66144	3.024	9.99E-01
1.00	0.66144	2.268	9.88E-01
1.50	0.66144	1.512	9.35E-01
2.00	0.66144	0.756	7.75E-01
2.25	0.66144	0.378	6.47E-01
2.50	0.00000	#########	##############
3.00	0.00000	#########	##############
4.00	0.00000	#########	##############
5.00	0.00000	#########	##############
10.00	0.00000	#########	##############
11.00	0.00000	#########	##############
12.00	0.00000	#########	##############
15.00	0.00000	#########	##############
30.00	0.00000	#########	##############
45.00	0.00000	#########	##############
60.00	0.00000	#########	##############
75.00	0.00000	#########	##############
90.00	0.00000	#########	##############
105.00	0.00000	#########	##############
120.00	0.00000	#########	##############

cumulative probability distribution



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

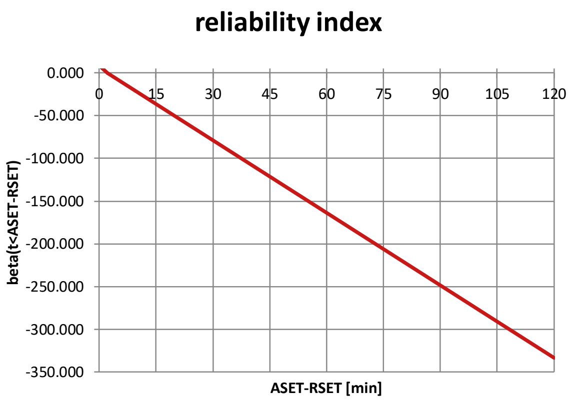
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Adjacent apartments 11.09

SENSITIVITY ANALYSIS
Stochastic boundary conditions

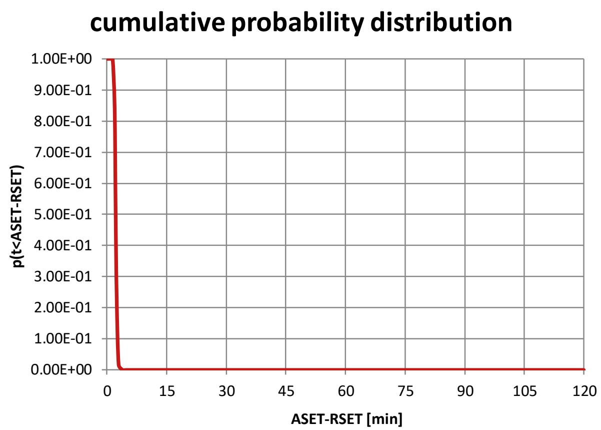
Stochastic boundary conditions	unit	Deterministic: average x	Deterministic: ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	2.25

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	2.25
-0.70	-0.70	0.30	2.25
1.50	1.50	2.50	2.25
-0.50	-0.50	0.50	2.50
1.50	180.00	300.00	2.25
-0.50	-60.00	60.00	2.25
2.00	40.00	60.00	2.25
-0.50	-10.00	10.00	2.25
0.50	5.00	15.00	2.25
-0.50	-5.00	5.00	2.25
1.00	1.00	2.00	2.00
-0.30	-0.30	0.70	2.50

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.50	0.25	0.06	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.25	-0.25	0.00	0.06
-0.83	0.25	0.06	0.00
	variancy(t) =	0.125	0.063
	s(t) =	0.354	-0.250



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0.00	0.25000	9.000	1.00E+00
0.50	0.25000	7.000	1.00E+00
1.00	0.25000	5.000	1.00E+00
1.50	0.25000	3.000	9.99E-01
2.00	0.25000	1.000	8.41E-01
2.25	0.35355	0.000	5.00E-01
2.50	0.35355	-0.707	2.40E-01
3.00	0.35355	-2.121	1.69E-02
4.00	0.35355	-4.950	3.72E-07
5.00	0.35355	-7.778	3.68E-15
10.00	0.35355	-21.920	8.32E-107
11.00	0.35355	-24.749	1.60E-135
12.00	0.35355	-27.577	1.05E-167
15.00	0.35355	-36.062	4.40E-285
30.00	0.35355	-78.489	0.00E+00
45.00	0.35355	-120.915	0.00E+00
60.00	0.35355	-163.342	0.00E+00
75.00	0.35355	-205.768	0.00E+00
90.00	0.35355	-248.194	0.00E+00
105.00	0.35355	-290.621	0.00E+00
120.00	0.35355	-333.047	0.00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

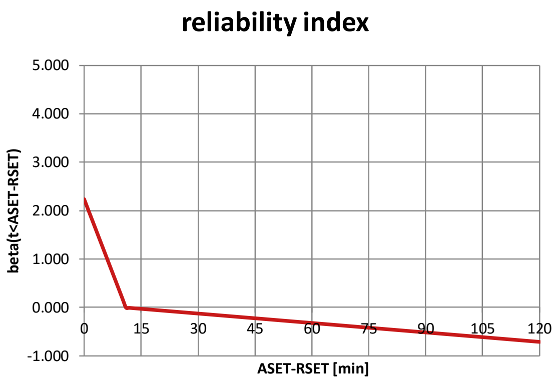
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Adjacent partments above 12.07

SENSITIVITY ANALYSIS
Stochastic boundary conditions

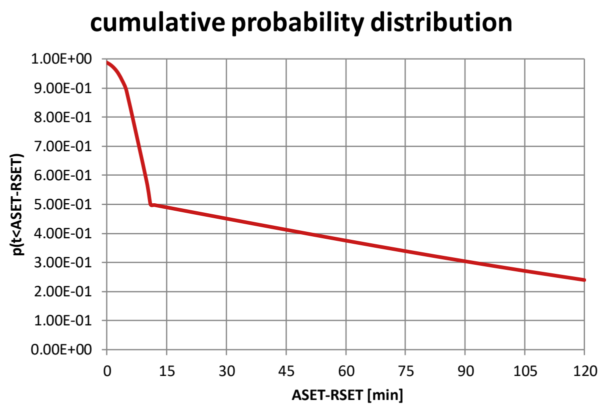
		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		**ASET**	**11.00**

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	11.50
-0.70	-0.70	0.30	11.00
1.50	1.50	2.50	6.50
-0.50	-0.50	0.50	120.00
1.50	180.00	300.00	11.00
-0.50	-60.00	60.00	11.50
2.00	40.00	60.00	11.50
-0.50	-10.00	10.00	11.25
0.50	5.00	15.00	120.00
-0.50	-5.00	5.00	11.00
1.00	1.00	2.00	9.00
-0.30	-0.30	0.70	13.50

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0.71	0.50	0.25	0.00
0.00	0.00	0.00	0.00
-3.00	-4.50	0.00	20.25
-218.00	109.00	11881.00	0.00
0.00	0.00	0.00	0.00
-0.01	0.50	0.25	0.00
0.01	0.50	0.25	0.00
-0.03	0.25	0.06	0.00
21.80	109.00	11881.00	0.00
0.00	0.00	0.00	0.00
-2.00	-2.00	0.00	4.00
-8.33	2.50	6.25	0.00
	variancy(t) =	23768.813	24.250
	s(t) =	154.171	-4.924



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0.00	4.92443	2.234	9.87E-01
0.50	4.92443	2.132	9.84E-01
1.00	4.92443	2.031	9.79E-01
1.50	4.92443	1.929	9.73E-01
2.00	4.92443	1.828	9.66E-01
2.25	4.92443	1.777	9.62E-01
2.50	4.92443	1.726	9.58E-01
3.00	4.92443	1.625	9.48E-01
4.00	4.92443	1.421	9.22E-01
5.00	4.92443	1.218	8.88E-01
10.00	4.92443	0.203	5.80E-01
11.00	154.17137	0.000	5.00E-01
12.00	154.17137	-0.006	4.97E-01
15.00	154.17137	-0.026	4.90E-01
30.00	154.17137	-0.123	4.51E-01
45.00	154.17137	-0.221	4.13E-01
60.00	154.17137	-0.318	3.75E-01
75.00	154.17137	-0.415	3.39E-01
90.00	154.17137	-0.512	3.04E-01
105.00	154.17137	-0.610	2.71E-01
120.00	154.17137	-0.707	2.40E-01



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

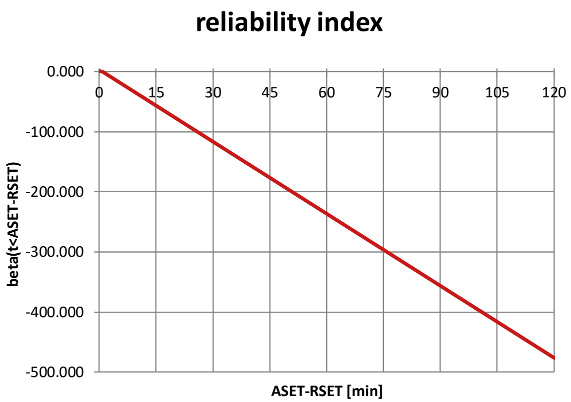
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Apartments above 12.08

SENSITIVITY ANALYSIS
Stochastic boundary conditions

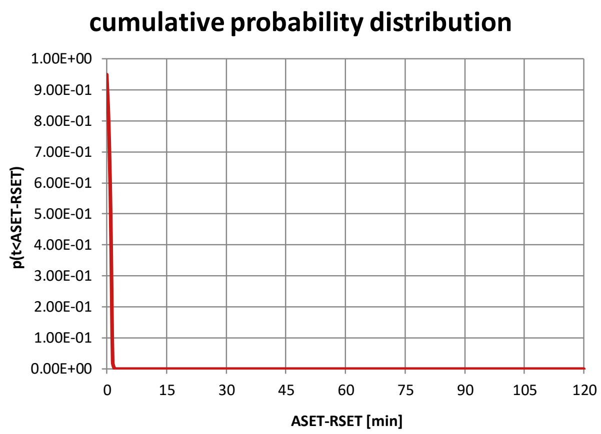
Stochastic boundary conditions		Deterministic: average x	Deterministic: ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	1.00

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0.70	0.70	1.70	1.00
-0.70	-0.70	0.30	0.75
1.50	1.50	2.50	0.75
-0.50	-0.50	0.50	1.00
1.50	180.00	300.00	0.75
-0.50	-60.00	60.00	1.00
2.00	40.00	60.00	1.00
-0.50	-10.00	10.00	1.00
0.50	5.00	15.00	1.00
-0.50	-5.00	5.00	1.00
1.00	1.00	2.00	0.50
-0.30	-0.30	0.70	1.25

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0.00	0.00	0.00	0.00
0.36	-0.25	0.00	0.06
-0.17	-0.25	0.00	0.06
0.00	0.00	0.00	0.00
0.00	-0.25	0.00	0.06
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
-0.50	-0.50	0.00	0.25
-0.83	0.25	0.06	0.00
	variancy(t) =	0.063	0.375
	s(t) =	0.250	-0.612



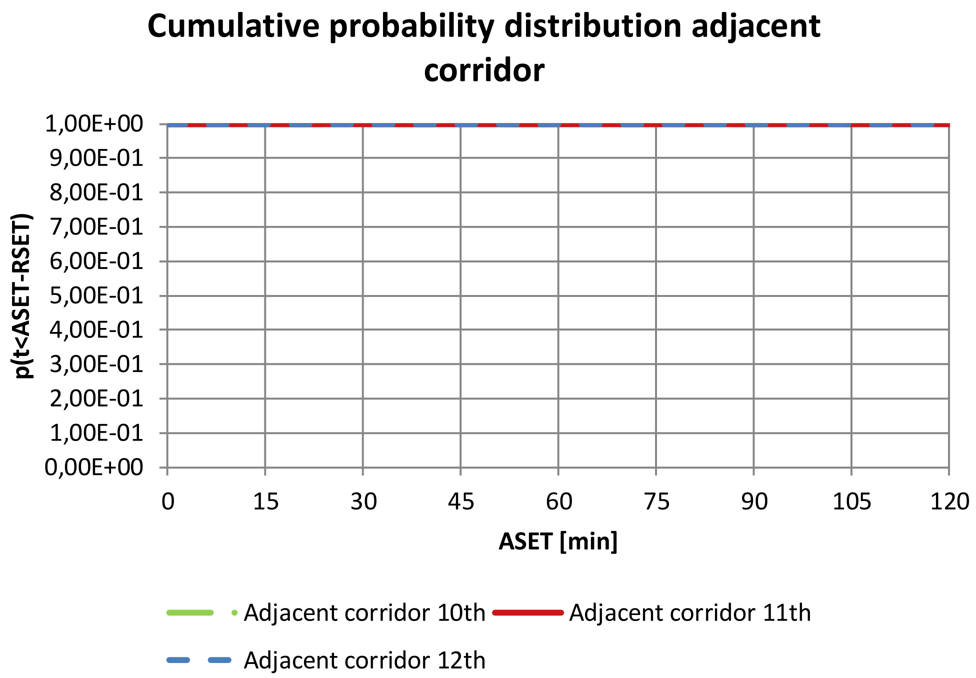
Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0.00	0.61237	1.633	9.49E-01
0.50	0.61237	0.816	7.93E-01
1.00	0.25000	0.000	5.00E-01
1.50	0.25000	-2.000	2.28E-02
2.00	0.25000	-4.000	3.17E-05
2.25	0.25000	-5.000	2.87E-07
2.50	0.25000	-6.000	9.87E-10
3.00	0.25000	-8.000	6.22E-16
4.00	0.25000	-12.000	1.78E-33
5.00	0.25000	-16.000	6.39E-58
10.00	0.25000	-36.000	4.18E-284
11.00	0.25000	-40.000	0.00E+00
12.00	0.25000	-44.000	0.00E+00
15.00	0.25000	-56.000	0.00E+00
30.00	0.25000	-116.000	0.00E+00
45.00	0.25000	-176.000	0.00E+00
60.00	0.25000	-236.000	0.00E+00
75.00	0.25000	-296.000	0.00E+00
90.00	0.25000	-356.000	0.00E+00
105.00	0.25000	-416.000	0.00E+00
120.00	0.25000	-476.000	0.00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Overview: Adjacent corridors floor 10, 11 and 12

Reliability and failure probability			
t [min]	corridor 10th	corridor 11th	corridor 12th
0	1,00000	1,00000	1,000
15	1,00000	1,00000	1,000
30	1,00000	1,00000	1,000
45	1,00000	1,00000	1,000
60	1,00000	1,00000	1,000
75	1,00000	1,00000	1,000
90	1,00000	1,00000	1,000
105	1,00000	1,00000	1,000
120	1,00000	1,00000	1,000



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Adjacent corridors floor 10

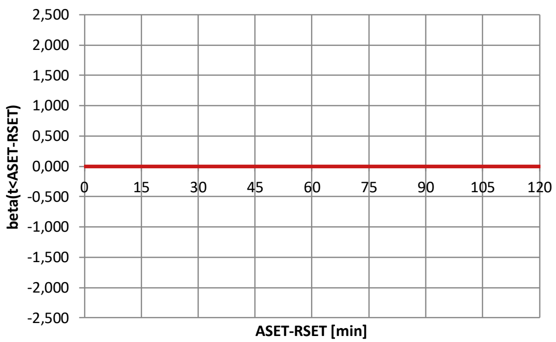
SENSITIVITY ANALYSIS
Stochastic boundary conditions

Stochastic boundary conditions	Unit	Deterministic: average x	Deterministic: ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	120,00

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	120,00
-0,70	-0,70	0,30	120,00
1,50	1,50	2,50	120,00
-0,50	-0,50	0,50	120,00
1,50	180,00	300,00	120,00
-0,50	-60,00	60,00	120,00
2,00	40,00	60,00	120,00
-0,50	-10,00	10,00	120,00
0,50	5,00	15,00	120,00
-0,50	-5,00	5,00	120,00
1,00	1,00	2,00	120,00
-0,30	-0,30	0,70	120,00

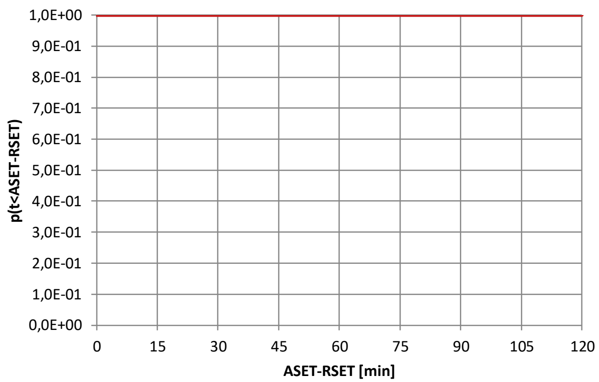
Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
variancy(t) =		0,000	0,000
s(t) =		0,000	0,000

reliability index



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00

cumulative probability distribution



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

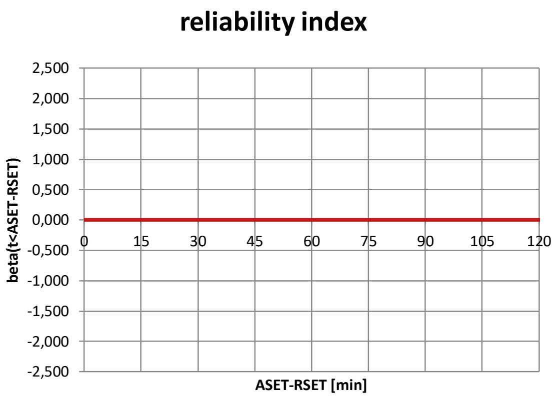
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Adjacent corridors floor 11

SENSITIVITY ANALYSIS
Stochastic boundary conditions

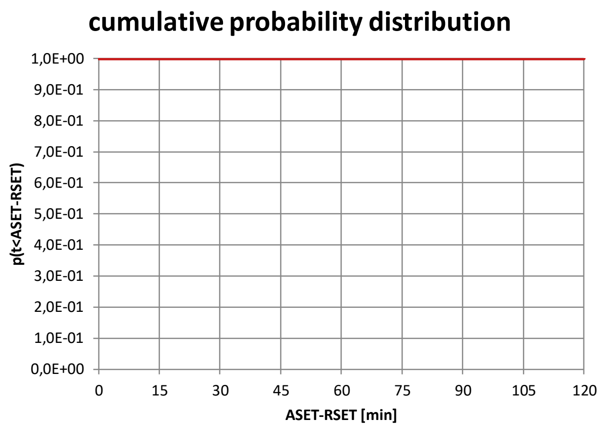
		Deterministic		Probabilistic: sensitivity analysis				
		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]	
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00	
				-0,70	-0,70	0,30	120,00	
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00	
				-0,50	-0,50	0,50	120,00	
Time door opens	s	120		1,50	180,00	300,00	120,00	
				-0,50	-60,00	60,00	120,00	
Time door closes	s	20		2,00	40,00	60,00	120,00	*
				-0,50	-10,00	10,00	120,00	
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00	
				-0,50	-5,00	5,00	120,00	
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00	
				-0,30	-0,30	0,70	120,00	
Acceptable conditions		ASET	120,00					

* A small peak in optical density exceeds the limit of 0.20 m-1 for a short period of time. The peak continues for 150 seconds from 120 seconds to 270 seconds, with the maximum after 180 seconds when the door closes

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

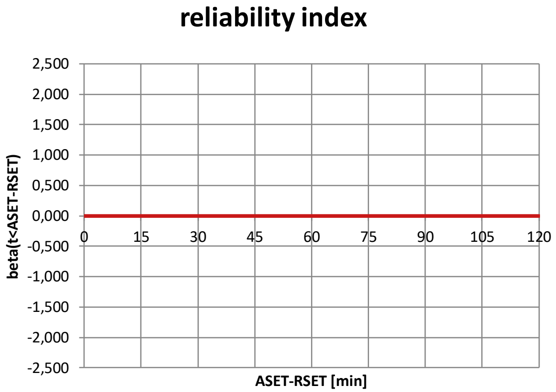
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Adjacent corridors floor 12

SENSITIVITY ANALYSIS
Stochastic boundary conditions

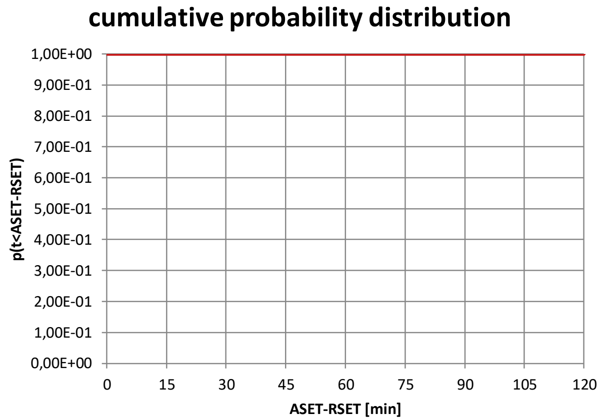
		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	120,00

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	120,00
-0,70	-0,70	0,30	120,00
1,50	1,50	2,50	120,00
-0,50	-0,50	0,50	120,00
1,50	180,00	300,00	120,00
-0,50	-60,00	60,00	120,00
2,00	40,00	60,00	120,00
-0,50	-10,00	10,00	120,00
0,50	5,00	15,00	120,00
-0,50	-5,00	5,00	120,00
1,00	1,00	2,00	120,00
-0,30	-0,30	0,70	120,00

Standard deviation			
dt/dx	s·dt/dx	$(s·dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000



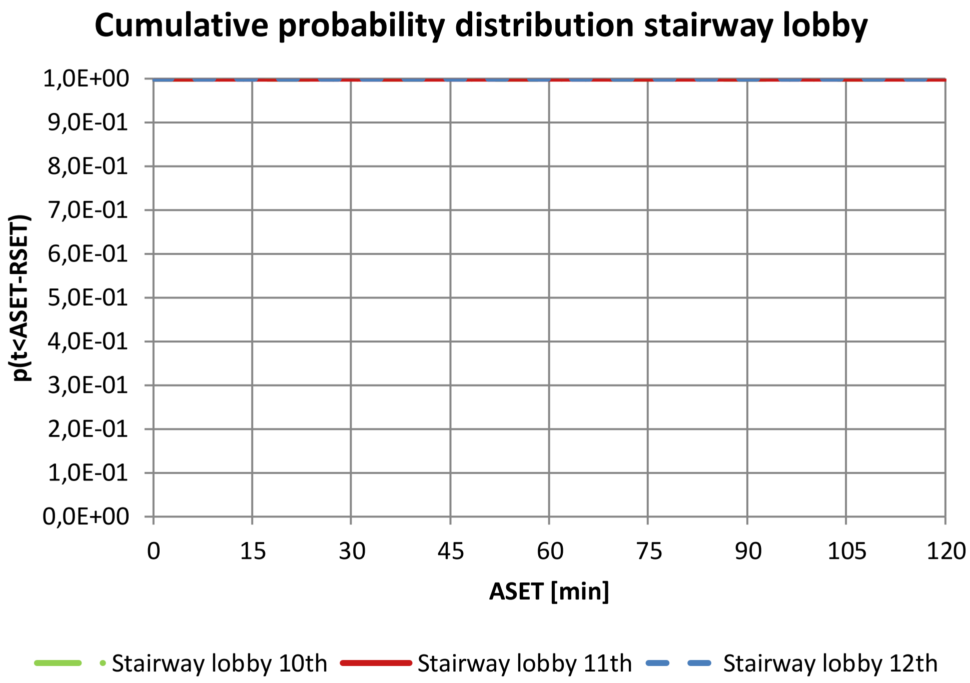
Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Overview: Stairway Lobbies floor 10, 11 and 12

Reliability and failure probability			
t [min]	Stairway lobby 10th	Stairway lobby 11th	Stairway lobby 12th
0	1,00000	1,00000	1,000
15	1,00000	1,00000	1,000
30	1,00000	1,00000	1,000
45	1,00000	1,00000	1,000
60	1,00000	1,00000	1,000
75	1,00000	1,00000	1,000
90	1,00000	1,00000	1,000
105	1,00000	1,00000	1,000
120	1,00000	1,00000	1,000



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Stairwaylobby floor 10

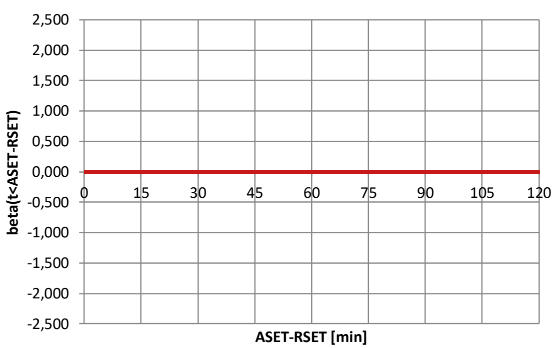
SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	120,00

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	120,00
-0,70	-0,70	0,30	120,00
1,50	1,50	2,50	120,00
-0,50	-0,50	0,50	120,00
1,50	180,00	300,00	120,00
-0,50	-60,00	60,00	120,00
2,00	40,00	60,00	120,00
-0,50	-10,00	10,00	120,00
0,50	5,00	15,00	120,00
-0,50	-5,00	5,00	120,00
1,00	1,00	2,00	120,00
-0,30	-0,30	0,70	120,00

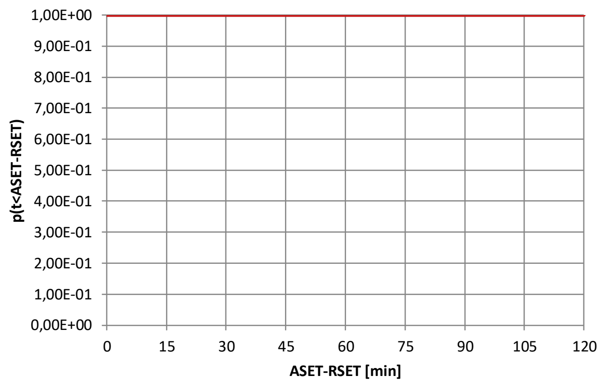
Standard deviation			
dt/dx	s·dt/dx	$(s\cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000

reliability index



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00

cumulative probability distribution

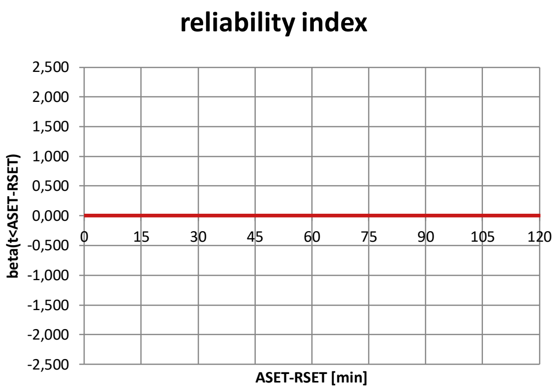


PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Stairwaylobby floor 11

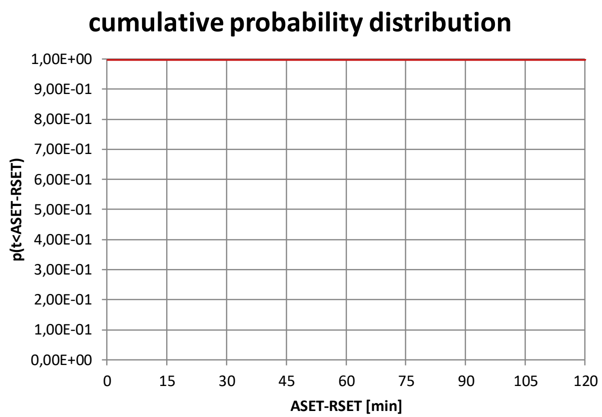
SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic		Probabilistic: sensitivity analysis				Standard deviation			
		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]	dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00	0,00	0,00	0,00	0,00
				-0,70	-0,70	0,30	120,00	0,00	0,00	0,00	0,00
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00	0,00	0,00	0,00	0,00
				-0,50	-0,50	0,50	120,00	0,00	0,00	0,00	0,00
Time door opens	s	120		1,50	180,00	300,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-60,00	60,00	120,00	0,00	0,00	0,00	0,00
Time door closes	s	20		2,00	40,00	60,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-10,00	10,00	120,00	0,00	0,00	0,00	0,00
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-5,00	5,00	120,00	0,00	0,00	0,00	0,00
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00	0,00	0,00	0,00	0,00
				-0,30	-0,30	0,70	120,00	0,00	0,00	0,00	0,00
Acceptable conditions		ASET	120,00						variancy(t) =	0,000	0,000
									s(t) =	0,000	0,000



Reliability and failure probability

t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

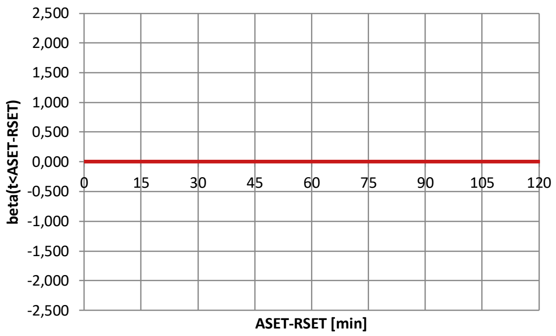
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Stairwaylobby floor 12

SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic		Probabilistic: sensitivity analysis			
		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00
				-0,70	-0,70	0,30	120,00
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00
				-0,50	-0,50	0,50	120,00
Time door opens	s	120		1,50	180,00	300,00	120,00
				-0,50	-60,00	60,00	120,00
Time door closes	s	20		2,00	40,00	60,00	120,00
				-0,50	-10,00	10,00	120,00
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00
				-0,50	-5,00	5,00	120,00
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00
				-0,30	-0,30	0,70	120,00
Acceptable conditions		ASET	120,00				

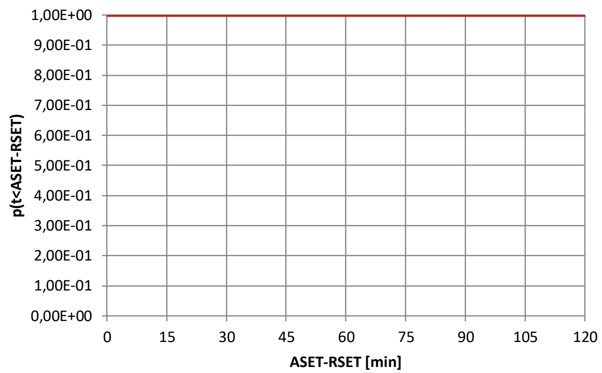
Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000

reliability index



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00

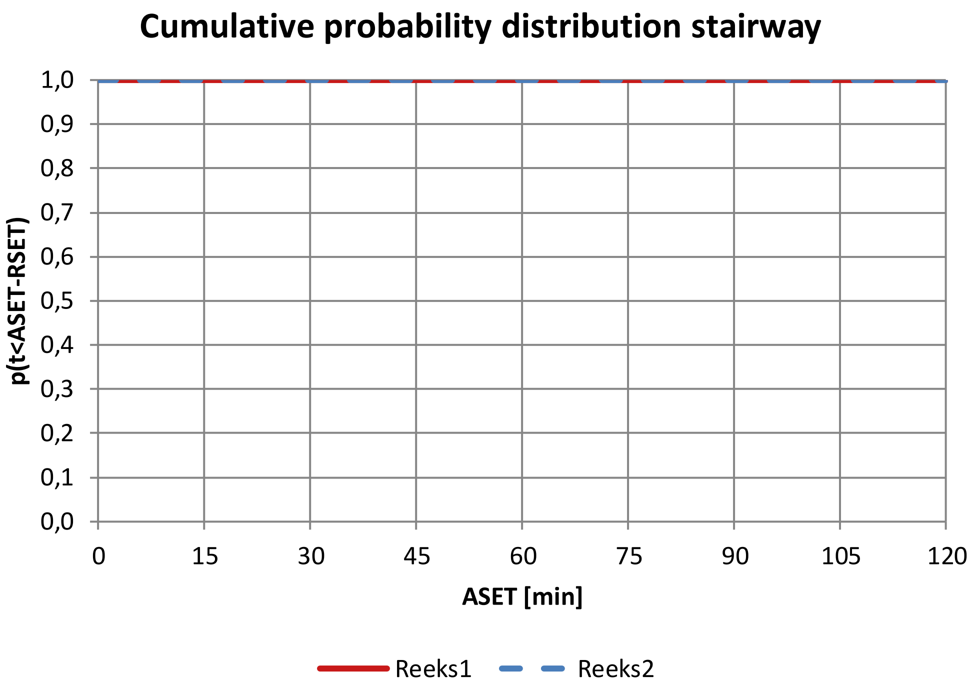
cumulative probability distribution



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Overview: Stairway 1 and 2

Reliability and failure probability		
t [min]	Stairs 1	Stairs 2
0	1,00E+00	1,00E+00
15	1,00E+00	1,00E+00
30	1,00E+00	1,00E+00
45	1,00E+00	1,00E+00
60	1,00E+00	1,00E+00
75	1,00E+00	1,00E+00
90	1,00E+00	1,00E+00
105	1,00E+00	1,00E+00
120	1,00E+00	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

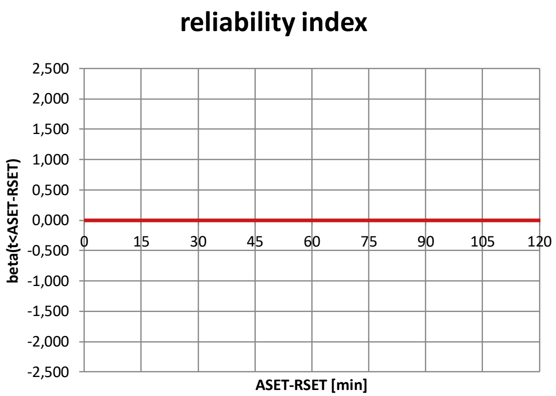
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Stairway 1

SENSITIVITY ANALYSIS
Stochastic boundary conditions

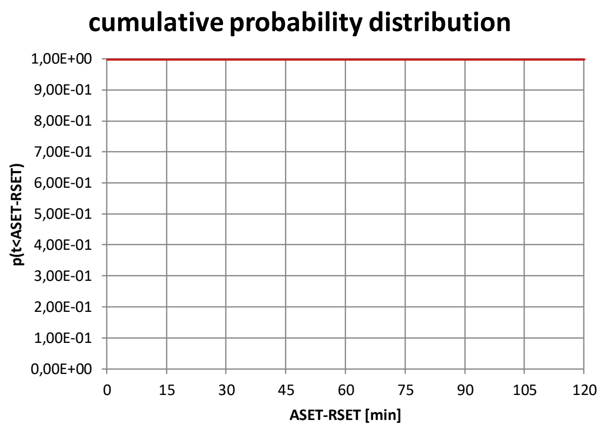
		Deterministic	
		average x	ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	120,00

Probabilistic: sensitivity analysis			
variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	120,00
-0,70	-0,70	0,30	120,00
1,50	1,50	2,50	120,00
-0,50	-0,50	0,50	120,00
1,50	180,00	300,00	120,00
-0,50	-60,00	60,00	120,00
2,00	40,00	60,00	120,00
-0,50	-10,00	10,00	120,00
0,50	5,00	15,00	120,00
-0,50	-5,00	5,00	120,00
1,00	1,00	2,00	120,00
-0,30	-0,30	0,70	120,00

Standard deviation				
	dt/dx	s·dt/dx	$(s·dt/dx)^2$	
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00
		variancy(t) =	0,000	0,000
		s(t) =	0,000	0,000



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

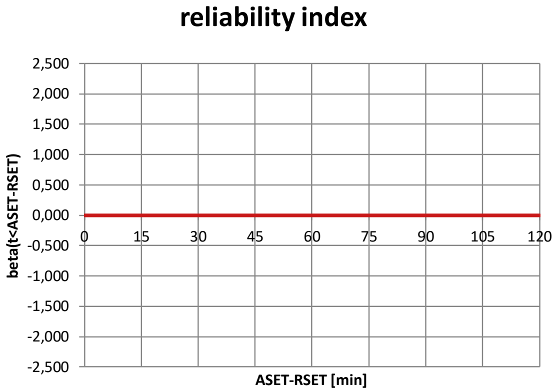
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Stairway 2

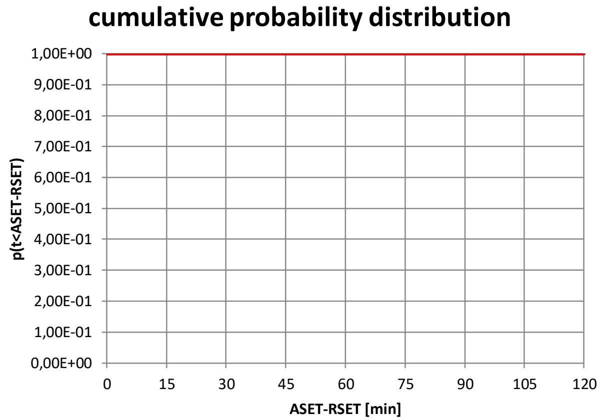
SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic		Probabilistic: sensitivity analysis				Standard deviation			
		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]	dt/dx	s·dt/dx	$(s·dt/dx)^2$	
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00	0,00	0,00	0,00	0,00
				-0,70	-0,70	0,30	120,00	0,00	0,00	0,00	0,00
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00	0,00	0,00	0,00	0,00
				-0,50	-0,50	0,50	120,00	0,00	0,00	0,00	0,00
Time door opens	s	120		1,50	180,00	300,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-60,00	60,00	120,00	0,00	0,00	0,00	0,00
Time door closes	s	20		2,00	40,00	60,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-10,00	10,00	120,00	0,00	0,00	0,00	0,00
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-5,00	5,00	120,00	0,00	0,00	0,00	0,00
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00	0,00	0,00	0,00	0,00
				-0,30	-0,30	0,70	120,00	0,00	0,00	0,00	0,00
Acceptable conditions		ASET	120,00					variancy(t) =		0,000	0,000
								s(t) =		0,000	0,000

Reliability and failure probability

t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00

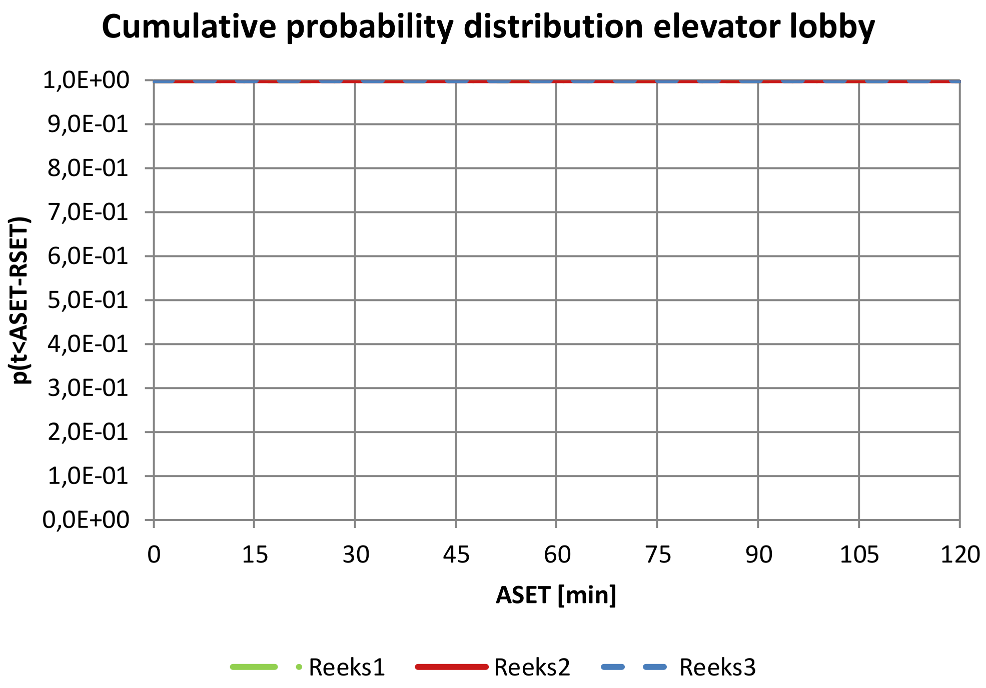




PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Overview: Elevator Lobbies floor 10, 11 and 12

Reliability and failure probability			
t [min]	Elevator lobby 10th	Elevator lobby 11th	Elevator lobby 12th
0	1,00E+00	1,00E+00	1,00E+00
15	1,00E+00	1,00E+00	1,00E+00
30	1,00E+00	1,00E+00	1,00E+00
45	1,00E+00	1,00E+00	1,00E+00
60	1,00E+00	1,00E+00	1,00E+00
75	1,00E+00	1,00E+00	1,00E+00
90	1,00E+00	1,00E+00	1,00E+00
105	1,00E+00	1,00E+00	1,00E+00
120	1,00E+00	1,00E+00	1,00E+00



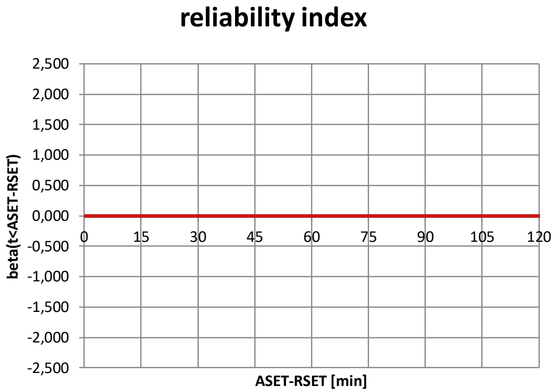
PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Elevator Lobbies floor 10

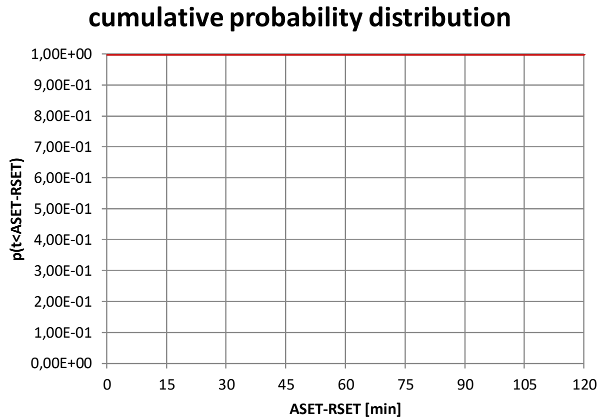
SENSITIVITY ANALYSIS
Stochastic boundary conditions

		Deterministic		Probabilistic: sensitivity analysis			
		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00
				-0,70	-0,70	0,30	120,00
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00
				-0,50	-0,50	0,50	120,00
Time door opens	s	120		1,50	180,00	300,00	120,00
				-0,50	-60,00	60,00	120,00
Time door closes	s	20		2,00	40,00	60,00	120,00
				-0,50	-10,00	10,00	120,00
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00
				-0,50	-5,00	5,00	120,00
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00
				-0,30	-0,30	0,70	120,00
Acceptable conditions		ASET	120,00				

Standard deviation			
dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
variancy(t) =		0,000	0,000
s(t) =		0,000	0,000



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Elevator Lobbies floor 11

SENSITIVITY ANALYSIS
Stochastic boundary conditions

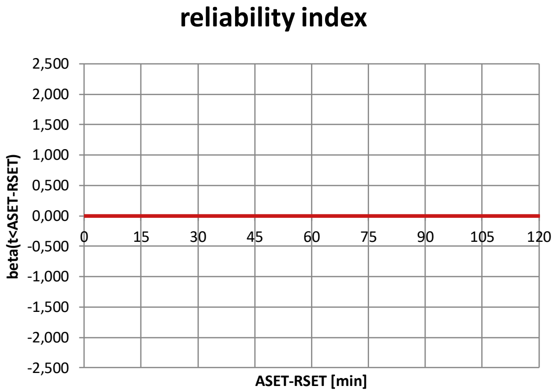
Stochastic boundary conditions	unit	Deterministic: average x	Deterministic: ASET t [min]
External airtightness multiplier	-	1	
Internal airtightness multiplier	-	1	
Time door opens	s	120	
Time door closes	s	20	
Lower oxygen limit	%	10	
Soot yield multiplier	-	1	
Acceptable conditions		ASET	120,00

Probabilistic: sensitivity analysis

variation V	st. deviation s	value x + dx	ASET t [min]
0,70	0,70	1,70	120,00
-0,70	-0,70	0,30	120,00
1,50	1,50	2,50	120,00
-0,50	-0,50	0,50	120,00
1,50	180,00	300,00	120,00
-0,50	-60,00	60,00	120,00
2,00	40,00	60,00	120,00
-0,50	-10,00	10,00	120,00
0,50	5,00	15,00	120,00
-0,50	-5,00	5,00	120,00
1,00	1,00	2,00	120,00
-0,30	-0,30	0,70	120,00

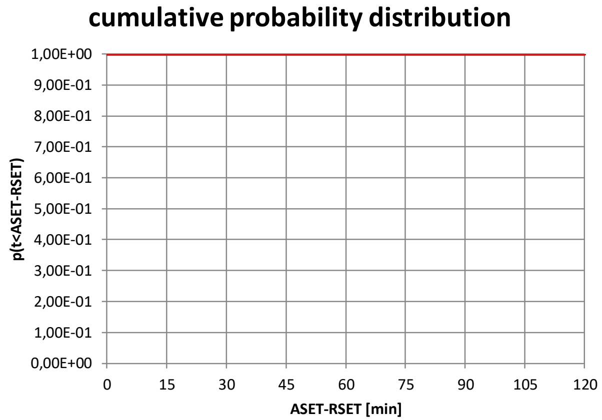
Standard deviation

dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000



Reliability and failure probability

t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00

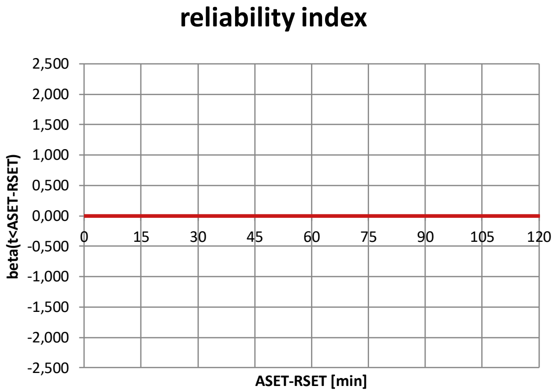


PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

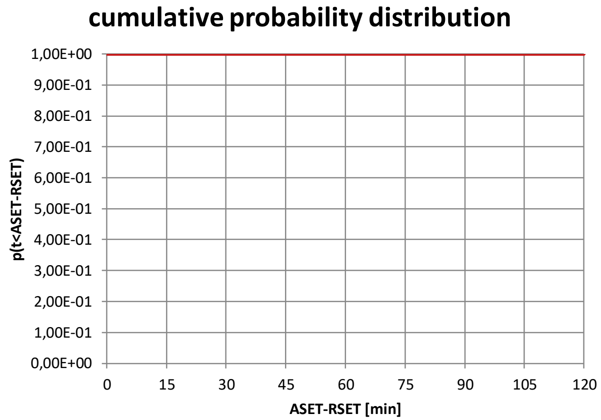
ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Elevator Lobbies floor 12

SENSITIVITY ANALYSIS		**Deterministic**		**Probabilistic: sensitivity analysis**			
Stochastic boundary conditions		**average x**	**ASET t [min]**	**variation V**	**st. deviation s**	**value x + dx**	**ASET t [min]**
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00
				-0,70	-0,70	0,30	120,00
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00
				-0,50	-0,50	0,50	120,00
Time door opens	s	120		1,50	180,00	300,00	120,00
				-0,50	-60,00	60,00	120,00
Time door closes	s	20		2,00	40,00	60,00	120,00
				-0,50	-10,00	10,00	120,00
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00
				-0,50	-5,00	5,00	120,00
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00
				-0,30	-0,30	0,70	120,00
Acceptable conditions		**ASET**	**120,00**				

Standard deviation			
dt/dx	**s·dt/dx**	**$(s\cdot dt/dx)^2$**	
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00
	variancy(t) =	0,000	0,000
	s(t) =	0,000	0,000



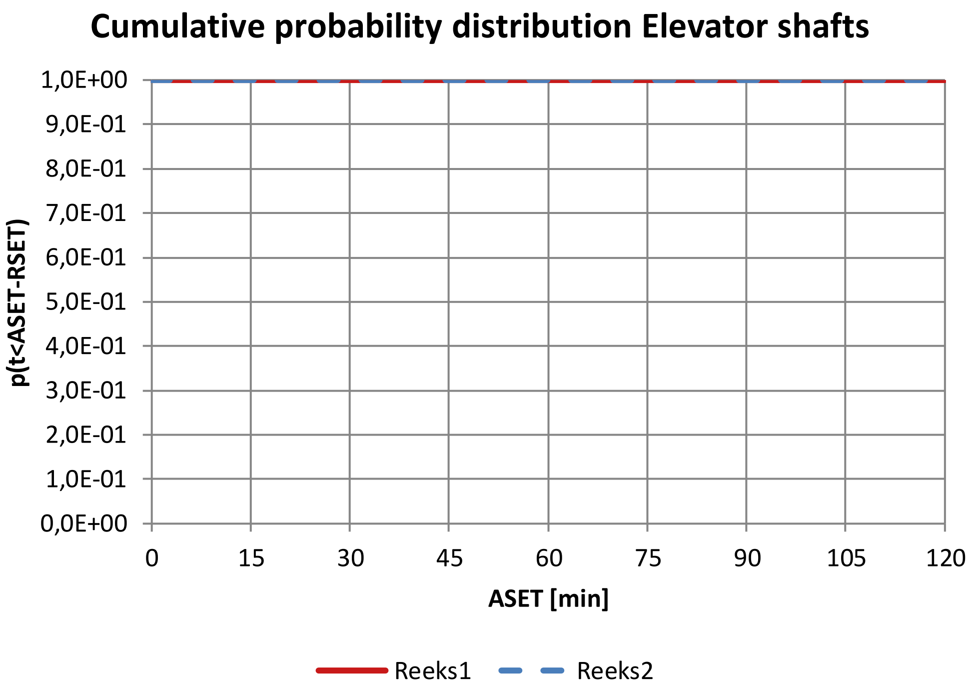
Reliability and failure probability			
t [min]	**s(t)**	**beta(t|fi)**	**p(t|fi)**
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Overview: Elevator shafts

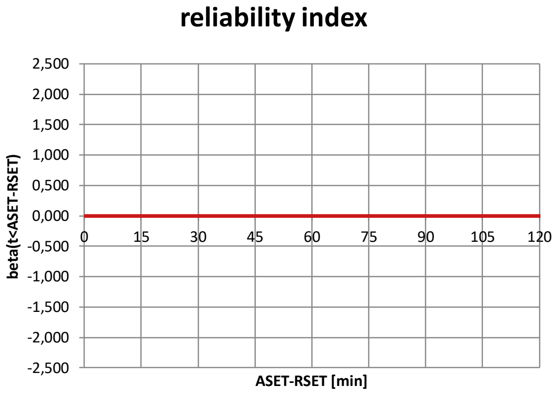
Reliability and failure probability		
t [min]	Elevator 1	Elevator 2
0	1,00E+00	1,00E+00
15	1,00E+00	1,00E+00
30	1,00E+00	1,00E+00
45	1,00E+00	1,00E+00
60	1,00E+00	1,00E+00
75	1,00E+00	1,00E+00
90	1,00E+00	1,00E+00
105	1,00E+00	1,00E+00
120	1,00E+00	1,00E+00



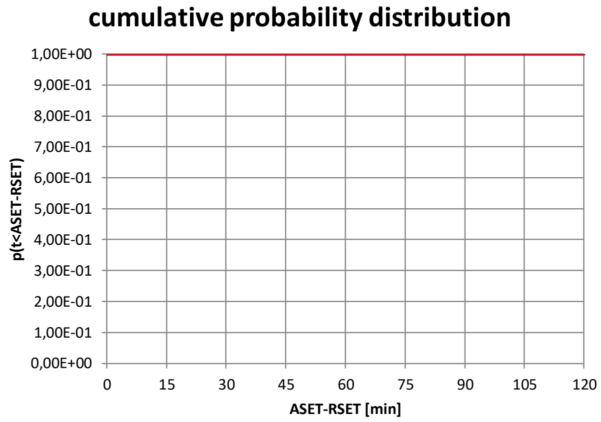
PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Elevator shaft 1

SENSITIVITY ANALYSIS		Deterministic		Probabilistic: sensitivity analysis				Standard deviation			
Stochastic boundary conditions		average x	ASET t [min]	variation V	st. deviation s	value x + dx	ASET t [min]	dt/dx	s·dt/dx	$(s·dt/dx)^2$	
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00	0,00	0,00	0,00	0,00
				-0,70	-0,70	0,30	120,00	0,00	0,00	0,00	0,00
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00	0,00	0,00	0,00	0,00
				-0,50	-0,50	0,50	120,00	0,00	0,00	0,00	0,00
Time door opens	s	120		1,50	180,00	300,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-60,00	60,00	120,00	0,00	0,00	0,00	0,00
Time door closes	s	20		2,00	40,00	60,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-10,00	10,00	120,00	0,00	0,00	0,00	0,00
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-5,00	5,00	120,00	0,00	0,00	0,00	0,00
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00	0,00	0,00	0,00	0,00
				-0,30	-0,30	0,70	120,00	0,00	0,00	0,00	0,00
Acceptable conditions		ASET	120,00						variancy(t) =	0,000	0,000
									s(t) =	0,000	0,000



Reliability and failure probability			
t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00



PROBABILISTIC APPROACH FIRE SCENARIO
AVAILABLE SAFE TIME FOR EVACUATION

ASET - RSET
Case: Super-tall residential building
Assessment criterion: Optical density ULOD
Compartment: Elevator shaft 2

SENSITIVITY ANALYSIS
Stochastic boundary conditions

Stochastic boundary conditions	unit	Deterministic: average x	Deterministic: ASET t [min]	Probabilistic: variation V	st. deviation s	value x + dx	ASET t [min]	Standard deviation: dt/dx	s·dt/dx	$(s \cdot dt/dx)^2$	
External airtightness multiplier	-	1		0,70	0,70	1,70	120,00	0,00	0,00	0,00	0,00
				-0,70	-0,70	0,30	120,00	0,00	0,00	0,00	0,00
Internal airtightness multiplier	-	1		1,50	1,50	2,50	120,00	0,00	0,00	0,00	0,00
				-0,50	-0,50	0,50	120,00	0,00	0,00	0,00	0,00
Time door opens	s	120		1,50	180,00	300,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-60,00	60,00	120,00	0,00	0,00	0,00	0,00
Time door closes	s	20		2,00	40,00	60,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-10,00	10,00	120,00	0,00	0,00	0,00	0,00
Lower oxygen limit	%	10		0,50	5,00	15,00	120,00	0,00	0,00	0,00	0,00
				-0,50	-5,00	5,00	120,00	0,00	0,00	0,00	0,00
Soot yield multiplier	-	1		1,00	1,00	2,00	120,00	0,00	0,00	0,00	0,00
				-0,30	-0,30	0,70	120,00	0,00	0,00	0,00	0,00
Acceptable conditions		ASET	120,00						variancy(t) =	0,000	0,000
									s(t) =	0,000	0,000

Reliability and failure probability

t [min]	s(t)	beta(t|fi)	p(t|fi)
0	0,00000	#########	1,00E+00
15	0,00000	#########	1,00E+00
30	0,00000	#########	1,00E+00
45	0,00000	#########	1,00E+00
60	0,00000	#########	1,00E+00
75	0,00000	#########	1,00E+00
90	0,00000	#########	1,00E+00
105	0,00000	#########	1,00E+00
120	0,00000	#########	1,00E+00