A method of quantifying user uncertainty in FDS by using Monte Carlo analysis

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Abstract
Several hundred FDS simulations have been run using Monte Carlo analysis and probability distributions of input variables. The simulations have been run to investigate the propagation of uncertainty from model inputs to outputs in order to quantify uncertainties that could arise due to the choices of an FDS user. A method has also been presented for performing FDS Monte Carlo analyses. The results show that a large degree of uncertainty can arise in output data due to the user and that this uncertainty can be quantified.

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Summary

When using FDS for fire modelling there is a degree of uncertainty concerning input variables. When obtaining results from a simulation, there is consequently a degree of uncertainty in the results introduced by the user. In this thesis, several hundred FDS simulations of the same model have been run, with three input variables, being soot yield, mass extinction coefficient and heat release rate, independently varied by use of Monte Carlo analysis. These three variables were selected by using a sensitivity analysis. Finally, simulations have also been run where all three variables were varied simultaneously. The output quantity investigated in all simulations was visibility. Distributions of the input variables have been created based on a literature study and qualitative reasoning. Random samples from these distributions have then been used in the simulations.

In order to create the vast number of input files needed, custom software has been written for this purpose. In order to handle the massive amount of output data, custom software was written for this purpose as the total amount of output data comprises more than 285 million values.

The results from the simulations show that there is a large degree of uncertainty in the output data when using Monte Carlo simulations in FDS given the chosen distributions of input variables. If a user simply chooses a static value of any of the input parameters in this thesis, there is a high probability that the results could vary outside accepted criteria. The results of the subject simulations show that at a height of 1.4 m, for example, 65 percent of the simulations yield non-acceptable results. However, this value is only applicable to the circumstances in this thesis but clearly show that there is a risk that the simulation yields unacceptable results.

The method of using Monte Carlo analysis directly on FDS simulations has not been attempted before, and this thesis represents a first step in managing uncertainty in FDS by connecting it to risk analysis. The method could be used by any FDS user to perform multiple Monte Carlo-based FDS simulations, thus managing the uncertainty that often arises due to user uncertainty.

Sammanfattning

När FDS används för brandmodellering så finns det en viss grad av osäkerhet vad gäller indata. Således finns det också en grad av osäkerhet i utdata som har introducerats av användaren. I detta examensarbete har flera hundra FDS-simuleringar av samma modell utförts. Tre olika indatavariabler (soot yield, mass extinction coefficient och heat release rate) har tagits fram genom en känslighetsanalys och sedan varierats oberoende av varandra genom en Monte Carlo analys. Slutligen har också simuleringar körts där alla tre variabler varierades samtidigt. Utdata som undersöktes som undersöktes i alla simuleringar var sikt. Fördelningar över indatavariablerna har skapats baserat på litteraturstudier och kvalitativt resonemang. Slumpmässiga stickprov från dessa fördelningar har sedan använts i simuleringarna.

För att kunna skapa det stora antal indatafiler som krävdes har egna program skrivits. För att kunna hantera den enorma mängden utdata så skrevs även egna program för detta ändamål, då den totala mängden utdata bestod av fler än 285 miljoner värden.

Resultatet från simuleringarna visar att det finns en stor grad av osäkerhet i utdata när man använder Monte Carlo-simuleringar i FDS baserat på de valda indatafördelningarna. Om en användare enbart använder ett deterministiskt värde på någon av indatavariablerna som undersökts i detta arbete så finns det en hög sannolikhet att resultaten skulle kunna hamna utanför valda acceptanskriterier. Resultaten från simuleringarna visar till exempel att på en höjd av 1.4 meter ovanför golvet så ger 65 procent av simuleringarna icke-acceptabla resultat. Det skall understrykas att detta värde endast är giltigt för omständigheterna som gäller i detta arbete, men att resultaten tydligt visar att det finns en risk att simuleringen ger oacceptabla resultat.

Att använda Monte Carlo-analys direkt på FDS-simuleringar har inte gjorts tidigare, och detta examensarbete är ett första steg i att hantera osäkerhet i FDS genom att koppla det till riskanalys. Metoden kan användas av alla FDS-användare för att utföra flera Monte Carlo-baserade FDS-simuleringar och därmed hantera osäkerheten som ofta uppstår på grund av användarosäkerhet.

Preface

The authors would like to thank the following persons for their help during the work on this thesis:

Håkan Frantzich	*Supervisor, Lund University*
Patrick van Hees	*Supervisor, Lund University*
Daniel Nilsson	*Lund University*

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1 Introduction

This master thesis is written at the Department of Fire Safety Engineering and Systems Safety at Lund University during the fall of 2009. The objective is to investigate how a user's choice of input values variables may influence the resulting output data when using the computational fluid dynamics (CFD) code Fire Dynamics Simulator (FDS)[1] and also to provide a method of quantifying the uncertainty.

1.1 Background

The Swedish building code [1] allows a proprietor of a building to adopt performance based design as opposed to prescriptive design. This allows for analytical fire design solutions to fulfil the requirements of the building code instead of following the prescriptive guidelines.

The legislative responsibility to ensure the safety of individuals using any building lies upon the proprietor according to the Swedish building code (SFS 1987:10). In order to do this the proprietor usually hires a fire engineering consultant, many of whom use CFD codes in order to simulate the spread of smoke. The outcome of this simulation is used as a basis for the design of fire mitigating measures. However, the outcome of any fire simulation is directly linked to the choice of input variables and the choice of values for these variables. Any changes to these values will affect the outcome, and it is not certain that the choice of values is always justified. It is also possible that some FDS users are not aware of the number of variables that are possible to change and how these choices affect the outcome. In addition, since a consultant is a private actor on the market, he or she is driven by economic interest but also by the need to deliver a solution to a client within a reasonable timeframe. This means that there is a necessity to be time and cost efficient. The usage of CFD in this

[1] For more on CFD and FDS, see Section 3.

context could mean that some decisions about the design are made in a hastily order, without conducting a thorough sensitivity analysis of choices made.

Since 2000 the CFD code FDS is available free of charge and is being actively developed by The National Institute of Standards and Technology (NIST) in the USA. This has resulted in FDS5 (the current version at the time of writing) being the perhaps most readily used CFD code today. At the same time the computational power of computers has increased radically. These two factors combined has allowed for more frequent use of FDS as a simulation tool. Since the outcome of any FDS simulation is the direct result of the input variables and their respective values a user chooses, the quality of simulations are bound to differ.

This thesis seeks to investigate the uncertainty of input variables chosen by an FDS user, and how these choices affect the results.

There has been some previous work in the area of probability and CFD modelling. Hostikka [2] has created a model that combines Monte Carlo analysis with CFD modelling. That approach is not the same as the approach used in this thesis. Hostikka combined the results of fast but approximate two-zone models with more accurate but computationally demanding CFD models.

Najm [3] used probabilistic uncertainty quantification methods to investigate the uncertainty that propagates from input to output in a number of different CFD models when the input has been characterized probabilistically. The CFD models considered were not of fire design character but rather more general.

1.2 Objectives

The objective of this thesis is to make a connection between FDS and risk analysis by demonstrating a method of doing a Monte Carlo analysis of an FDS simulation. This will be done by showing how the choice of values of input variables affects the result of an FDS simulation, from a statistical perspective.

The thesis also intends to provide basic data on levels of uncertainty when using FDS by applying the method to a fire scenario.

In order to achieve this, the following questions will need to be answered:

- Which input variables are the most sensitive in an FDS simulation, based on the chosen output data?
- To what degree does the input data affect the output data?

- How uncertain is the output of an FDS simulation given a variation in the input data?
- What recommendations can be made to FDS users?

1.3 Limitations

Certain limitations have been made. These limitations are listed below.

- Only one CFD code was used, namely FDS5
- Only the selected input variables were further investigated
- The input variables were assumed not to be correlated
- Only one scenario was used for comparison
- Only one output quantity was investigated, being visibility along a path
- Visibility was measured in cells, not along a path
- Placement of mesh boundaries was not considered in the analysis
- No investigation of parallel versus serial simulations was conducted
- The heat release rate in any given scenario was constant
- All simulations were well-ventilated in FDS

Many of these limitations have been made in order to limit the number of simulations that need to be conducted.

The output quantity, visibility, was measured in cells. This means that the measurements are point measurements, as opposed to measurements along a path. This is mainly due to technical limitations. This issue is discussed further in Section 6.

The simulations use several meshes and parallel processing, but the placement of the meshes was not investigated in any manner. The mesh placement has been based on general recommendations [4,5], and the placement was identical in all simulations. There has been no investigation of errors due to running the simulations on parallel processors. Any errors that may have been introduced from doing so will have been introduced in all simulations and thus would have had no or little effect on the results from comparing simulations of different values of input variables [5].

Since the input variables act within given intervals, the smoke layer is bound to vary within certain heights as well. It would be possible to record FDS measurements at the height required by the building code, but it is possible that measurements at this height do not vary that much. Because of this it may not be possible to take current fire design legislation into account. For the purpose of this thesis it is more interesting to show differences in measurements, and because of this a measurement height will be chosen where there is a larger variation in measurements.

2 Methodology

To handle the uncertainty introduced by a user in FDS by connecting it to risk analysis it is necessary to develop a method. The method needs to take into account the inherent uncertainty of the input variables by some means. In order to produce meaningful results from a large array of possible input variables, it is also necessary to use some sort of statistical method to perform multiple simulations in FDS. In this thesis, multiple simulations were performed by way of Monte Carlo modelling. This section details the methodology used in this thesis in applying this model.

In the initial part of this thesis, a scenario was chosen to use in all simulations, where the input parameters (materials, building dimensions etc.) were representative of a real building. This scenario has then acted as a foundation for all simulations.

Finding relevant input variables has been done in two ways; partly through qualitative reasoning and partly through a sensitivity study where one variable at a time was varied to see how that variation affected the output.

The next step was to find and decide the distributions of the input variables. This was done mostly in a qualitative manner.

Once the distributions were chosen, the variables were sampled randomly according to their previously determined distributions. To achieve a large enough base for the Monte Carlo simulations but still weigh it against the computational load of running CFD simulations, each variable was sampled 200 times. These samples of input variables have then been simulated in FDS5, independent of each other. There have also been simulations where all chosen input variables were varied simultaneously according to their previously determined distributions.

As an output quantity, this thesis only looks at visibility along a path. Visibility is a common criterion in fire safety engineering, together with temperature and incident radiation [6]. However, due to the amount of data it was deemed necessary to limit the scope of this thesis to only one output quantity.

The methodology described above is visualised in the flowchart in Figure 2.1 and is represented by straight lines.

The "user risk flow" (perhaps more correctly termed the user uncertainty flow) is also shown in the flowchart, as shown by the dotted lines, and originates with the user. User risk flow, in this context, means how the uncertainty essentially "created" by the user propagates to the output that FDS produces. The input to FDS is coupled with a certain uncertainty that in term could be represented by probability distributions. When running FDS, these uncertainties are propagated to the output data produced by FDS and in turn yields probability distributions of that output data. An FDS user would not, however, typically use probability distributions when choosing input data. Rather, the input data would consist of a best guess (maybe based on an assumed worst-case scenario) or perhaps just common practice for that user. This thesis intends to investigate how different input values, based on probability distributions, affect the output and also demonstrate a method for doing this.

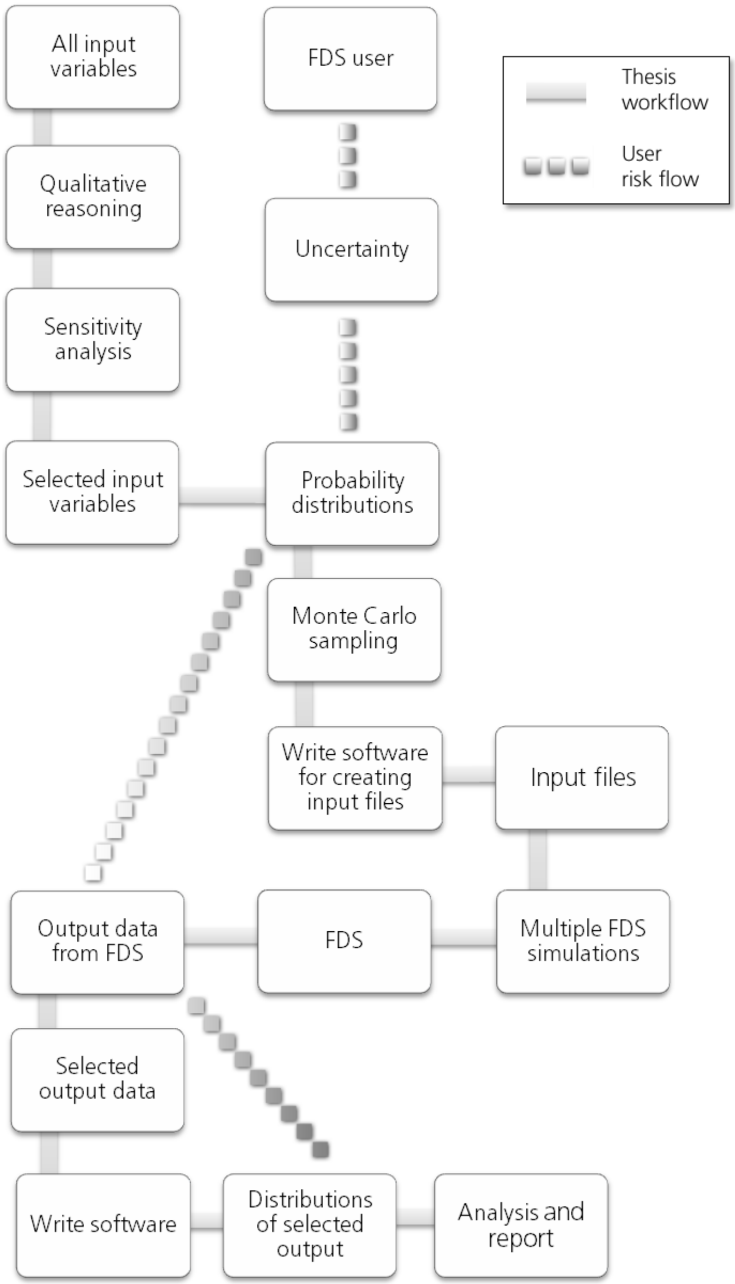

FIGURE 2.1 Flowchart showing the workflow methodology for this thesis

3 Fire Dynamics Simulator (FDS)

Computational Fluid Dynamics (CFD) is a branch of fluid dynamics that uses numerical methods to solve the governing equations of fluid flows using computers. CFD models are sometimes termed *field models*.

The National Institute of Standards and Technology (NIST) has for several years developed a CFD code for fire dynamics applications. Their code, *Fire Dynamics Simulator* (FDS), solves a form of the Navier-Stokes equations appropriate for fire-driven fluid flow with an emphasis on smoke and heat transport from fires [4]. The first public version of FDS was released in 2000.

3.1 Brief history of CFD

The *Navier–Stokes equations*, named after Claude-Louis Navier and George Gabriel Stokes, describe the motion of fluid substances; that is substances which can flow. Their form of the differential mathematical equations, proposed nearly 200 years ago, are the basis of the modern day computational fluid dynamics applications. The Navier-Stokes equations contain expressions for the conservation of mass, momentum, pressure, species and turbulence. The equations are so closely coupled and difficult to solve that it was not until the advent of modern computers in the 1960s that they could be resolved numerically for real flow problems within reasonable timeframes [7].

The use of computers as a tool in fire protection engineering has increased with the development of more powerful computers. Historically, two-zone models were the first type of models to be widely used and accepted. These models assume two gas layers in an enclosure, one hot gas layer and one cold gas layer. As computational power increased, the possibility of CFD modelling became possible [8].

CFD modelling is a much more complex way of modelling a fire than two zone modelling. The CFD programme numerically solves the Navier-Stokes equations in each of the cells in the computational domain. Because of the size of the computational domain in a simulation, powerful computers are needed.

There are three general approaches to solving the turbulence within the Navier-Stokes equations, *Direct Numerical Solution* (DNS), *Reynolds Averaged Navier Stokes* (RANS) and *Large Eddy Simulation* (LES). The RANS and LES approaches solve the equations with different turbulence models while DNS solves the Navier-Stokes equations numerically without any turbulence model, as it is not needed. A DNS solution requires the size of the individual cells to be at the Kolmogorov micro scale, or 10^{-6} m of length [9], which is not realistic for larger models considering the computational power of modern computers.

RANS averages instantaneous values in time. Due to this, this approach is suited for steady state type problems and solutions. A programme that uses RANS code is SOFIE (Simulation of Fires in Enclosures). As the aim of this thesis is to investigate uncertainties in FDS, SOFIE is not further discussed [8].

LES assumes that all turbulent energy is preserved in the largest scale. This means that nothing that occurs below this scale is calculated. Any phenomena that occur are instead modelled by sub grid models. As opposed to the RANS approach, LES is transient, which means that all calculations use output from the previous time step as input to the next time-step. Because LES is transient as opposed to RANS, it requires much more time to calculate all time steps. FDS is probably the most used LES programme for fire engineering applications today.

3.2 Features of FDS

This section summarises the main features in FDS. For more detailed information, refer to the FDS user guide and technical guide [4,10].

HYDRODYNAMIC MODEL

FDS solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow. Turbulence is treated by means of Large Eddy Simulation using a Smagorinsky sub-model [4].

COMBUSTION MODEL

For most applications, FDS uses a single step chemical reaction whose products are tracked via a two-parameter mixture fraction model. The mixture fraction is a conserved scalar quantity that represents the mass fraction of one or more components of the gas at a given point in the flow field. By default, two components of the mixture fraction are explicitly computed. The first is the mass fraction of unburned fuel and the second is the mass fraction of burned fuel (i.e. the mass of the combustion products that originated as fuel) [4].

RADIATION TRANSPORT

Radiative heat transfer is included in the model via the solution of the radiation transport equation for a grey gas, and in some limited cases using a wide band model. The grey gas model assumes uniform radiation over all frequencies, while the wide band model divides the radiation frequencies in sex different bands. The radiation equation is solved using a technique similar to a finite volume method for convective transport coupled with the absorption coefficient of the gas mixture [4,10].

MESHES AND PARALLEL PROCESSING

FDS approximates the governing equations on a rectilinear mesh. Any rectangular obstructions are forced to conform to the underlying mesh. Since its first public release, the ability to use several meshes has been introduced. This feature is crucial for larger simulations where the computational domain is not easily embedded within a single mesh.

It is possible to run an FDS calculation on more than one computer using parallel processing. This is discussed in more detail in Appendix A.

The computational mesh that FDS uses to perform its calculations on can exist of several different rectilinear meshes, all of whom are connected to each other. Meshes can also be placed without abutting, in which case a separate calculation is essentially carried out on each zone of meshes without any communication with other meshes. This latter approach is not employed in this thesis. When using multiple meshes, they can (by default) be set to be synchronized with each other, meaning that the mesh with the smallest time step in each iteration will control the time step of all other meshes [4]. All models in this thesis are simulated using synchronized meshes

MESH CELL SIZE

In any CFD calculation (not only related to fire applications) all calculations take place in several cells (essentially control volumes) on a larger computational mesh. The size and geometry of these cells is perhaps the single most important factor for attaining good results from a CFD calculation [4]. If the cells are too large, the model cannot accurately capture the fluid dynamics of the problem. On the other hand, if the cells are too small, there is no way to run the model with today's computers.

For fire applications, it is crucial to properly resolve the actual fire, as the fire is what drives the buoyant flow. Entrainment of air is highly dependent on cell size and is the most important factor in smoke production from any fire. It has been found [11] that a critical parameter for an FDS model is the non-dimensional ratio $D^*/\delta x$ where D^* is the characteristic fire diameter and δx is the mesh cell size across the fire according to Equation 3.1.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \tag{3.1}$$

If this parameter is sufficiently large, the fire can be considered well-resolved [11]. Studies have shown that values of 10 or more are required to resolve most fires well and attain adequate flame temperatures [12,13].

To have a grid resolution such that $D^*/\delta x \geq 10$ with a fire size of 300 kW (which is the steady fire size of the target experiment) a cell size (using cubic cells) of roughly 0.05 m would be needed.

BOUNDARY CONDITIONS

All solid surfaces (termed obstructions in FDS) are assigned thermal boundary conditions and if necessary information about the burning behaviour of the material. Heat and mass transfer to and from solid surfaces is handled with empirical correlations using 1-D heat transfer.

GEOMETRY

As previously mentioned, FDS employs a rectilinear computational mesh. Any obstructions introduced into the model need to conform to this rectilinear mesh. A non-rectangular geometry needs to be approximated using stair-stepping methods, as is visualized in Figure 3.1.

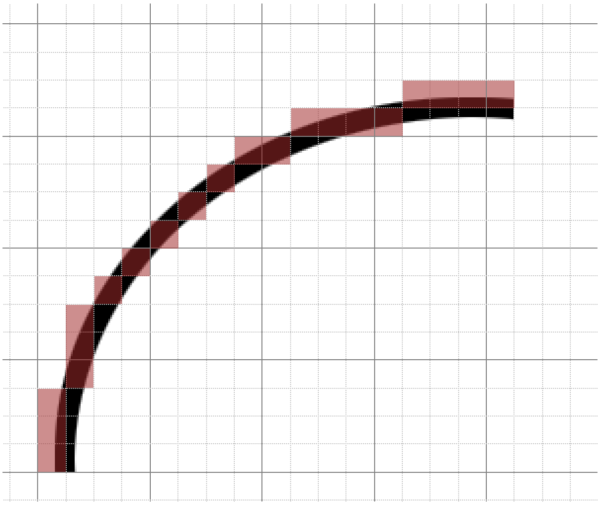

FIGURE 3.1 Schematic example of stair-stepping of sloping object.

3.3 Validation and verification

FDS has been extensively validated against experimental data. This is partly summarised in [11]. The numerical and mathematical models, which are presented in [10], have also been the subject of verification and robustness tests [14]. Verification and sensitivity analysis of the mathematical and numerical model are not subjects of this thesis.

4 Monte Carlo simulations in FDS

Monte Carlo simulation is a method of performing multiple experiments using random sampling of variables that belong to a certain probability distribution. As Monte Carlo methods rely on repeated computation and random numbers, they are most suited for use with computers and when it is unfeasible or impossible to compute an exact result with a deterministic algorithm [15].

4.1 Probability and FDS

In FDS, any outcome, such as the temperature in a certain location or the visibility along a path, is a function of all possible input variables having an effect on that outcome. For example, if we define an event *E* as the visibility along a path being above a certain value *s*, the probability of *E* happening depends on a number of random variables, each having a probability distribution. These random variables can be denoted by a vector $\boldsymbol{X} = [X_1, X_2, \dots, X_n]^T$. The probability that *E* happens is then a function of $\boldsymbol{X}$ and time, as FDS is a transient or time-dependent model:

$$Pr_E(S \geq s) = g(\boldsymbol{X}, t) \qquad (4.1)$$

Pr_E belongs to a random distribution and is in this thesis calculated using Monte Carlo simulations where the input variables are sampled randomly from their respective distributions. The usability of a Monte Carlo simulation, however, depends on the number of random samples and thus the number of simulations that needs to be made.

4.2 Latin Hypercube Sampling

The sampling simulations are made using a sampling scheme called *Latin Hypercube sampling* (LHS). LHS uses a technique called stratified sampling without replacement [16]. When using LHS, the probability distribution, also called the cumulative distribution function *F(x)*, is split into *n* intervals of equal probability, where *n* is the number of iterations that are performed. In the first iteration, one of these intervals is selected using a random number. Another random number is subsequently generated; deciding where within that interval *F(x)* should lie. A sampled value is then calculated for that value of *F(x)*. The process is repeated for the number of desired iterations, but for each iteration the interval used is marked and will not be selected again. As the number of iterations is the same as the number of intervals, each interval will only have been sampled once and the distribution will be reproduced with predictable uniformity over the *F(x)* range [17].

4.3 Software

For the purpose of this thesis, different pieces of software were created. All software written could be customised for other applications in this area.

4.3.1 Creating input files

In order to run several hundred simulations with FDS, a separate input file needs to be created for each simulation. In each of these files, the values of the chosen variables need to be changed to the values from the Monte Carlo sampling process. For this purpose, an application was written to create these input files and insert a list of sampled values into each file. The software is customizable, and depends on user input for several parameters. To create the FDS input files, desired filenames (and FDS headers), number of files to create and desired location of the created files is entered by the user. For use on LUNARC (see Appendix A), or any cluster using the same queue management system, script files are also created. The user can customize the desired number of CPU:s, wall time, e-mail address for notifications and the path to the FDS executable.

4.3.2 Managing output data

In order to interpret the considerable amount of data created from the simulations, software also needed to be written for this purpose. The software takes as input the path where FDS output files are stored. The software reads the comma separated device output files that FDS creates and prints time-averaged values from these files based on desired quantities.

5 Simulated fire experiment and FDS setup

As a base for the models in this thesis, a well-documented fire experiment was used. The experiment was conducted by the Centre for Environmental Safety and Risk Engineering at Victoria University in Australia [18]. The specific experiment was set in a multi-room building containing three rooms and one corridor and is shown in Figure 5.1. It was deemed suitable to use as a model in this thesis because of its layout, being similar to part of a school, hospital, student housing or such. Except for the location of the fire source, geometry and basic buildings materials, no other specifics of the experiment have been used for the simulated models.

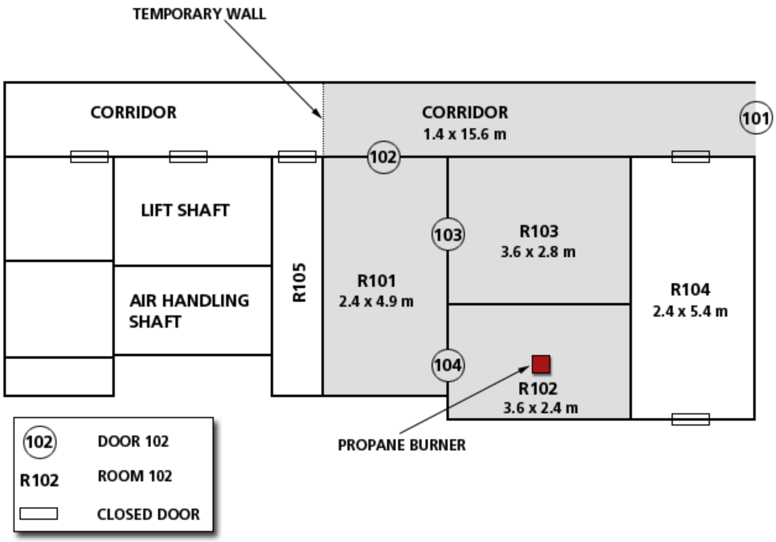

FIGURE 5.1 Layout of the experiment; grey areas indicate where the experiment took place, all other areas were sealed off.

The cell size of the mesh affects the size of any obstructions in the model. Obstructions cannot have dimensions smaller than the mesh cell size. The general geometry of the model has been faithfully reproduced according to Figure 5.1. It should also be noted that FDS can calculate heat transfer through obstructions regardless of their geometrical size on the mesh. The desired thickness and material composition of obstructions is entered separately, and is used by the heat transfer code in lieu of the geometrical size. Figure 5.2 shows the FDS model as seen in Smokeview. General information on the model can be found in Table 5.1.

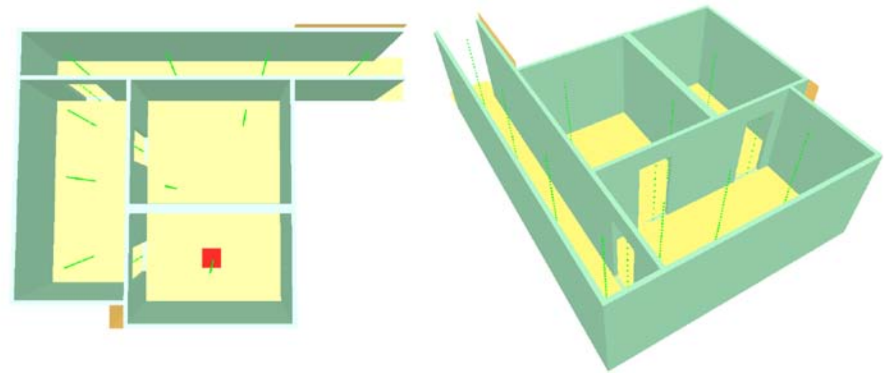

FIGURE 5.2 The FDS model as seen in Smokeview.

TABLE 5.1 General information on the FDS model

Parameter	Value
Number of meshes	14
Mesh cell size	0.1 m (cubic cells)
Radiative fraction	35 %
Ambient temperature	20 °C

5.1 Materials

The materials used in the model were made to resemble those of the experiment to the extent possible. The walls were made of concrete and gypsum, with no material properties given in the experiment. For this reason, common values of respective material properties [19] are given in Table 5.2 below.

TABLE 5.2 Properties of the materials used in the model

Material	Density (kg/m^3)	c_p (kJ/kg K)	k (W/m K)
Gypsum	1,440	0.84	0.48
Concrete	2,100	0.88	1.1

5.2 Meshes and parallel processing

For the purposes of parallel processing, any FDS model must be divided into two or more meshes. Each processor in any parallel computation needs at least one mesh to work with. Due to the large number of simulations needed for this thesis, using parallel processing was a necessity to be able to run them within a reasonable timeframe. For this purpose, the subject models were divided into a total of 14 meshes.

5.3 Mesh cell size

The simulations in this thesis are run with a resolution of 0.1 m, even if it had been desirable to run the simulations with a cell size of 0.05 m, as stated in Section 3.2. Due to the number of simulations however, this was not possible. Still, it is assumed that any error that may be introduced from running simulations with a cell size of 0.1 m is equally introduced in all simulations, consequently not affecting any comparison between simulations.

6 Investigated output variable

As an output quantity, this thesis will only look at visibility along a path. Visibility is a common criterion in fire safety engineering, together with temperature and incident radiation [6]. However, due to the amount of data it was deemed necessary to limit the scope of this thesis to only one output quantity. Also, the purpose of this thesis is to demonstrate a method, and for that reason one output quantity is adequate.

In order to further limit the amount of data, it was decided to only take measurements of visibility in the corridor. The corridor was chosen partly because it is more interesting from a fire design perspective since it may be used to evacuate. The other reason for choosing the corridor was that the visibility of the other rooms was quickly reduced to zero in most simulations.

Visibility is measured in single cells at different heights. However, since visibility is a quantity that typically needs to be evaluated along a path, it is necessary to investigate if the point measurements are representative of measurements along a path. It is also necessary to evaluate if the measurements used in the thesis, taken in the middle of the corridor, differ from measurements taken in adjacent cells. For these purposes, a study has been performed to find any differences in measuring visibility in a single cell, compared to measuring over a path and width, respectively. The measurement points can be seen in Figure 6.1 below. The measurements used in the thesis correspond to location 3 (the middle of the corridor) in position 1.

It was also deemed necessary to find if there were any differences in measurements over time.

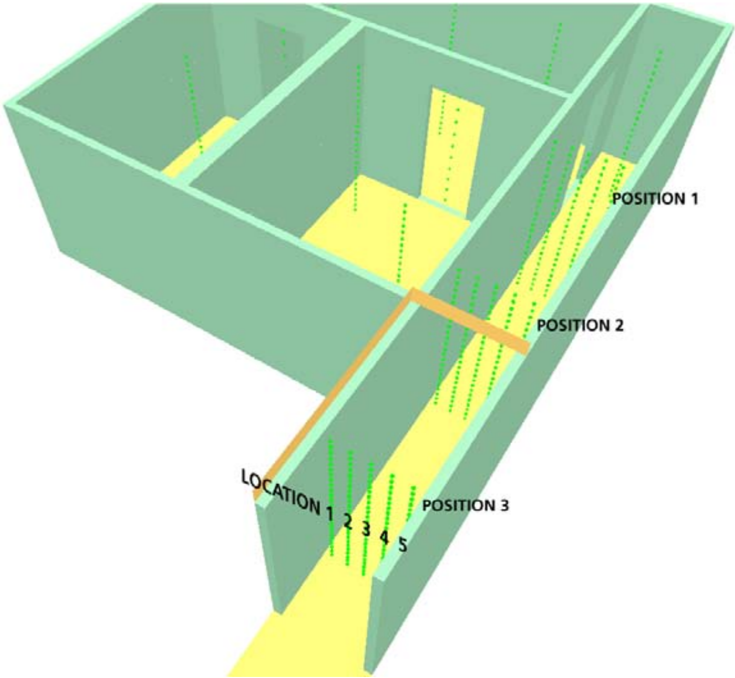

FIGURE 6.1 The corridor showing thermocouple locations used in the study.

6.1 Path

To investigate what potential errors point measurements may introduce, simulations have been conducted where the visibility is measured at several positions, at the same height throughout the corridor of the geometry, to try and emulate a sight path. As shown in the Figure 6.2 below, the measurements closer to the corridor exit indicate a slightly better visibility at lower heights, compared to the other measurement positions. This is not entirely unexpected since the smoke layer slopes in the corridor.

As the simulations show, measuring visibility in single cells is not an optimal solution, but as the differences are small, and the purpose is to compare different simulations against each other, this method has been employed in this thesis.

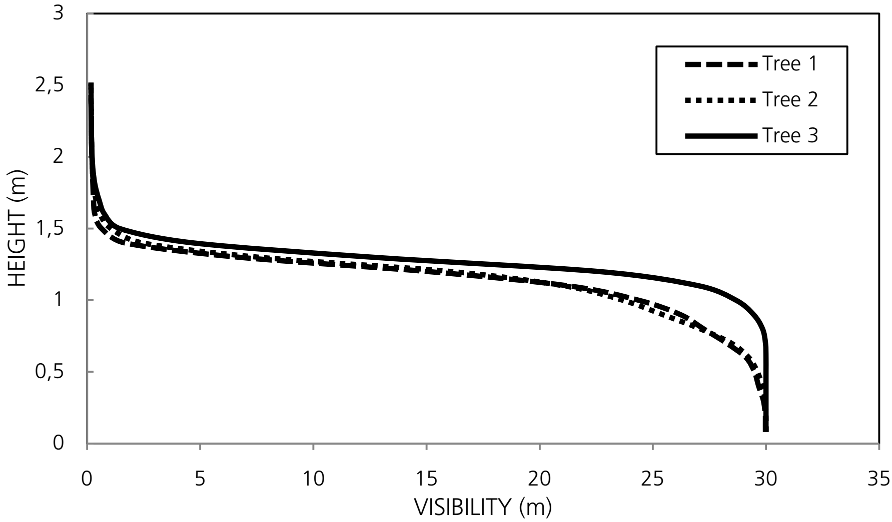

FIGURE 6.2 Differences in visibility at different location in the corridor.

6.2 Width

The values of visibility in the measured cells will also be compared to the values of visibility in the connecting cells, to find any differences over the width of the corridor. This is done simply by running a simulation with points of measurement added to the adjacent cells, at a total of three positions in the corridor, with each position having five locations across the width of the corridor as is visualised in Figure 6.1.

Figure 6.3 to Figure 6.5 below shows the results at steady state for all measurement locations at heights from floor to ceiling. As can be seen, there are only slight differences across the width of the corridor.

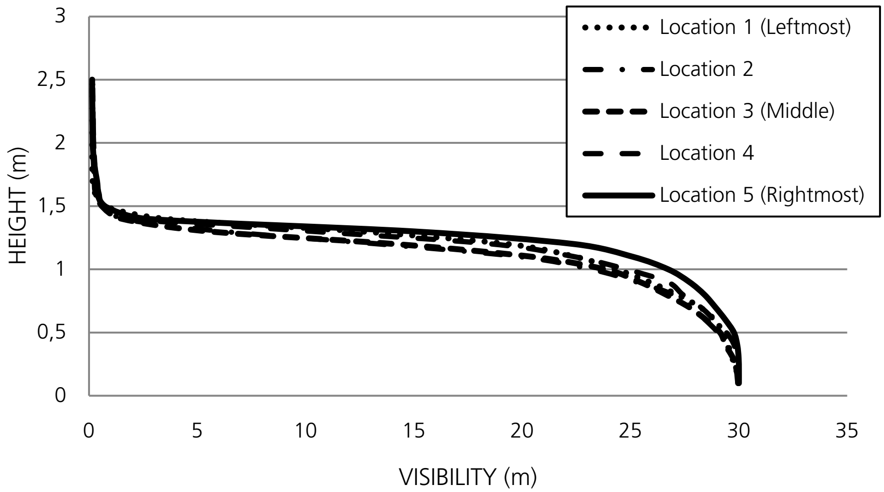

FIGURE 6.3 Measurements at position 1 in the corridor.

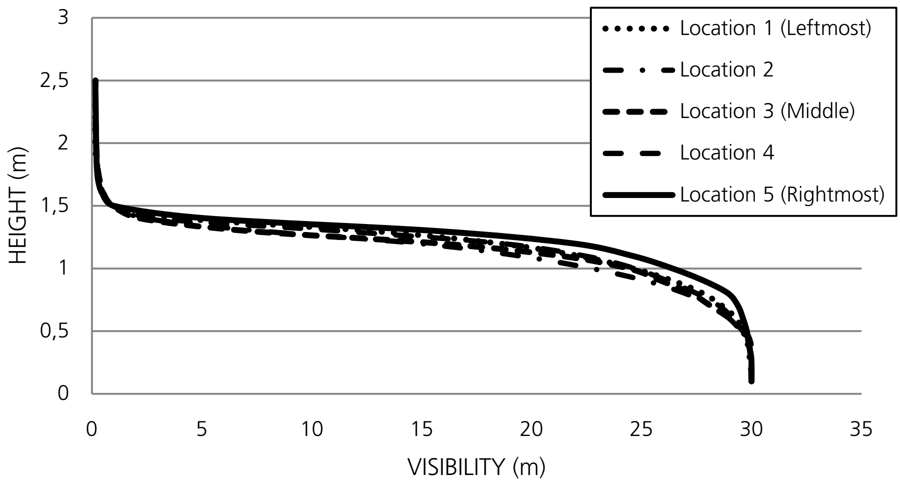

FIGURE 6.4 Measurements at position 2 in the corridor.

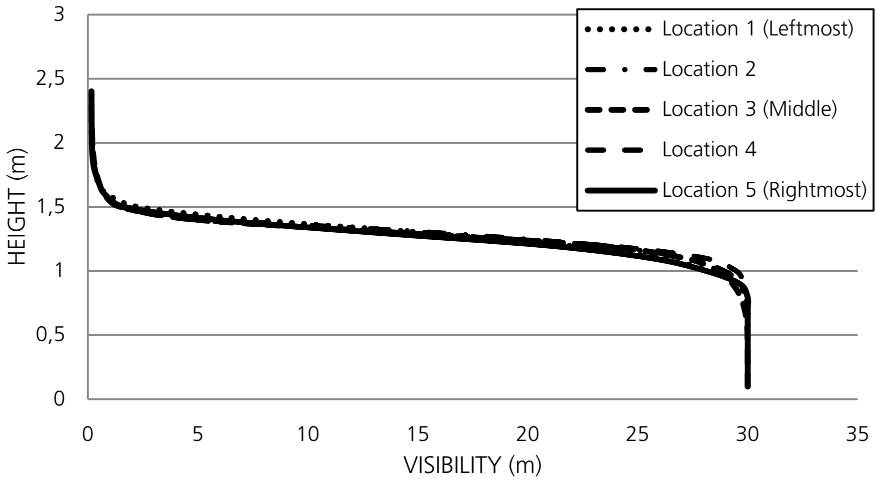

FIGURE 6.5 Measurements at position 3 in the corridor.

6.3 Time

Visibility fluctuates over time with smoke movement in the enclosure. In order to have viable measurements it is necessary that the visibility at the measured locations does not fluctuate too much. It was established that visibility had reached steady state in the last 200 seconds, as shown in the diagram below. Due to instantaneous fluctuations, all diagrams have been time averaged over that time.

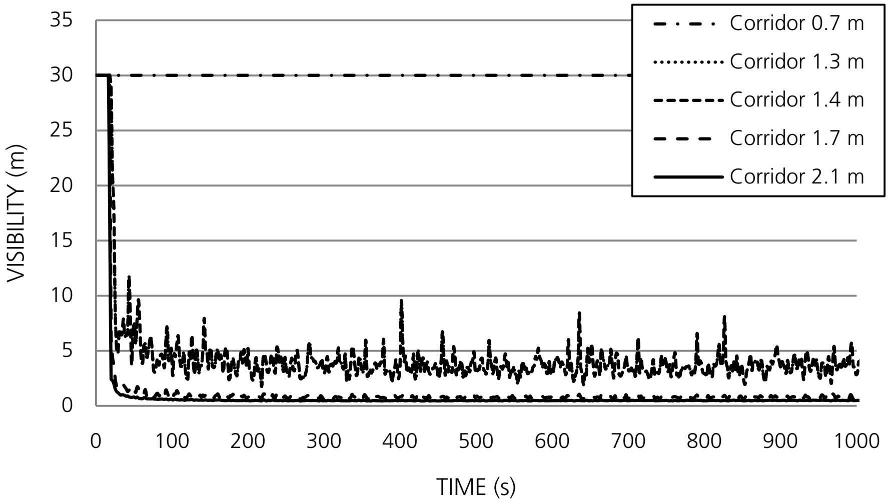

FIGURE 6.6 Visibility over time at different heights at position 3. Steady state at t > 750 s.

All diagrams showing the visibility at any location have been time averaged over the last 200 seconds in order to show steady state conditions.

7 Selection of input variables for Monte Carlo simulations

In order to analyze how output data from FDS varies a number of different input variables need to be considered. Qualitative reasoning combined with a sensitivity analysis has been used to find the most relevant variables to use.

7.1 Qualitative reasoning

7.1.1 Factors affecting visibility

There are several factors affecting visibility in any real or simulated fire scenario. At its core, it is the smoke particulate that limits visibility. In the absence of particles, visibility is, in some sense, "infinite". The characteristics of fire smoke include the composition, shape and size of the smoke particles, which in turn depend on the combustible materials involved and the conditions of combustion. These characteristics are also highly dependent on the surrounding flow and temperature field and vary with time [20]. In FDS, the amount of fire smoke created is based on the *soot yield.* This is simply the fraction of fuel mass that is directly converted into smoke particulate.

There are two reasons for the decrease in visibility through smoke. Assuming an observer looking at an exit sign through smoke, the reflected light from the sign and its background is interrupted by smoke particles which reduce the intensity of the light as it reaches the observer. Furthermore, the reflected light from the general lighting of corridors or rooms is scattered by the smoke particles, further impacting visibility [20]. There has been some research on smoke movement taking into account direct illumination and indirect illumination from surfaces and particulate scattering [21]. This thesis does not take this into account.

The most useful quantity for assessing visibility is the *light extinction coefficient* [20]. The intensity of monochromatic light passing a distance L

through smoke (as described in the previous paragraph) is attenuated according to

$$\frac{I}{I_0} = e^{-KL} \tag{7.1}$$

Where K is the light extinction coefficient [4], L is the path length and I and I_0 is the attenuated intensity and the source intensity, respectively. The light extinction coefficient is a product of the density of smoke particulate, ρY_s, and a mass extinction coefficient that is fuel dependent

$$K = K_m \rho Y_s \tag{7.2}$$

Estimates of visibility through smoke can then be made using equation (7.3) [4], [20]

$$S = \frac{C}{K} \tag{7.3}$$

where C is a non-dimensional constant that depends on the object being viewed through the smoke. This constant is based on a correlation between visibility of test subjects and the extinction coefficient which found that the visibility of light emitting signs were two to four times greater than light reflecting signs [22]. Values of $C = 8$ for light-emitting signs and $C = 3$ for light-reflecting signs were found to correlate well with the data.

7.1.2 Other factors

Several other factors have a potential effect on visibility, including temperatures and flow characteristics. The most prominent factor that effectively decides the rate at which energy, and thus also smoke, is released into the model is the *heat release rate* (HRR). In a field model, the HRR is the source term in the energy equation, hence its importance [10]. In FDS, a fire is typically specified using a boundary condition of a specific area where heat is released according to a specific *heat release rate per unit area* (HRRPUA). It is thus possible to achieve the same total HRR by using different areas and heat release rate densities of the boundary condition. Some research has been done showing that the heat release rate density in FDS has an effect on flame temperatures [12].

In FDS there must by necessity be a gas phase reaction. In effect, the user specifies a gas phase reaction that acts as a surrogate for all potential fuel sources

[4]. Even if no reaction is specified, FDS uses the default reaction which is that of propane.

In order to further investigate the effect temperature has on smoke production and thus visibility, independent of the HRR, material characteristics (conductivity, density and specific heat) and radiative fraction will also be considered. Lower gas temperatures mean lower density and thus a lower gas layer height, possibly affecting visibility at that height.

Heat loss through walls has an effect on the temperature of the hot gases in the room. If the heat loss is greater than the gas temperature will be lower, and vice versa. FDS uses a one-dimensional equation in order to determine this heat loss. The one-dimensional heat transfer caused by conductivity through walls and ceiling of a scenario are directly linked to the material characteristics, thermal conductivity (k), density (ρ) and specific heat capacity (c). For the materials used in the subject model, the conductivity is the dominant factor of these three. For the purposes of this sensitivity analysis, the product of all three values has been changed together.

The radiative fraction represents the fraction of energy released from the fire as thermal radiation. Variations in this input variable will consequently mean different amounts of energy released as convective energy as well. The effect the radiative fraction has on temperature may affect the visibility.

7.2 Variables chosen for sensitivity study

Based on Section 7.1, the following variables have been chosen to be further investigated in the sensitivity study.

TABLE 7.1 Variables chosen for sensitivity study

Variable	FDS Name	Default value
Mass extinction coefficient	MASS_EXTINCTION_COEFFICIENT	8,700 m^2/kg
Fire Area/HRRPUA	(HRRPUA)[a]	N/A
Soot yield	SOOT_YIELD	0.01 g/g
Heat Release Rate	(HRRPUA)[b]	N/A
Reaction (fuel)	(REAC)[c]	Propane
Radiative fraction	RADIATIVE_FRACTION	0.35
Conductivity (kρc)	(CONDUCTIVITY)[d]	N/A
Cell size	(MESH)[e]	N/A

[a]Fire area is defined as the size of the boundary condition used as the fire source
[b]Heat Release Rate is the product of the fire area and the HRRPUA
[c]The reaction group consists of several variables
[d]Conductivity is defined as kρc, and is user-defined
[e]Meshes are user-defined

7.3 Sensitivity study

A sensitivity study was conducted with the intention to establish which of the variables chosen in Section 7.2 had the largest effect on visibility. The study was performed by assigning chosen variables an estimated value. These variables were then generally varied by a factor of approximately 0.5 in order to determine the difference in visibility. Exceptions apply to the fuel variable where different fuels were chosen, conductivity where the product of $k\rho c$ was varied as a whole as opposed to the different variables individually, and the radiative fraction which was only decreased to 10 % (see Table 7.2).

TABLE 7.2 Variation of values of selected input variables in the sensitivity study

Variable	Estimated value	Value -50 %	Value +50 %
Mass extinction coefficient	8,700 m^2/kg	4,350 m^2/kg	13,050 m^2/kg
Fire Area/HRRPUA[a]	1.28 m^2	0.72 m^2	2 m^2
Soot yield	0.1 g/g	0.05 g/g	0.15 g/g
HRR	400 kW	200 kW	600 kW
Reaction (fuel)	Propane	Ethanol	Polyurethane
Radiative fraction	0.35	0.1[b]	N/A
Conductivity (kρc)	580 (Gypsum) 2,033 (Concrete)	285 (Gypsum) 1,001 (Concrete)	870 (Gypsum) 3,060 (Concrete)
Cell size	0.1	0.05	N/A

[a] Due to limitations in FDS, the fire area has not been changed by exactly 50 %
[b] Radiative fraction has not been reduced with 50 %

The results from the simulations are shown in Figure 7.1 to Figure 7.7.

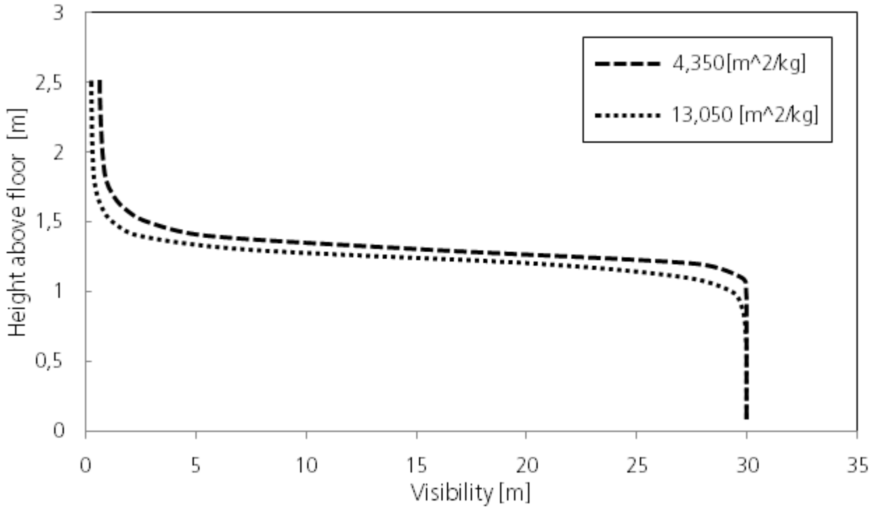

FIGURE 7.1 Variations in visibility at different heights as a result of changes made to the mass extinction coefficient.

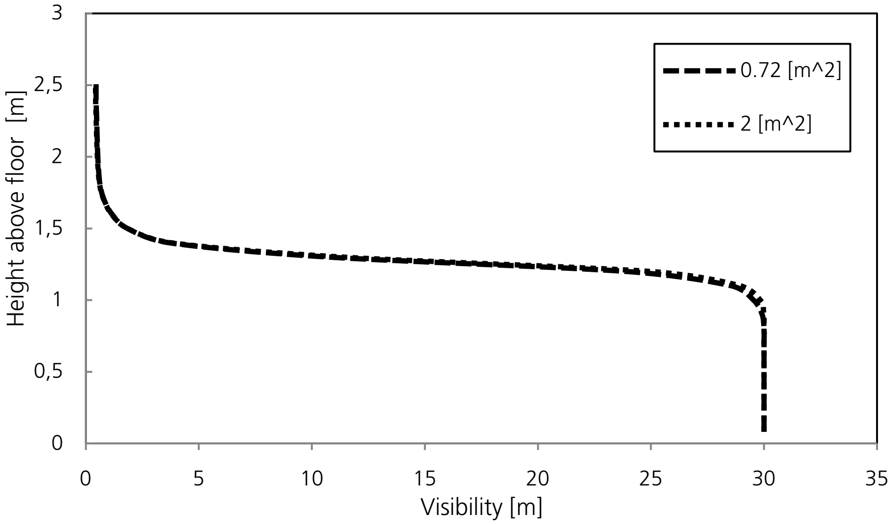

FIGURE 7.2 Variations in visibility at different heights as a result of changes made to the fire area.

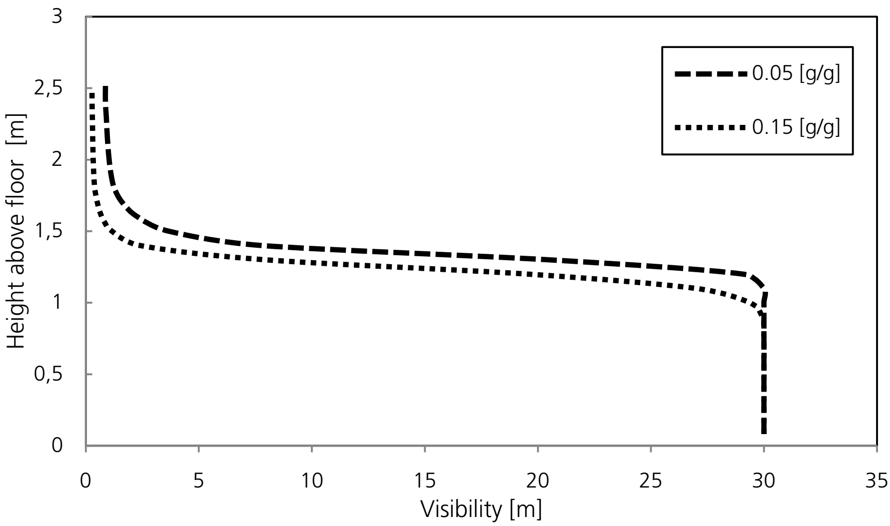

FIGURE 7.3 Variations in visibility at different heights as a result of changes made to soot yield.

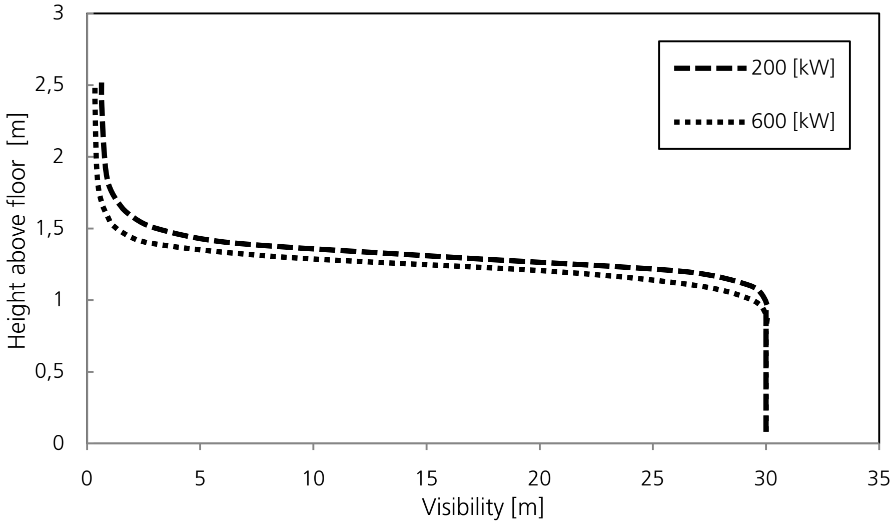

FIGURE 7.4 Variations in visibility at different heights as a result of changes made to the HRR.

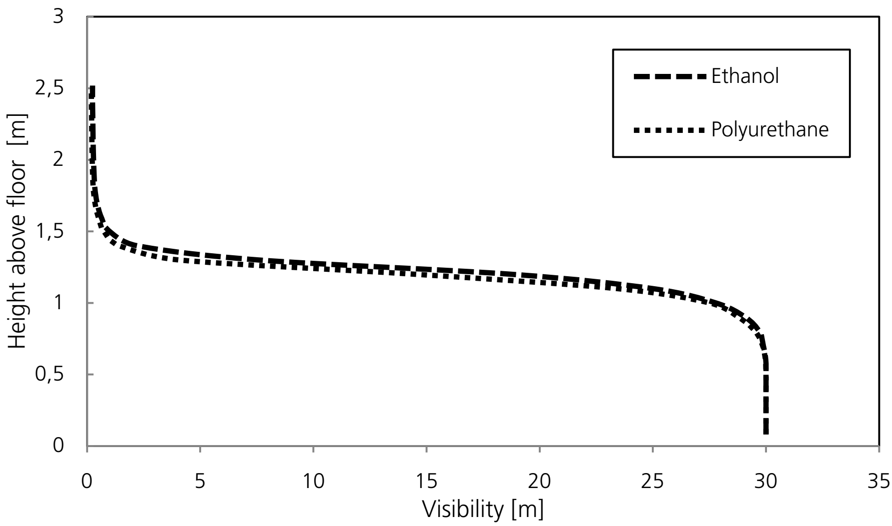

FIGURE 7.5 Variations in visibility at different heights as a result of changes made to the fuel.

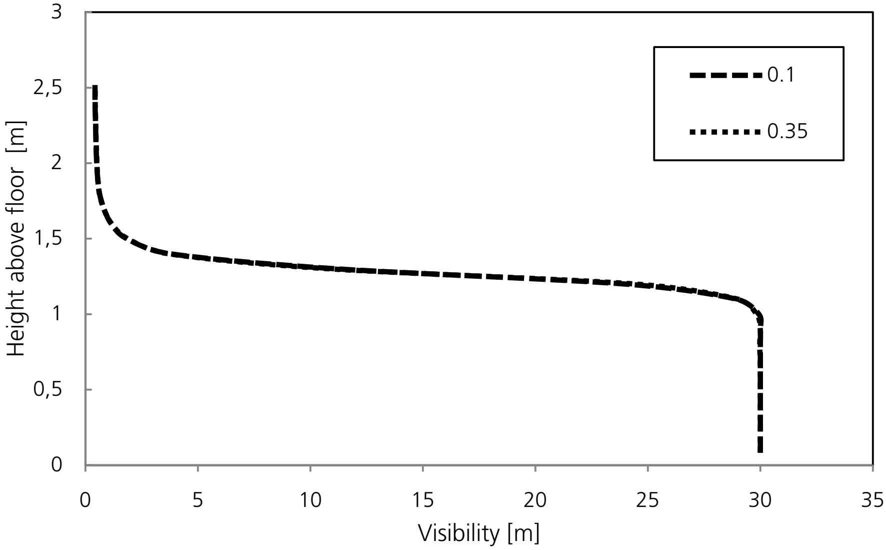

FIGURE 7.6 Variations in visibility at different heights as a result of changes made to the radiative fraction (the two graphs superimpose).

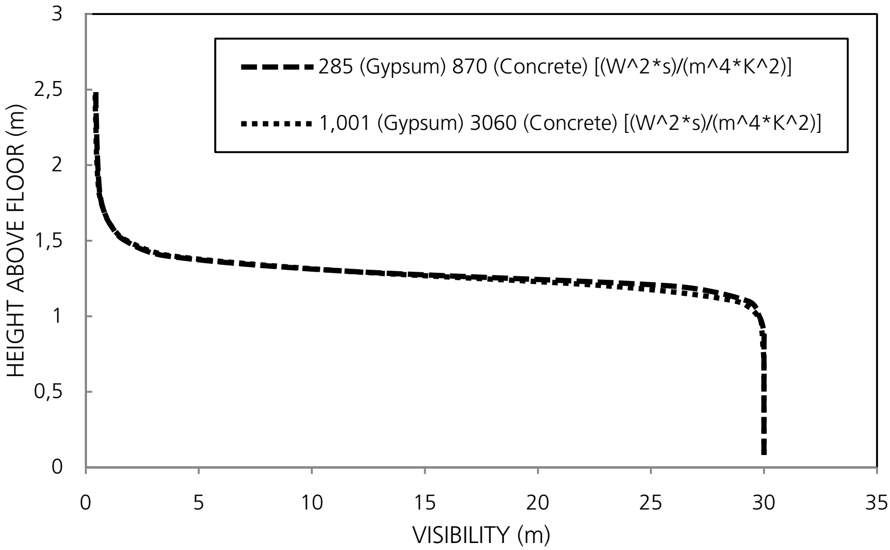

FIGURE 7.7 Variations in visibility at different heights as a result of changes made to kρc.

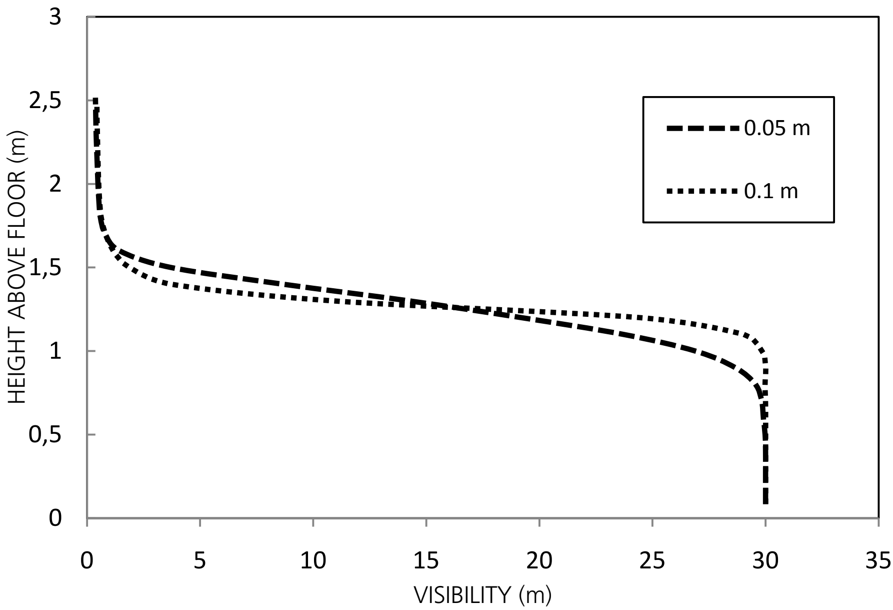

FIGURE 7.8 Variations in visibility at different heights as a result of changes made to cell size.

The figures show how visibility changes at different heights as a result of varying one input variable at a time. Table 7.3 below shows the ratio of the visibility for each of the variables, at the given height.

TABLE 7.3 Results from sensitivity analysis

Variable	Ratio of visibility at a height of 1.4 m
Mass extinction coefficient	2.24
Fire Area/HRRPUA	1.03
Soot yield	3.24
HRR	2.35
Reaction (fuel)	1.54
Radiation	1.06
kρc	1.07
Cell size	2.33

The four variables that had the largest ratio of visibility were:

- Mass extinction coefficient
- Soot yield
- HRR
- Cell size

However, the ratio of visibility regarding the cell size variable varies considerably depending on the height at which one compares, as can be seen in Figure 7.8. Furthermore, it would not be possible to conduct 200 simulations where the cell size is varied each time. For these reasons the cell size variable is disregarded for further study and only the following three variables are selected:

- Mass extinction coefficient
- Soot yield
- HRR

8 Distributions of input variables

This section details the process of selecting statistical distributions of the input data, to attempt to account for their inherent uncertainty or statistical nature.

8.1 Soot yield

Soot particles are produced as a result of incomplete combustion and vary depending on the type of combustible material as well as other factors such as ventilation conditions. In FDS, the user specifies the desired soot yield as a fraction of fuel mass that is then converted into smoke particulate.

In a fire, the probability distribution of the soot yield depends on the fuel. It is therefore necessary to know the rough distribution of combustibles in the type of setting being modelled. Due to the uncertainty of this, a triangular distribution has been deemed reasonable, owing to the fact that reasonable assumptions can be made of an expected value together with a minimum and maximum value.

In an office type setting, the fire load is typically dominated by paper, plastics and wood [18]. For the purpose of this thesis, the proportions have been assumed to be 60 % (paper), 30 % (wood) and 10 % (plastics). It should be noted that these proportions can vary, but it is not the aim of this thesis to absolutely represent reality, but rather to show a method and the sensitivity due to user input.

By weighting soot yields found in the literature [23] and presented in Table 8.1 of materials commonly present in office type settings together with the percentages in the above paragraph, the triangular distribution in Figure 8.1 was created.

TABLE 8.1 Experimental soot yields for different materials

Material	Soot Yield (g/g)
Wood	0.015
Polyethylene	0.06
Polystyrene	0.164
Polyurethane (rigid)	0.1
Polyurethane (flexible)	0.227

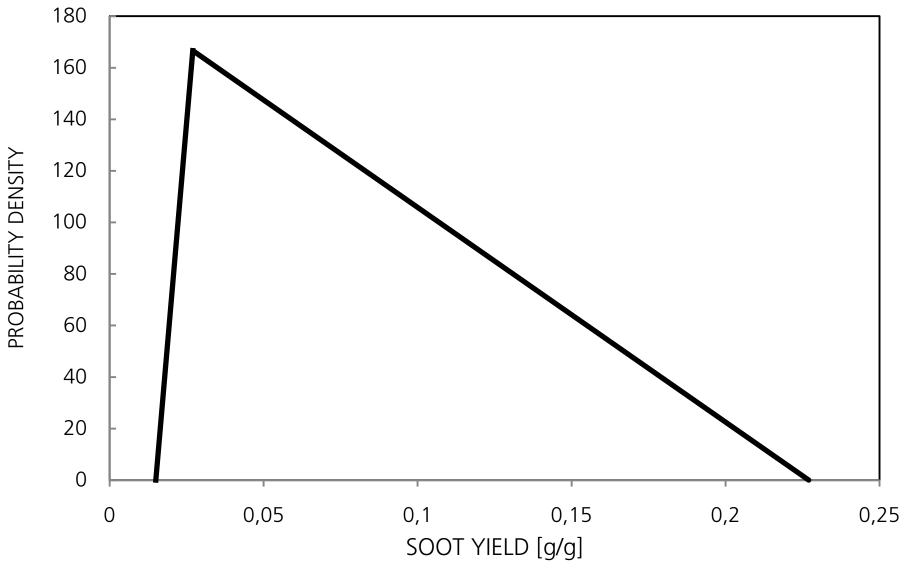

FIGURE 8.1 Triangular probability distribution of soot yield.

8.2 Mass extinction coefficient

The mass extinction coefficient is a measurement of how much a substance scatters light at a given wavelength ($\lambda = 633\ nm$). It affects visibility via the following relationship:

$$S = \frac{C}{K_m \cdot \rho Y_s} \tag{8.1}$$

Where S is visibility, C is a non-dimensional constant characteristic of the object being viewed, K_m is the mass extinction coefficient, and ρY_s is the smoke particulate [4].

Experimental data [24] reveals values of mass extinction coefficients from some types of wood and plastics. There are however quite large experimental uncertainties [24] and the values differ between experiments. These values are given in Table 8.2.

TABLE 8.2 Experimental mass extinction coefficients for wood

Material	Mean (m^2/kg)	± (m^2/kg)
Wood	10,300	-
Wood crib	8,500	1,000
Oak	7,600	2,400
Average	8,800	1,700

TABLE 8.3 Experimental mass extinction coefficients for plastic materials

Material	Mean (m^2/kg)	± (m^2/kg)
Polystyrene (test 1)	10,000	-
Polystyrene (test 2)	9,600	-
Polycarbons (test 1)	7,600	1,000
Polycarbons (test 2)	10,200	-
Polyurethane crib	8,100	1,100
Average	9,100	1,050

With the office type setting and proportions of materials mentioned in Section 8.1, the weighted average mean will be 8,830 m^2/kg ± 1,635 m^2/kg. Due to the significant experimental uncertainties, as well as the weighted average being reasonably similar to the recommended value, it was decided to go forth with the recommended value of 8,700 ± 1,100 [4,24]. These values are suggested specifically for flaming combustion of wood and plastics. For the purpose of this thesis, a uniform distribution between 7,600 and 9,800 will be used for this variable.

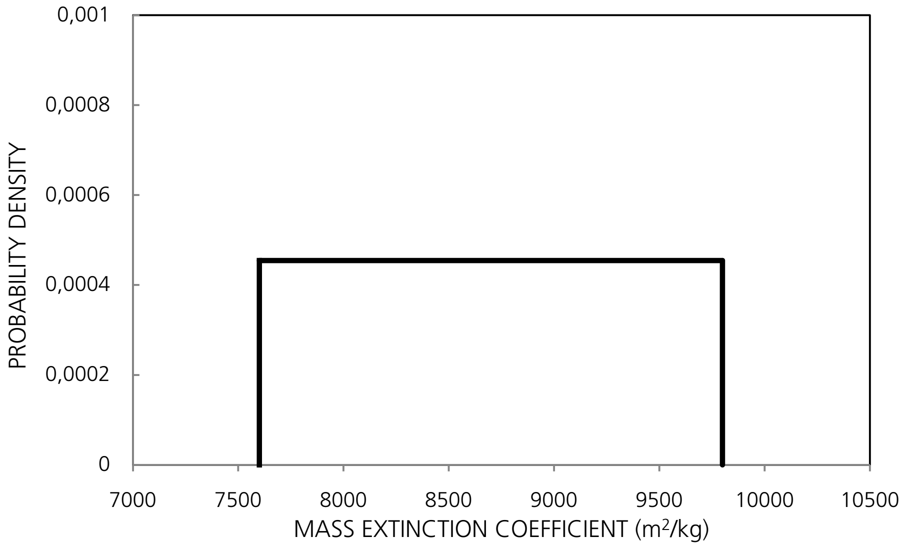

FIGURE 8.2 Uniform distribution of mass extinction coefficient.

8.3 Heat Release Rate

A distribution of the HRR is very subjective since it is entirely up to the FDS user to assess what may be involved in a fire in any given scenario. It is still needed in order to achieve the aim of this thesis. The maximum ventilation controlled fire size in the fire-room is 3.4 MW based on simple calculations on maximum oxygen mass flow into the room. This however is a very large heat release rate for the present setting; also the HRR is the single most controlling variable in any FDS simulation, as it is the source term in the energy equation. It is for this reason necessary to choose an HRR distribution that does not dominate the other selected variables.

Bearing this in mind, the distribution of HRR will be set to a relatively low interval, with a minimum of 100 kW ranging up to a maximum of 900 kW. Since nothing is known about the distribution function, it is assumed to be uniform.

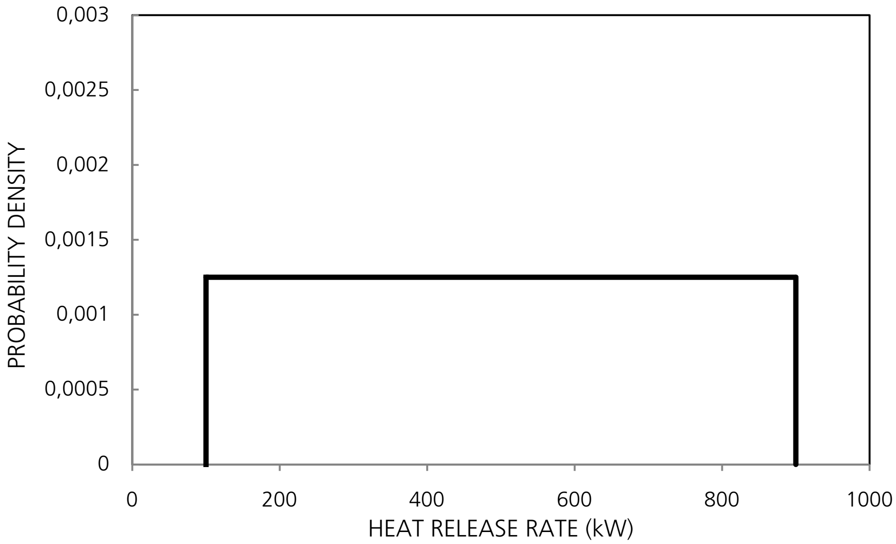

FIGURE 8.3 Uniform distribution of Heat Release Rate.

8.4 Monte Carlo sampling

In order to sample variables from the distributions a software system called @RISK was used. @RISK can be integrated into Microsoft Excel for the analysis of technical situations impacted by risk, via Monte Carlo simulations [25]. The program allows a user, among other things, to sample random numbers, based on the given probability distribution of a variable. The distributions are listed in Table 8.4.

TABLE 8.4 Distributions with attributes of input variables

Variable	Unit	Distribution	Expected value	Min.	Max.
Mass extinction coefficient	m^2/kg	Uniform	8,700	7,600	9,800
Soot yield	g/g	Triangular	0.027	0.015	0.227
HRR	kW	Uniform	500	100	900

In this thesis, 200 random numbers were sampled from each distribution function belonging to a variable. The sampled values can be found in Appendix B.

9 Results from simulations

In this chapter the results from the simulations are shown, where each variable was varied one at a time. The figures in this chapter are given at a height (1.4 m) where there is more variation in visibility in order to show the uncertainty, as well as the height at which most humans would be able to look at (1.8 m). Figures from selected heights are found in Appendix D

Also given for each of the figures is the probability that a simulation results in a visibility less than 10 meters, i.e. $Pr(S < 10)$. A complete table of this probability can be found in Section 9.3.

9.1 Independent variable simulations

In this section, figures are presented for the simulations where only one variable at a time was varied.

9.1.1 Soot yield

The results of the simulations are shown below in Figure 9.1 and Figure 9.2.

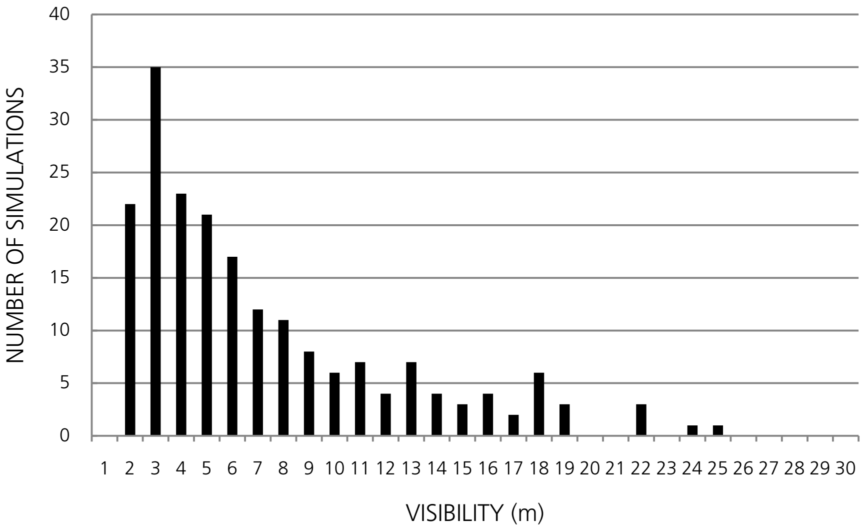

FIGURE 9.1 Distribution of the visibility in the soot yield simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility *$Pr(x<10) = 0.745$*.

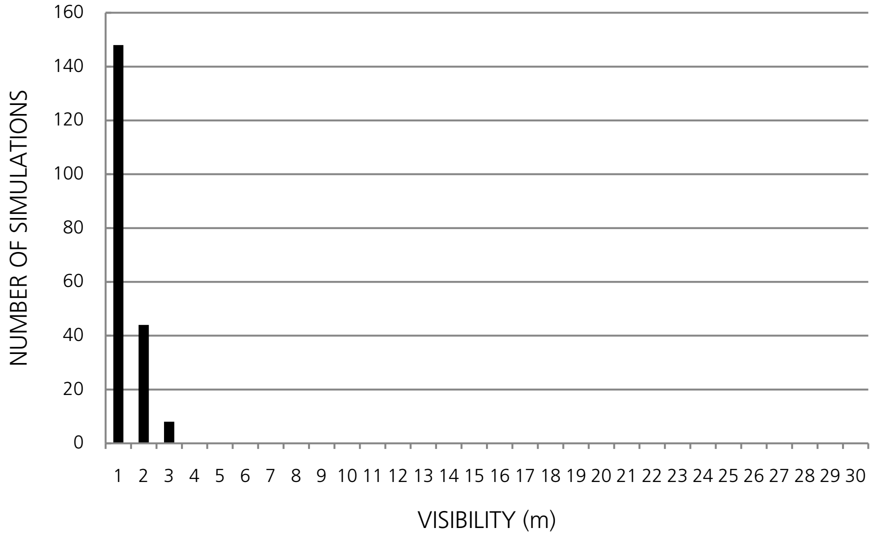

FIGURE 9.2 Distribution of the visibility in the soot yield simulations at a height of 1.8 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 1*.

9.1.2 Mass extinction coefficient

The results of the simulations are shown below in Figure 9.3 to Figure 9.4.

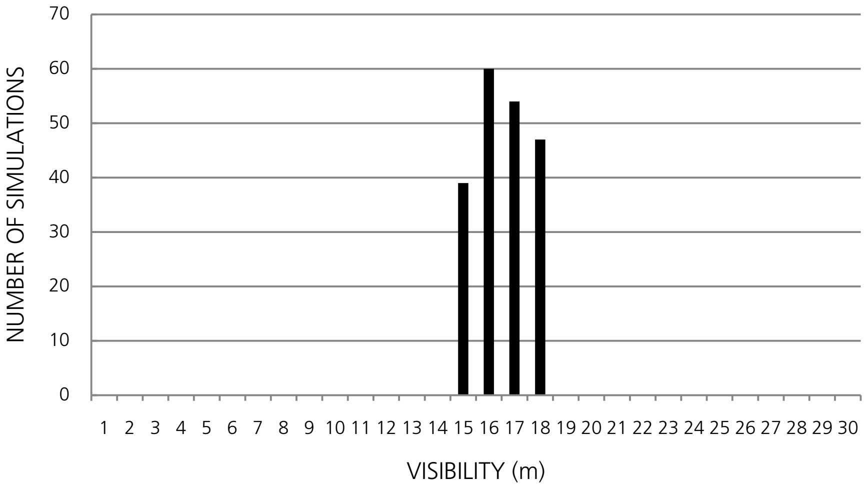

FIGURE 9.3 Distribution of the visibility in the mass extinction coefficient simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0*.

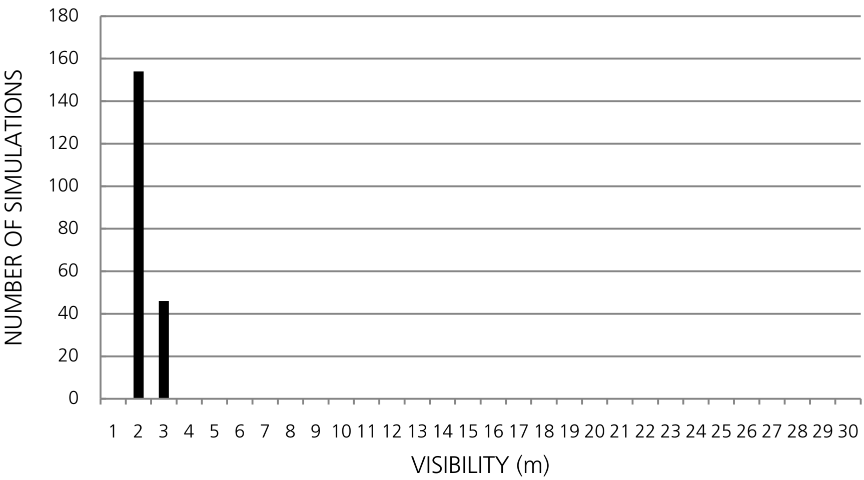

FIGURE 9.4 Distribution of the visibility in the mass extinction coefficient simulations at a height of 1.8 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 1*.

As the results show, there is quite little variation in the visibility at any given height.

9.1.3 HRR

The results of the simulations are shown below in Figure 9.5 and Figure 9.6.

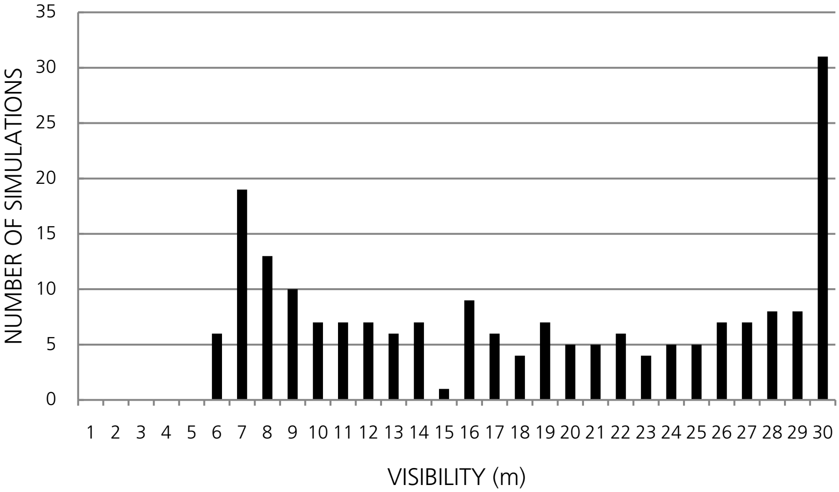

FIGURE 9.5 Distribution of the visibility in the heat release rate simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.24*.

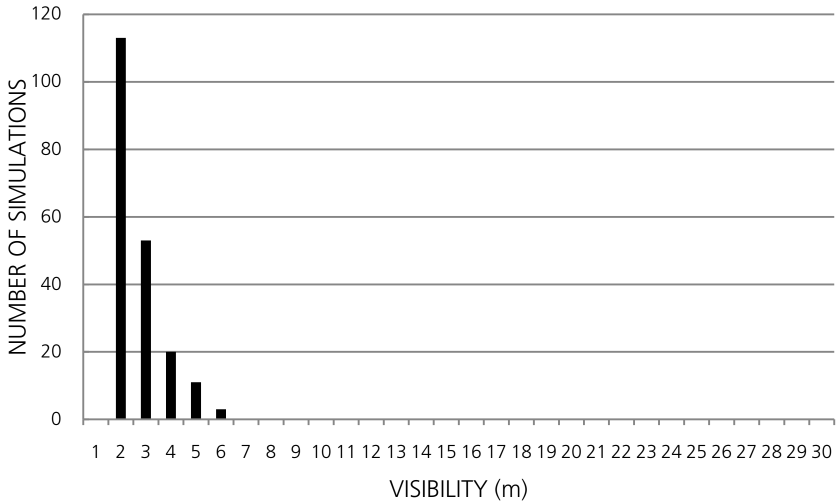

FIGURE 9.6 Distribution of the visibility in the heat release rate simulations at a height of 1.8 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 1*.

9.2 Simultaneous variable simulations

In this section, figures are presented for the simulations where all variables were varied at the same time.

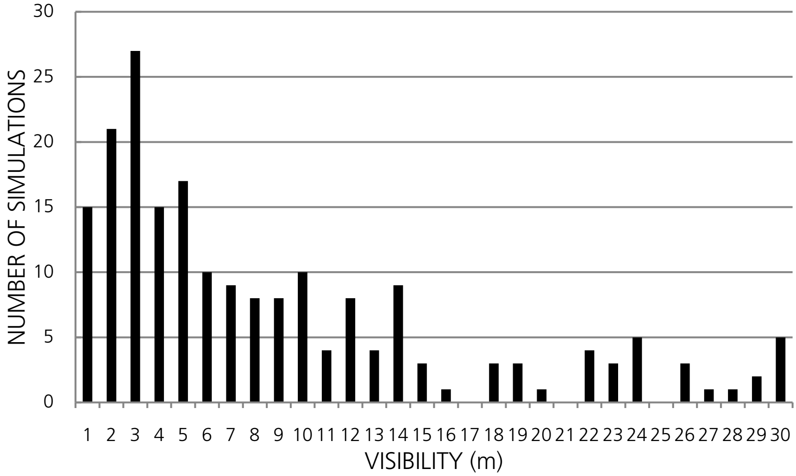

FIGURE 9.7 Distribution of the visibility in the simultaneous variable simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.65*.

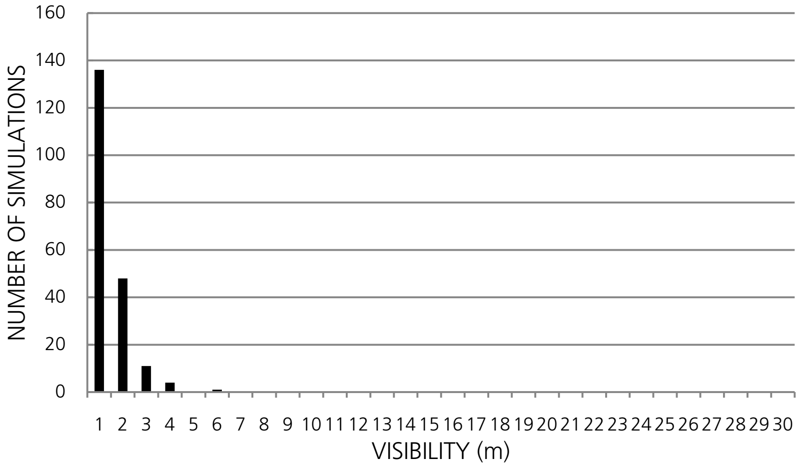

FIGURE 9.8 Distribution of the visibility in the simultaneous variable simulations at a height of 1.8 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 1*.

9.3 Summary of results

In Table 9.1 below the results are summarized by presenting the probability that the visibility is less than 10 meters, for all input variables at all heights. For example, between 0.1 and 1.1 meters, the visibility in all simulations is always above 10 meters, i.e. the probability that the visibility is greater than 10 meters is 1 for all those heights.

TABLE 9.1 Probability of visibility not exceeding 10 m for all heights and simulations

Height (m)	Soot yield	Mass ext. coeff.	HRR	Simultaneous
0.1	0	0	0	0
0.2	0	0	0	0
0.3	0	0	0	0
0.4	0	0	0	0
0.5	0	0	0	0
0.6	0	0	0	0
0.7	0	0	0	0
0.8	0	0	0	0
0.9	0	0	0	0
1.0	0	0	0	0
1.1	0	0	0	0
1.2	0	0	0	0.075
1.3	0.195	0	0	0.24
1.4	0.745	0	0.24	0.65
1.5	0.99	1	0.7	0.955
1.6	1	1	0.965	0.995
1.7	1	1	1	1
1.8	1	1	1	1
1.9	1	1	1	1
2.0	1	1	1	1
2.1	1	1	1	1
2.2	1	1	1	1
2.3	1	1	1	1
2.4	1	1	1	1
2.5	1	1	1	1

10 Discussion and conclusion

10.1 Conclusion

The objectives of this thesis were to investigate a number of issues listed below in order to develop a method of connecting FDS with risk analysis.

- Which input variables are the most sensitive in an FDS simulation, based on the chosen output data?
- To what degree does the input data affect the output data?
- How uncertain is the output of an FDS simulation given a variation in the input data?
- What recommendations can be made to FDS users?

Based on the chosen output quantity visibility, a sensitivity study was conducted based on a selected number of possible input variables having an effect on visibility. While it is possible that other variables could have had an impact on visibility, the selected variables were chosen based on qualitative reasoning as is detailed in Section 7. The sensitivity study showed that three of the variables had the largest impact on the output, these variables being soot yield, mass extinction coefficient and heat release rate. A user interested in another output quantity such as temperature or radiation would need to conduct a similar study in order to determine the most sensitive input variables for that specific output and scenario.

The degree to which the input variables affect the output data is dependent on the location where a user is interested in the output data. In this thesis for example, the visibility varies very little close to the floor and ceiling, whereas the variation is significant at around 1.4 meters above the floor. This is connected to the uncertainty of the output data given a variation in the input data. The simulations conducted in this thesis show that when all input variables are varied simultaneously there is a considerable spread in output data. For example, at a height 1.4 meters above the floor, 35 % of the 200 simulations achieved the criterion of visibility being equal to or exceeding 10 meters.

With a probability of achieving an acceptable visibility of 35 %, for example, the major recommendation to FDS users is to be very conscious about any decisions made concerning input variables. Due to the time consuming task of applying the method presented in this thesis to larger buildings, it is unreasonable to expect fire engineers to conduct similar analyses at present. A strong recommendation to FDS users is to conduct informed sensitivity analyses where not only the HRR is varied, but any variables that may affect the output quantity in question.

10.2 Discussion of assumptions and method

Fire scenarios are dynamic phenomena and the scenario used in this thesis is not necessarily representative of other fire design settings encountered by fire engineers. The results presented in this thesis are heavily dependent on the chosen scenario and the static parameters attached to it. The uncertainties presented should therefore only be used as indicative data, and not an absolute truth. The aim of this thesis has been to use a scenario as realistic as possible, but still manageable due to the immense workload that is connected to running several hundred CFD simulations.

While this thesis does not present an absolute truth to user uncertainty when using FDS, it does provide a method for connecting FDS with statistical analysis to deal with the inherent uncertainty of CFD modelling in general and fire engineering in particular.

Only visibility has been used as an output quantity, as has been presented previously in Section 6. The method, however, could be used with any other desired output from an FDS simulation, such as temperature, toxicity, incident radiation or any other quantity available. In FDS, visibility is output as point measurements. This puts some responsibility in the hands of the user, as visibility needs to be evaluated along a path, all the way to the desired target, for example an exit or an exit sign. In this thesis, the point measurements provided by FDS have been used, but only after a study to determine if those measurements are representative of path measurements. The study found that the point measurements, in this case, were indeed representative.

Crucial to any FDS simulation, regardless if doing only a few simulations or several hundred, are the input quantities that can be changed by the user. In this case, the quantities that were deemed to have the most impact on visibility were selected in a qualitative manner, and then included in a sensitivity analysis. This resulted in the three selected input quantities, being soot yield, mass extinction coefficient and heat release rate (HRR). It should be noted that it is possible that other input quantities were overlooked and that they could have an effect on visibility. An optimal solution to this would be to include all possible input parameters in a sensitivity study. This was not done in this thesis due to time constraints and the vast amount of possible options in FDS. The selected variables were not correlated in the Monte Carlo analysis. While it is reasonable to assume there is some correlation between heat release rate, soot yield and mass extinction coefficient, this was not considered in this thesis. Correlating the variables could possibly yield different results, something that should be taken into consideration in future research.

Mesh placement in all models have been the same, but it is possible that mesh placement does have an effect on the results. The placement of mesh boundaries (where meshes abut) have been chosen based on existing recommendations and as far away from areas of increased flow activity as possible. This includes areas around the fire source, door openings etc. In order to take advantage of parallel computing and to reduce the workload, it was deemed necessary to use several meshes.

Cell size is an important parameter in a CFD simulation and has been considered in this thesis. Decreasing the cell size by half results in a theoretical 16-fold increase in time (two times for each spatial dimension and two for the temporal). This means that the choice of cell size had to be based not only on what was desired, but also what was possible to do. The simulations in this thesis took approximately two months to finish. This was due to both human limitations and limitations in the computer cluster used. Halving the cell size would have radically increased this time. However, to investigate the choice of cell sizes, a sensitivity study was performed. This study showed minor differences between the chosen cell size of 0.1 m (cubic cells) and a cell size of 0.05 m. It is considered that the cell size used is reasonable and that the results are not overly sensitive as a result of that choice. Any FDS user needs to consider the cell size, it cannot be said that 0.1 m is an adequate cell size for any simulation in the fire engineering field.

There is some randomness built into FDS when the flow field is initialized. This results in fire plumes not being absolutely symmetric (as would be expected in reality) and that one simulation could, at least in the near-field, slightly differ from another. It is not expected that this randomness has any large effect in the far-field.

Selecting the distribution for the HRR was especially difficult due to the profound impact it has on the results. Ultimately, it was decided to use an interval with relatively low values, so as to not make the results totally dependent on the HRR alone. This is most likely the parameter that, in this thesis, is least representative of how a fire engineer would choose it in reality.

In all simulations in this thesis, steady state conditions based on visibility were achieved. It was a conscious choice to evaluate all results after steady state was achieved, but it should be noted that this method would work equally well at any desired time in a simulation, even though steady state has not been achieved.

10.3 Discussion of results

Not counting the models included in the sensitivity studies, a total of 800 simulations act as a foundation for the results in this thesis. When using visibility as a criterion in fire safety engineering, it is relevant to evaluate it at some height, usually what is called “head height” or the height at which a human head is expected to be exposed to smoke. This height is usually, with some safety margin, at roughly 1.8 to 2 m from the floor depending on the ceiling height. For the specific setting used in the subject model, this height would, according to guidelines in the Swedish building code, be roughly 1.8 m [1]. In all simulations in this thesis, it was not possible to fulfil this criterion, meaning that acceptable visibility was never achieved at around this height. In the subject simulations, the height at which visibility varied was found to be at around 1.4 m from the floor. This height would not normally be used in a fire engineering design, except perhaps if people would be expected to be able to crawl in very special circumstances such as airplanes or otherwise. But to obtain meaningful distributions without introducing mitigating measures such as smoke ventilation, output data was evaluated at around this height.

10.3.1 Soot yield

The results from the simulations where soot yield was varied yields a cumulative distribution with visibility plotted against number of simulations. We define an event E as the visibility S being less than 10 m at a height H m above the floor in the specific scenarios used in this thesis The probability of E happening at 1.4 m is $Pr_E(H=1.4) = 0.745$. This means that if an FDS user would select a value of soot yield randomly within the range of soot yields used in the subject simulations, the simulation would have a probability of actually achieving an acceptable visibility at that height of less than 26 percent. At 1.3 m $Pr_E(1.3)=0.195$ and at 1.5 m $Pr_E(1.5)=0.99$.

Soot yield is clearly a sensitive variable connected to visibility. Changing the soot yield within the given distribution has a large effect on the results. Selecting a static value of soot yield would give a certain result, but changing this value somewhat has a large impact on results as has been shown in this thesis.

10.3.2 Mass extinction coefficient

The results from the simulations where the mass extinction coefficient was varied yields a cumulative distribution with visibility plotted against number of simulations. At 1.4 m $Pr_E(H=1.4) = 0$. At 1.3 m $Pr_E(1.3)=0$ and at 1.5 m $Pr_E(1.5)=1$. This shows that despite the initial sensitivity analysis, visibility is not overly sensitive to changes in the mass extinction coefficient within the chosen range. With a larger range of values of the mass extinction coefficient, the resulting visibility distribution would most likely have looked different. However, the chosen range of input values were selected based on an extensive literature study and it would be unreasonable to expect values significantly higher or lower than those used. The sensitivity study used a base value of 8,700 m^2/kg and then used values of ± 50 percent. While this yielded noticeable differences in visibility, clearly, the values used in the distribution functions did not have that large an effect. This distribution was uniform with an expected value of 8,700 and a minimum and maximum value of about ± 13 percent.

10.3.3 Heat release rate

The results from the simulations where the HRR was varied yields a cumulative distribution with visibility plotted against number of simulations. At 1.4 m $Pr_E(H=1.4) = 0.24$. This means that if an FDS user would select a value of HRR randomly within the range of heat release rates used in the subject simulations, the simulation would have a probability of actually achieving an acceptable visibility at that height of more than 75 percent. At 1.3 m $Pr_E(1.3)=0$ and at 1.5 m $Pr_E(1.5)=0.7$.

Within the rather moderate range in which the HRR has been varied, output is still greatly affected. This was expected, as it is a very dominant variable. It however shows that even small changes in the heat release rate give large effects on the results.

10.3.4 Simultaneous variable simulations

The results from the simulations where all variables were varied yields a cumulative distribution with visibility plotted against number of simulations. At 1.4 m $Pr_E(H=1.4) = 0.65$. This means that if an FDS user would select a value of HRR, soot yield and mass extinction coefficient randomly within the ranges used in the subject simulations, the simulation would have a probability of actually achieving an acceptable visibility at that height of about 35 percent. At 1.3 m $Pr_E(1.3) = 0.24$ and at 1.5 m $Pr_E(1.5) = 0.955$.

Given the assumptions that the chosen variables are uncorrelated, that they are randomly chosen and that their respective distributions are representative of reality, the simultaneous variable simulations provide a probabilistic result of how visibility varies at any given height. An FDS user might use a certain value for each input variable and yield results that are, say, acceptable at a height of 1.4 m. The results of the subject simulations show, that at that height, there is only a 35 percent probability that these results are indeed acceptable. That means that there is a 65 percent probability that the results would not be acceptable.

Using safety margins is an approach that could possibly, in some way, ascertain that results from a fire simulation are conservative enough. However, that could create problems in the other end, meaning that a design is ultimately more conservative than it needs to be, resulting in excessive costs for contractors. The very purpose of fire engineering would also be somewhat moot if a fire engineer always simply used the most conservative approach to ensure the safety of a building. Clearly, using risk assessments is a way of ensuring adequate, probabilistic, safety while still delivering reasonable cost-effective solutions.

10.3.5 Summary of results

Naturally, a typical FDS user would not normally select values of soot yield randomly. However, he would most likely select a more or less static value and use that in all simulations. In reality, however, soot yield is not necessarily static, but follows a distribution based on type of setting and what combustibles exist within that setting. A resulting fire safety design could then both overestimate the height at which visibility fulfils the criterion, or underestimate it. This could either create an unsafe design, or a design that is overly conservative, perhaps resulting in excessive cost for fire mitigating measures or otherwise.

10.4 Errors

As with all CFD simulations, there are many uncertain parameters and potential errors that can be introduced by the user. The use of parallel computing was necessary to be able to conduct all simulations within a reasonable timeframe. While it is possible, it is not expected that this introduced any large errors into the simulations, as previous research has shown. Even if errors were introduced, all simulations where simulated in the same computer setting and in the exact same manner, therefore any errors are expected to be introduced equally into all simulations.

Visibility, as it is defined in fire safety engineering, is a somewhat subjective quantity that to some extent is based on experiments with humans. While this is something that a fire engineer or any FDS user needs to know, it does not have an impact on any of the results in this thesis.

The chosen input variables were selected for a number of reasons, but it is noted that other potential parameters exist and could equally well have been used. It could have been possible to conduct a survey of how fire engineers would have chosen the design fire, soot yield or any other parameter to try and obtain a distribution. This was deemed as unrealistic due to the nature of the simulations. The survey subjects would have needed to be thoroughly introduced into the purpose of the simulations in order to give reasonable answers. Ultimately, it was decided to use distributions of the selected input variables based on literature and reasonable assumptions.

The assumption that all input variables are uncorrelated is not necessarily correct. However, the literature study showed that it was very difficult to obtain any meaningful data on any correlation between the chosen variables. It was therefore decided to not attempt to correlate the variables.

10.5 Recommendations to FDS users

This thesis proposed a method of using Monte Carlo analysis with FDS. Using FDS to simulate fire scenarios is computationally intensive, and as such the authors acknowledge that it is not feasible to conduct hundreds of simulations of large buildings that is often the case in fire engineering design today. Given the advance in computers in the last 10-20 years and the assumed continued advances, it is important to develop and improve on methods such as the one presented in this thesis in order to increase the level of accuracy and certainty in fire models.

Presently, it would be quite possible to use the proposed method for more reasonably sized buildings, given that the user has access to parallel computing networks. For larger buildings today, the feasible approach would be to conduct a smaller scale analysis, not necessarily utilizing Monte Carlo, but rather an informed sensitivity analysis, preferably changing more than just the heat release rate. Changing more than just the heat release rate, but also any other input variable that could have an effect on a given output quantity, ascertains that an FDS user acknowledges the dynamic nature of fire modelling.

10.6 Further research

This thesis represents, to the authors' best knowledge, a first step in connecting risk analysis with FDS usage for fire engineering purposes. Apart from advances in computational power more research could be conducted in order to further simplify and develop the concept.

Finding reasonable distributions for selected input variables is time consuming and ultimately somewhat qualitative. An effort could be made to find reasonable distributions of key variables for different settings, much like fire growth numbers has been researched and recommendations have been published for different types of occupancies [26].

It is also reasonable that similar studies be conducted that focuses on other output quantities such as temperature, toxicity and radiation.

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Appendix A – Parallel computing with FDS

A.1 Parallel computing

Parallel computing is a form of computation where many calculations are carried out simultaneously by different computers or processors (also called *Central Processing Unit,* CPU), taking advantage of the fact that large problems often can be divided into smaller ones which are then solved simultaneously or "in parallel" [7].

In order for different computers or CPUs to communicate with each other, some sort of standardised interface is required. *Message Passing Interface* (MPI) is a communications protocol that has become the de facto standard for parallel computing.

A.2 LUNARC

Lund University Numeric Intensive Computation Application Research Center (LUNARC) is a scientific centre for technical and scientific computing started in 1986 at Lund University. The parallel computations in this thesis have been performed on one of LUNARC's homogenous clusters called Milleotto. Milleotto consists of 252 nodes with two Dual Core processors in each node, resulting in a total of 1008 CPUs. The nodes are connected by two independent Gigabit networks, one handling the MPI communication and one handling the rest of the data traffic. Specific node information can be seen in Table A.1 below.

TABLE A.1 Node configuration

Node configuration on Milleotto	
CPU	2 Intel Xeon 5160 (3.0 GHz dual core)
RAM	4 GB
Operating system	Linux CentOS 5.3 x86_64 (RHEL4 compatible)

A.3 Compiling FDS

FDS is made available by NIST both as source code and as pre-compiled executable files for a limited number of operating systems. In order to run FDS on LUNARC, it needed to be compiled specifically for this cluster and the operating system used. *Compiling*, in this context, means converting human readable source code from one programming language to another. This is usually in a binary format known as machine code. The machine code are a series of instructions that are read directly by the CPU and thus needs to be compatible with both the operating system and the specific type of CPU on the target system.

For all simulations in this thesis, the same version of FDS was used (see Table A.2 below). The version used was the latest stable version released at the time the simulations in this thesis were started. All changes made to FDS by the developers at NIST are saved and tracked by a version system software called Subversion (SVN)[2]. That means any previous version can be downloaded and compiled if required.

TABLE A.2 FDS version information

FDS version used	
Version	FDS 5.3.1 Parallel (No OpenMP-version)
SVN Revision No.	3729
Release date	April 8 2009

A.3 Running simulations on LUNARC

In order for several different users to run computing jobs on the LUNARC cluster, resource management and job scheduling software is used. LUNARC uses a resource manager called TORQUE[3] and a cluster scheduler called Maui[4]. In order to submit computing jobs to LUNARC a script file is used. The script file contains information about the maximum amount of time the job is allowed to run, the number of CPUs to be used, an e-mail address to send information on when the job starts and finishes and the path to the executable file that is to run the job as well as any input file the particular executable needs.

[2] See http://subversion.tigris.org/
[3] See http://www.clusterresources.com/products/torque-resource-manager.php
[4] See http://www.clusterresources.com/products/maui-cluster-scheduler.php

Appendix B – Sampled values

In this appendix the values of the input variables used for the simulations are presented. One value corresponds to one simulation except for the simultaneous simulations where the first, then second, then third etc., values from each table respectively was used at the same time.

B.1 Soot yield

Sampled values of soot yield (g/g).

0.036	0.1327	0.1622	0.0543	0.0508	0.1075
0.1155	0.0776	0.0617	0.0262	0.0563	0.0679
0.1418	0.0948	0.074	0.0763	0.0414	0.0512
0.06	0.0873	0.0316	0.0802	0.0959	0.1038
0.0592	0.0298	0.1069	0.0399	0.0217	0.1201
0.1557	0.0917	0.0754	0.0665	0.0391	0.0271
0.0458	0.0377	0.0994	0.0452	0.1466	0.0865
0.0765	0.0404	0.0649	0.1609	0.0352	0.0496
0.0573	0.1886	0.0789	0.0991	0.127	0.1347
0.081	0.1122	0.0318	0.0502	0.1092	0.126
0.1945	0.0201	0.1198	0.1002	0.0468	0.1439
0.093	0.0963	0.0709	0.128	0.0432	0.1081
0.1224	0.0331	0.1916	0.0448	0.0341	0.0311
0.2135	0.1099	0.1483	0.0559	0.0779	0.0384
0.1292	0.0644	0.0222	0.1163	0.1247	0.1239
0.0591	0.1453	0.0584	0.1011	0.1589	0.164
0.0231	0.0722	0.0794	0.1706	0.1741	0.0529
0.1139	0.0719	0.0898	0.1055	0.0249	0.1511
0.063	0.1212	0.0969	0.0441	0.0686	0.067
0.029	0.083	0.1391	0.0425	0.0908	0.2022
0.053	0.0327	0.1294	0.0816	0.0371	0.0241
0.0284	0.0518	0.1523	0.0839	0.1707	0.0927
0.0858	0.0936	0.1877	0.0883	0.0264	0.1032
0.1401	0.1124	0.0287	0.1378	0.0484	0.2006
0.0488	0.1673	0.1565	0.1315	0.118	0.041
0.2089	0.1577	0.0476	0.1843	0.0879	0.0257
0.0891	0.1792	0.1663	0.1492	0.0548	0.1316
0.0334	0.1763	0.0695	0.057	0.0616	0.0662
0.119	0.0276	0.181	0.0849	0.0624	0.0439
0.0305	0.0606	0.0736	0.1143	0.0419	0.1786
0.0192	0.0824	0.0361	0.0474	0.0637	
0.0347	0.0377	0.1049	0.1531	0.1361	
0.0175	0.0707	0.1113	0.0748	0.0982	
0.1427	0.1025	0.0536	0.1358	0.0696	

B.2 Mass extinction coefficient

Sampled values of mass extinction coefficient (m^2/kg).

8588	8223	8834	9615	9777	7676
8083	9280	8414	9532	8805	8473
8498	9557	7730	9048	9115	9258
8354	7741	8018	8637	9483	9190
8231	9497	8376	9727	7785	8390
7715	8533	8748	9086	9755	9299
9224	7889	7838	9068	8310	9405
8505	7974	7762	8884	9653	8634
8561	7772	7666	8599	7859	8090
7940	8440	8149	9364	7920	8576
8616	7881	8913	8737	8976	9322
8482	8158	9735	8686	9249	9588
9335	7693	7615	8046	8949	9631
9390	7798	7649	8986	9379	8361
8299	8394	8522	8548	9027	9052
8027	8245	8119	8927	8458	8262
9460	9178	9313	8717	8176	8191
7789	8054	8659	7826	9575	9676
8343	9401	8135	9509	8859	7955
9139	9159	8870	9439	9077	8164
9538	9290	7866	8955	9231	7989
7907	7946	9418	8429	9607	8792
8287	9593	8786	9341	7635	9036
7705	8197	9010	8966	9662	8730
7908	8421	7746	8692	8845	9785
8063	9356	8771	9102	9003	9698
8205	7604	7631	9208	8096	8939
8822	7809	7687	7977	9147	8281
9680	9520	9641	8538	9472	8031
9165	9797	9704	9431	8110	8905
8258	9568	8701	9451	8001	
9199	8675	9261	8320	8817	
8897	9122	8463	8756	9757	
8602	7845	8329	8649	9715	

B.3 HRR

Sampled values of HRR (kW). Divide with 0.25 m^2 to get HRRPUA as used in the FDS input files.

648.5	223.5	451.5	661.2	441.9	263.6
623.1	699	836.6	632.8	458.2	385
575	786.7	135.2	158.3	518.3	835.8
131.2	682.3	798.5	274.1	225.4	615.3
852.1	324.1	755.2	687.7	624.4	741.5
877.6	243.2	376.5	738.4	231.5	581.9
393.6	148.3	717.4	317.7	734.4	332.5
721.9	116.6	803.6	312.5	778.6	674
161.7	600.9	640.2	339.5	348.4	366.8
453.2	341.7	544.6	424.3	658.2	169.9
533.9	561.5	477.2	619.6	588	247.9
191.7	499	406.4	126.2	408.4	305.8
809.6	599.5	579.8	258.2	505	704.3
825.9	831.8	693.2	725.2	587.6	432
862.5	794	268.9	898.9	120.7	397.1
181.8	155.5	413.1	552.8	702.1	880.4
668.5	164.4	439.7	100.5	196.6	470.8
422.6	297	277.9	689.2	630.7	359
531	890.3	509.2	486.4	200.4	676.2
264.4	346.8	288	303.7	840.3	523
819.6	329.6	466	646.4	652.4	251.7
764.2	515.1	282.4	773.5	403.8	570.3
488.5	419.9	526.8	895.5	715.9	558.2
805.7	147.7	383.6	354.1	372.8	846.4
289.3	788.4	368.7	756.3	542.1	761.6
749.6	744.9	207.5	252.2	768.1	849.6
606.5	431.9	311.4	873.4	857.2	495.1
294.5	822.8	865.4	814.3	115.2	111.7
710.1	500.7	391.7	537.8	444.6	609.8
195.3	143.2	363.3	887.4	137.7	215
871.8	666.8	730.7	481.2	323.4	
187.6	567.6	462.9	237.5	105.2	
172.3	176	639	216.5	233.4	
211.7	475.1	780.7	594	551	

Appendix C – Input files

The input files used for the simulations are presented below, the highlighted sections correspond to the variables that needed to be changed between each simulation.

C.1 FDS input file

The template file used for the actual simulation in FDS is presented below. Highlighted parts indicate were variable values were used.

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for Mesh14
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for Mesh14
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&TAIL /
```

C.2 Script file

The template script file below was used in order to submit computing jobs to LUNARC.

```
#!/bin/sh
# Request number of nodes
#PBS -l nodes=14
# Request of wall-clock time
#PBS -l walltime=10:00:00
# regular output (stdout) and terminal output (stderr)
#PBS -o stdout.txt
#PBS -e stderr.txt
# Send notification when job starts, finishes and aborts.
#PBS -m bea
# Mail address to send notifications
#PBS -M xxx@student.lth.se
cd $PBS_O_WORKDIR
# Enable modules and add software
. use_modules
module add intel/10.1
module add mpich-intel10/1.2.7p1
# Run on all nodes and create output for monitoring simulation progress
mpiexec /sw/pkg/brand/fds_5.3.1_lunarc_dt sy101.fds >regoutput.out
2>terminaloutput.err
```

Appendix D – Selected figures

The figures presented in this appendix are the selected variables in Table D.1 below. All other output distributions have a probability of visibility not exceeding 10 meters of either 1 or 0 and are therefore not presented.

TABLE D.1 Probability of visibility not exceeding 10 m for selected heights

Height (m)	Soot yield	Mass ext. coeff.	HRR	Simultaneous
0 – 1.1	0	0	0	0
1.2	0	0	0	0.075
1.3	0.195	0	0	0.24
1.4	0.745	0	0.24	0.65
1.5	0.99	1	0.7	0.955
1.6	1	1	0.965	0.995
1.7 – 2.5	1	1	1	1

D.1 Soot yield

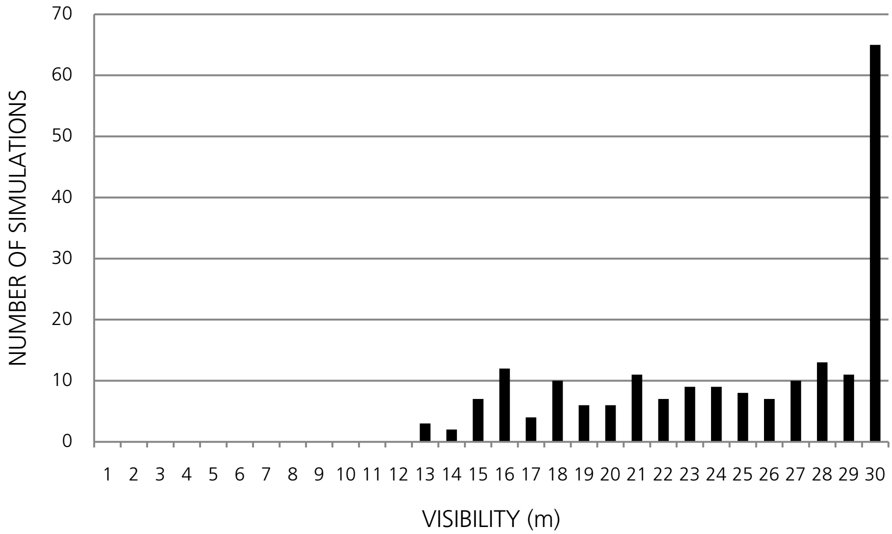

FIGURE D.1 Distribution of the visibility in the soot yield simulations at a height of 1.2 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0*.

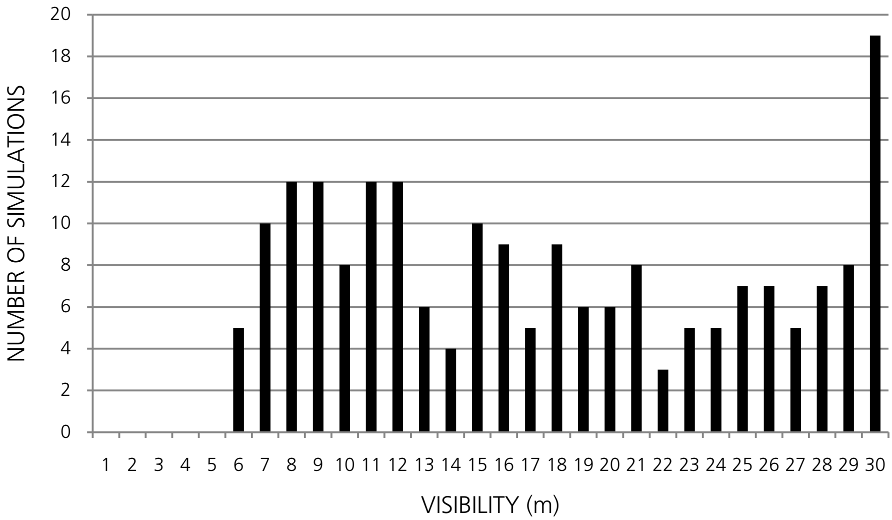

FIGURE D.2 Distribution of the visibility in the soot yield simulations at a height of 1.3 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.195*.

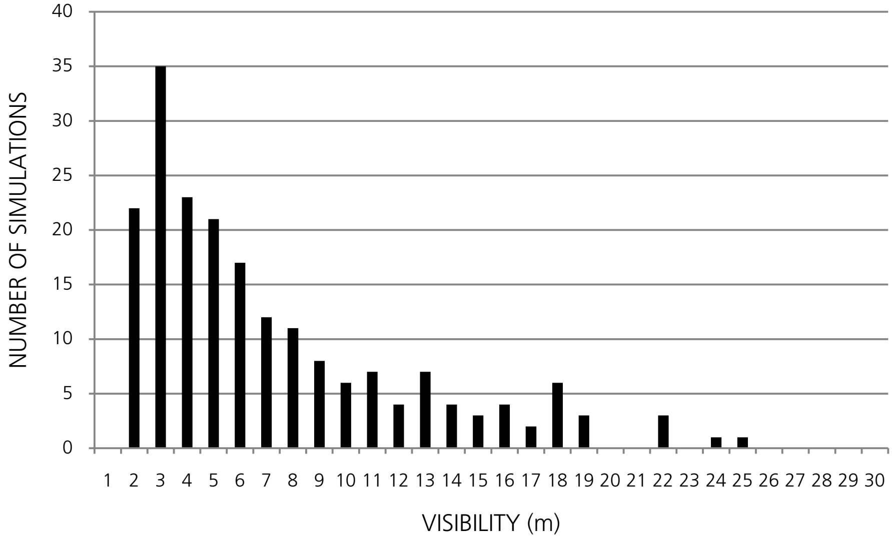

FIGURE D.3 Distribution of the visibility in the soot yield simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.745*.

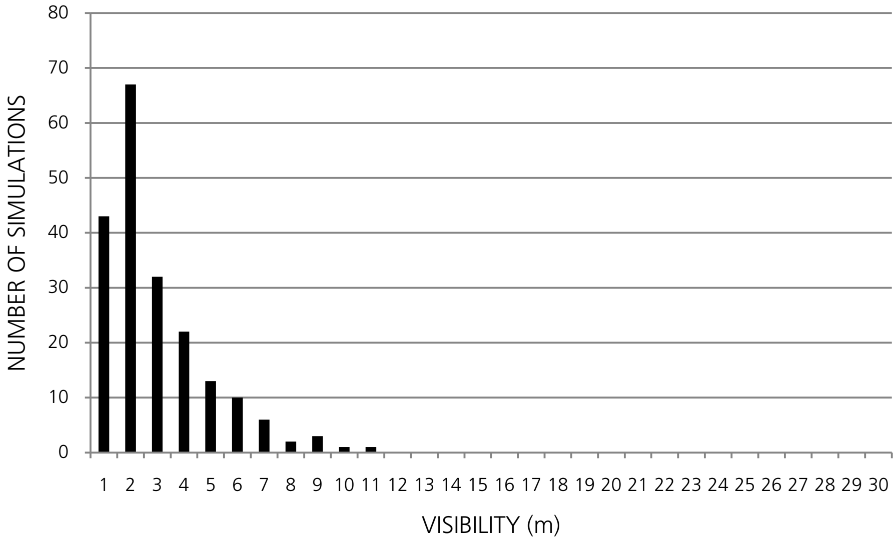

FIGURE D.4 Distribution of the visibility in the soot yield simulations at a height of 1.5 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.99*.

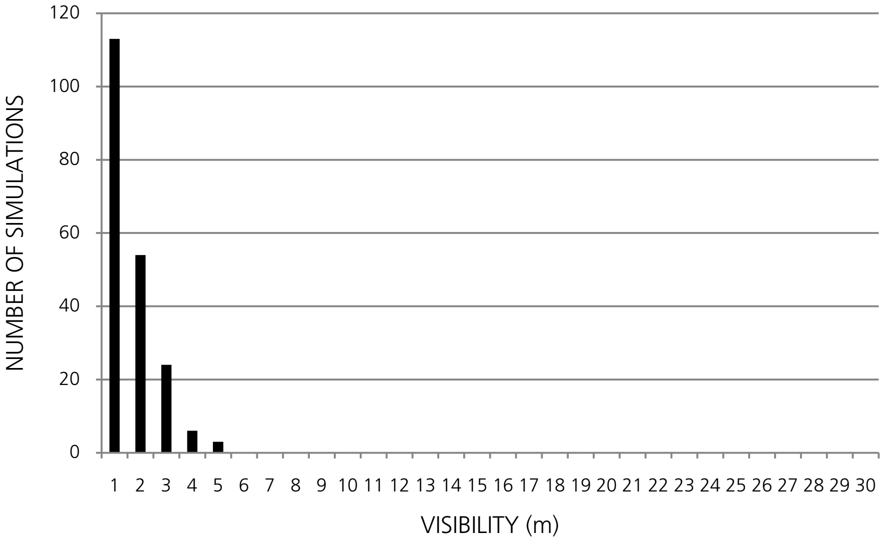

FIGURE D.5 Distribution of the visibility in the soot yield simulations at a height of 1.6 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 1*.

D.2 Mass extinction coefficient

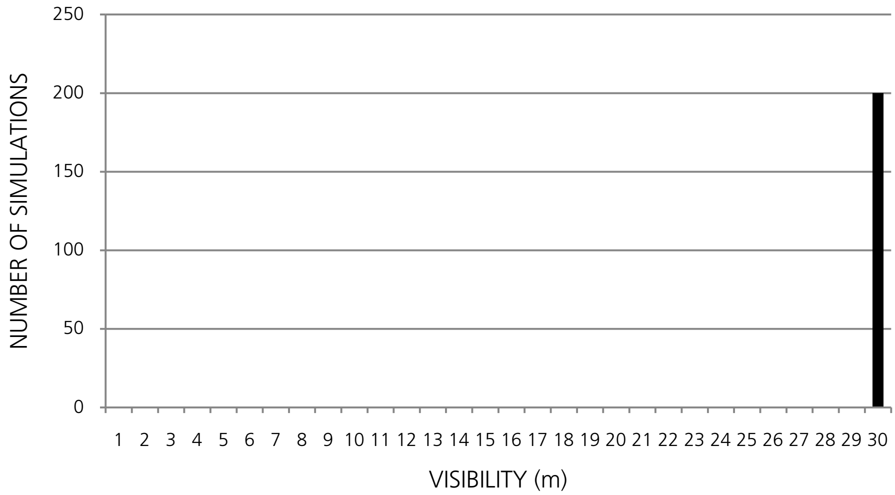

FIGURE D.6 Distribution of the visibility in the mass extinction coefficient simulations at a height of 1.2 meters. Y-axis is the number of simulations, X-axis is the visibility.
Pr(x<10) = 0.

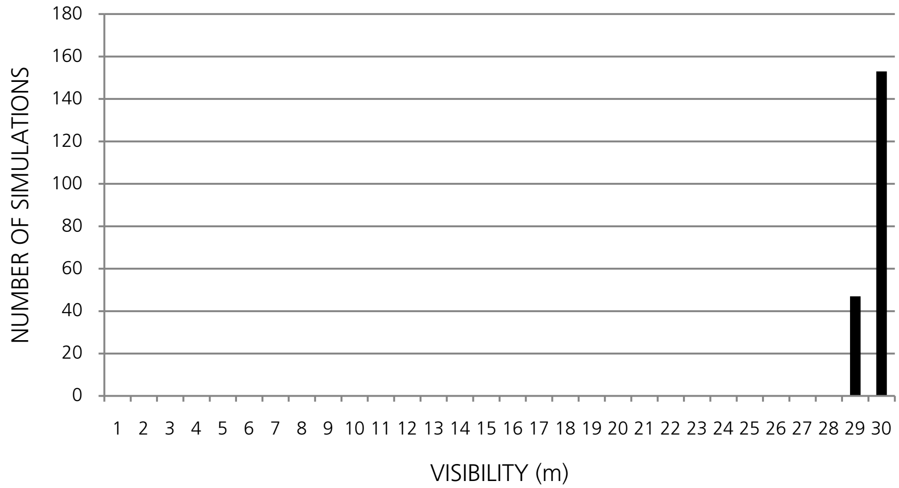

FIGURE D.7 Distribution of the visibility in the mass extinction coefficient simulations at a height of 1.3 meters. Y-axis is the number of simulations, X-axis is the visibility.
Pr(x<10) = 0.

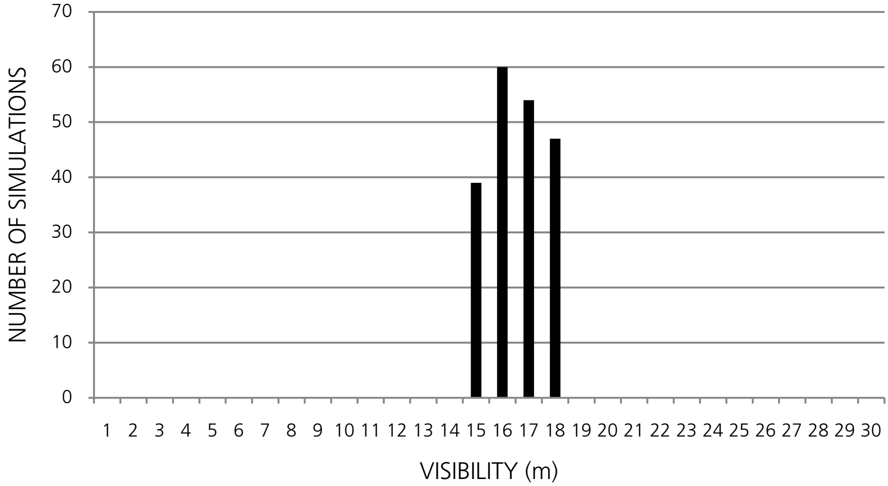

FIGURE D.8 Distribution of the visibility in the mass extinction coefficient simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0*.

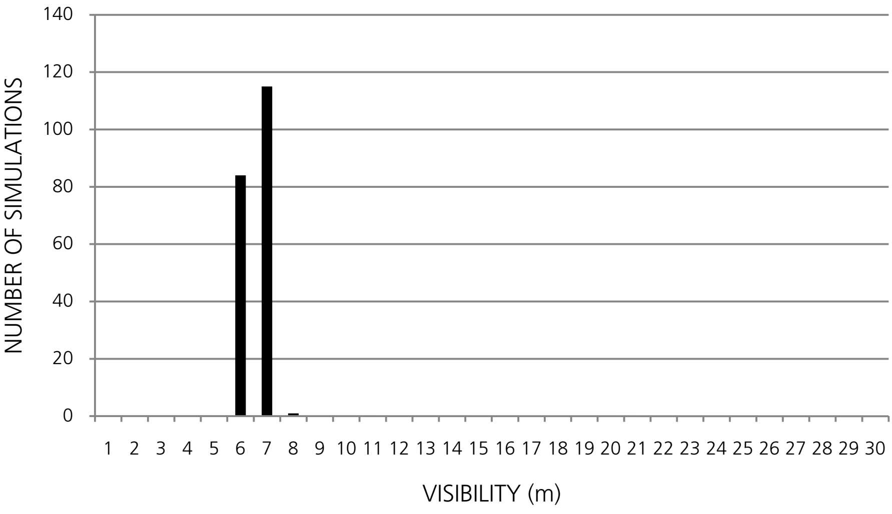

FIGURE D.9 Distribution of the visibility in the mass extinction coefficient simulations at a height of 1.5 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 1*.

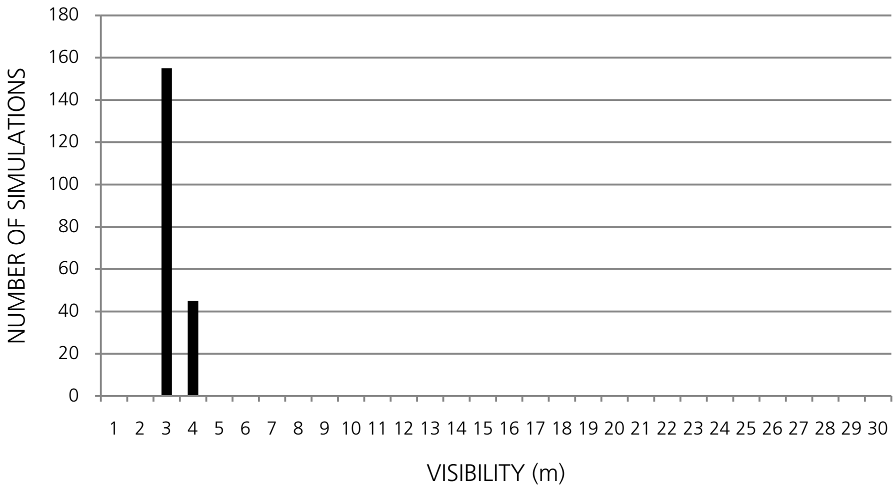

FIGURE D.10 Distribution of the visibility in the mass extinction coefficient simulations at a height of 1.6 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 1*.

D.3 HRR

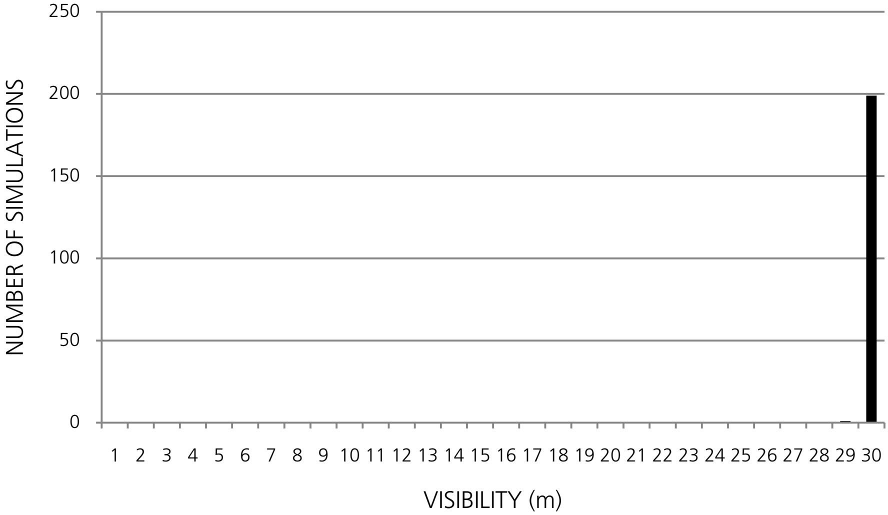

FIGURE D.11 Distribution of the visibility in the heat release rate simulations at a height of 1.2 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0*.

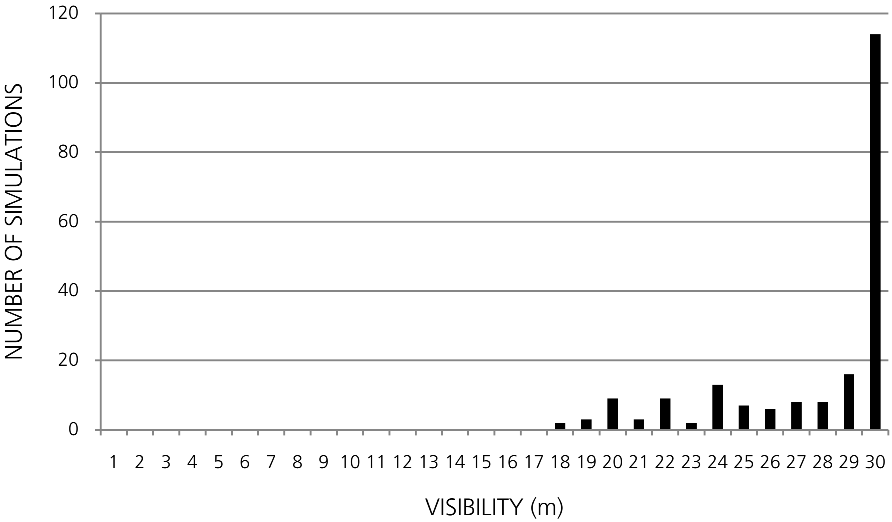

FIGURE D.12 Distribution of the visibility in the heat release rate simulations at a height of 1.3 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0*.

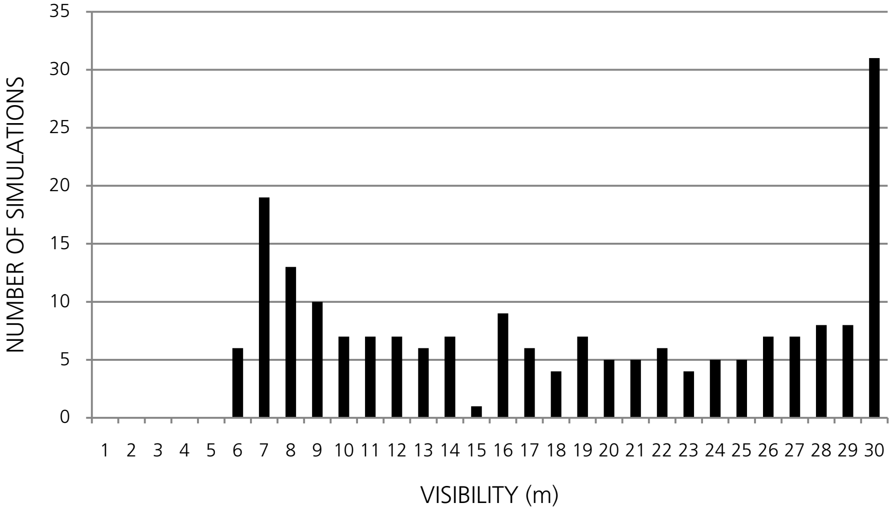

FIGURE D.13 Distribution of the visibility in the heat release rate simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.24*.

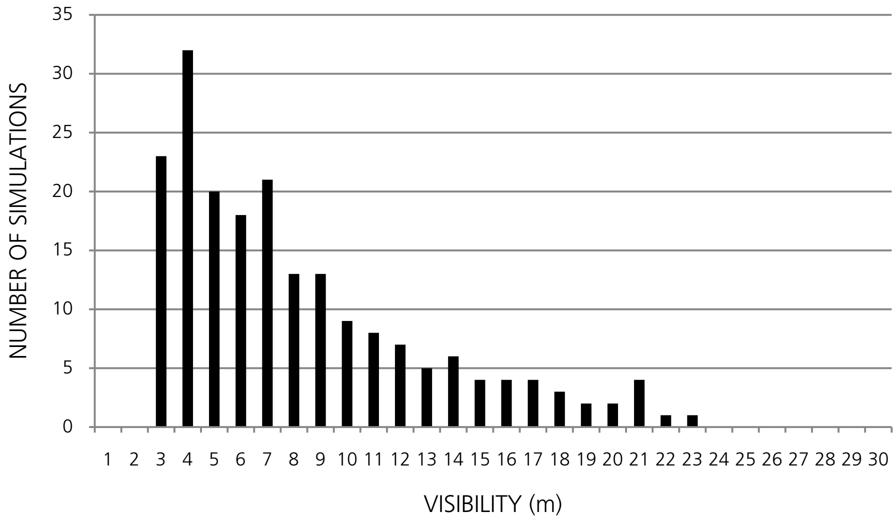

FIGURE D.14 Distribution of the visibility in the heat release rate simulations at a height of 1.5 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.7*.

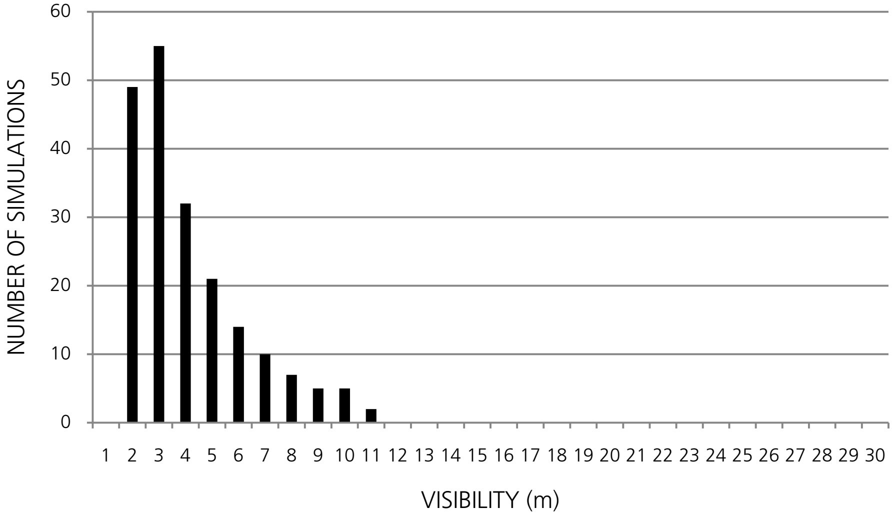

FIGURE D.15 Distribution of the visibility in the heat release rate simulations at a height of 1.6 meters. Y-axis is the number of simulations, X-axis is the visibility. Pr*(x<10) = 0.965*.

D.4 Simultaneous variables

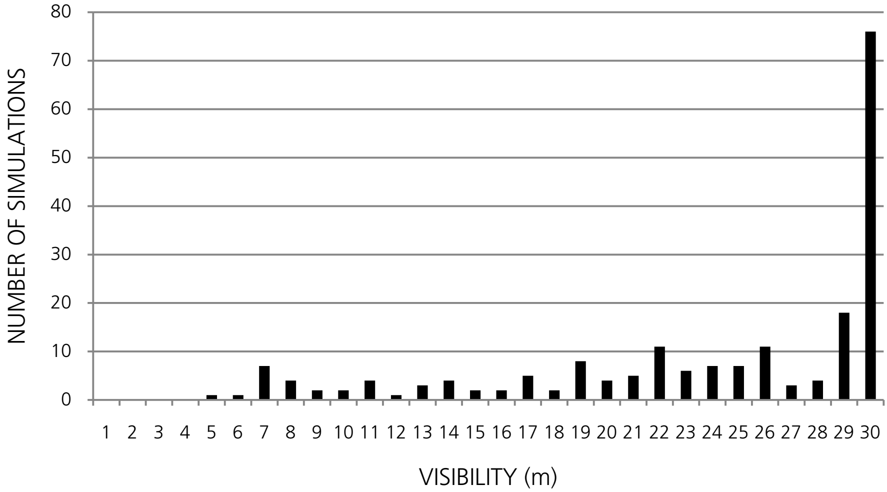

FIGURE D.16 Distribution of the visibility in the simultaneous variable simulations at a height of 1.2 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.075*.

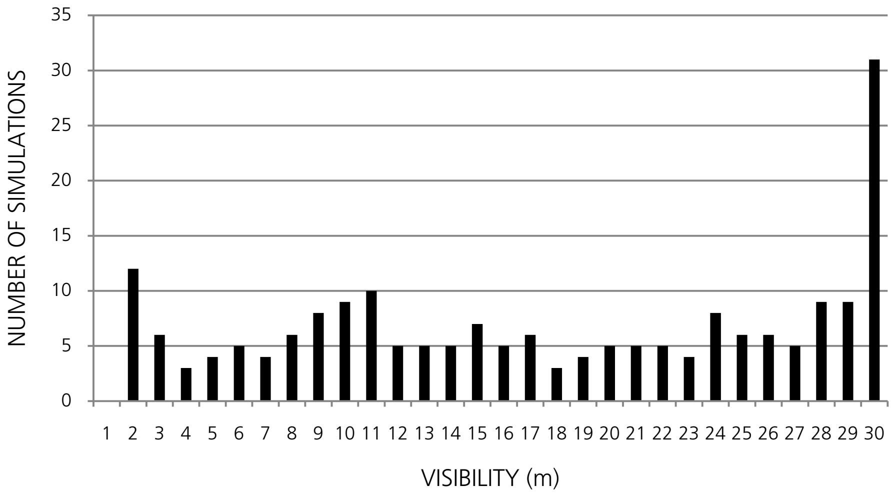

FIGURE D.17 Distribution of the visibility in the simultaneous variable simulations at a height of 1.3 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.24*.

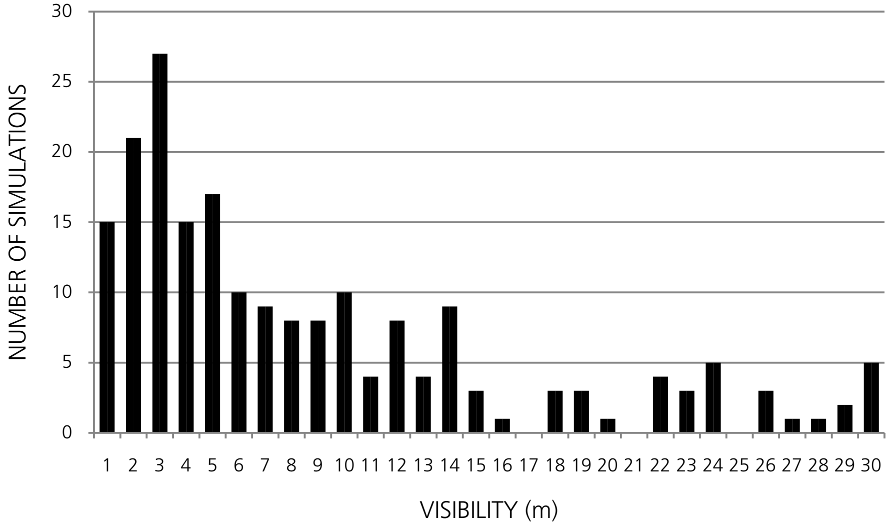

FIGURE D.18 Distribution of the visibility in the simultaneous variable simulations at a height of 1.4 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.65*.

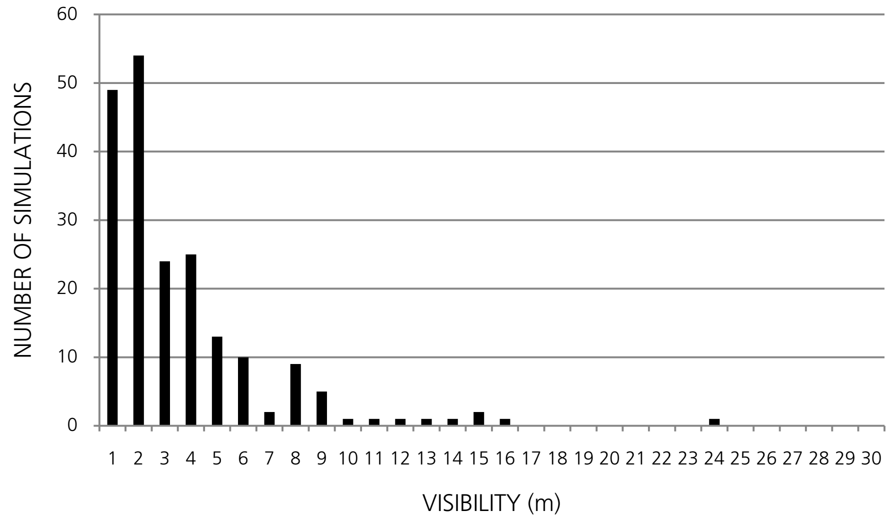

FIGURE D.19 Distribution of the visibility in the simultaneous variable simulations at a height of 1.5 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.955*.

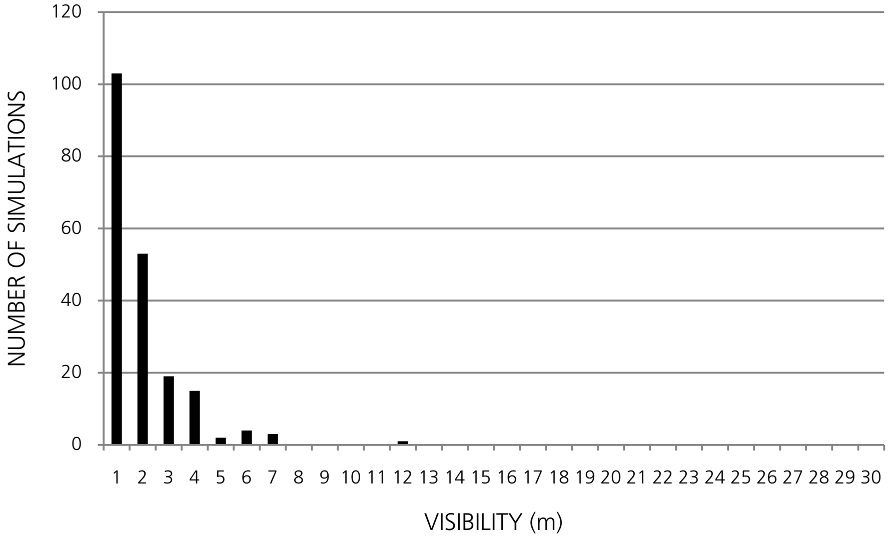

FIGURE D.20 Distribution of the visibility in the simultaneous variable simulations at a height of 1.6 meters. Y-axis is the number of simulations, X-axis is the visibility. *Pr(x<10) = 0.995*.

Appendix E – Output summary

This appendix presents the number of simulations resulting in a certain visibility at a given height.

E.1 Soot yield

H(m)[a] / V (m)[b]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	3
14	0	0	0	0	0	0	0	0	0	0	0	2
15	0	0	0	0	0	0	0	0	0	0	0	7
16	0	0	0	0	0	0	0	0	0	0	0	12
17	0	0	0	0	0	0	0	0	0	0	0	4
18	0	0	0	0	0	0	0	0	0	0	0	10
19	0	0	0	0	0	0	0	0	0	0	1	6
20	0	0	0	0	0	0	0	0	0	0	3	6
21	0	0	0	0	0	0	0	0	0	0	4	11
22	0	0	0	0	0	0	0	0	0	0	10	7
23	0	0	0	0	0	0	0	0	0	2	8	9
24	0	0	0	0	0	0	0	0	0	4	9	9
25	0	0	0	0	0	0	0	0	2	9	5	8
26	0	0	0	0	0	0	0	1	5	8	17	7
27	0	0	0	0	0	0	1	4	9	14	8	10
28	0	0	0	0	0	0	5	8	13	14	17	13
29	0	0	0	0	1	6	14	19	20	21	18	11
30	200	200	200	200	199	194	180	168	151	128	100	65

[a]Height above floor
[b]Visibility

H(m)[a] / V (m)[b]	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5
1	0	0	43	113	138	148	155	161	166	170	171	175	175
2	0	22	67	54	49	44	40	36	32	29	28	25	25
3	0	35	32	24	12	8	5	3	2	1	1	0	0
4	0	23	22	6	1	0	0	0	0	0	0	0	0
5	0	21	13	3	0	0	0	0	0	0	0	0	0
6	5	17	10	0	0	0	0	0	0	0	0	0	0
7	10	12	6	0	0	0	0	0	0	0	0	0	0
8	12	11	2	0	0	0	0	0	0	0	0	0	0
9	12	8	3	0	0	0	0	0	0	0	0	0	0
10	8	6	1	0	0	0	0	0	0	0	0	0	0
11	12	7	1	0	0	0	0	0	0	0	0	0	0
12	12	4	0	0	0	0	0	0	0	0	0	0	0
13	6	7	0	0	0	0	0	0	0	0	0	0	0
14	4	4	0	0	0	0	0	0	0	0	0	0	0
15	10	3	0	0	0	0	0	0	0	0	0	0	0
16	9	4	0	0	0	0	0	0	0	0	0	0	0
17	5	2	0	0	0	0	0	0	0	0	0	0	0
18	9	6	0	0	0	0	0	0	0	0	0	0	0
19	6	3	0	0	0	0	0	0	0	0	0	0	0
20	6	0	0	0	0	0	0	0	0	0	0	0	0
21	8	0	0	0	0	0	0	0	0	0	0	0	0
22	3	3	0	0	0	0	0	0	0	0	0	0	0
23	5	0	0	0	0	0	0	0	0	0	0	0	0
24	5	1	0	0	0	0	0	0	0	0	0	0	0
25	7	1	0	0	0	0	0	0	0	0	0	0	0
26	7	0	0	0	0	0	0	0	0	0	0	0	0
27	5	0	0	0	0	0	0	0	0	0	0	0	0
28	7	0	0	0	0	0	0	0	0	0	0	0	0
29	8	0	0	0	0	0	0	0	0	0	0	0	0
30	19	0	0	0	0	0	0	0	0	0	0	0	0

[a]Height above floor
[b]Visibility

E.2 Mass extinction coefficient

H(m)[a] / V (m)[b]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0
30	200	200	200	200	200	200	200	200	200	200	200	200

[a]Height above floor
[b]Visibility

H(m)[a] V (m)[b]	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	64	154	200	200	200	200	200	200	200
3	0	0	0	155	136	46	0	0	0	0	0	0	0
4	0	0	0	45	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	84	0	0	0	0	0	0	0	0	0	0
7	0	0	115	0	0	0	0	0	0	0	0	0	0
8	0	0	1	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	39	0	0	0	0	0	0	0	0	0	0	0
16	0	60	0	0	0	0	0	0	0	0	0	0	0
17	0	54	0	0	0	0	0	0	0	0	0	0	0
18	0	47	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0
29	47	0	0	0	0	0	0	0	0	0	0	0	0
30	153	0	0	0	0	0	0	0	0	0	0	0	0

[a]Height above floor
[b]Visibility

E.3 HRR

V (m)[b] \ H(m)[a]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	1
30	200	200	200	200	200	200	200	200	200	200	200	199

[a]Height above floor
[b]Visibility

V (m)[b] \ H(m)[a]	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5
1	0	0	0	0	0	0	0	0	0	5	9	33	33
2	0	0	0	49	88	113	130	141	150	152	151	134	134
3	0	0	23	55	62	53	44	39	36	33	32	28	28
4	0	0	32	32	25	20	19	18	14	10	8	5	5
5	0	0	20	21	14	11	7	2	0	0	0	0	0
6	0	6	18	14	9	3	0	0	0	0	0	0	0
7	0	19	21	10	2	0	0	0	0	0	0	0	0
8	0	13	13	7	0	0	0	0	0	0	0	0	0
9	0	10	13	5	0	0	0	0	0	0	0	0	0
10	0	7	9	5	0	0	0	0	0	0	0	0	0
11	0	7	8	2	0	0	0	0	0	0	0	0	0
12	0	7	7	0	0	0	0	0	0	0	0	0	0
13	0	6	5	0	0	0	0	0	0	0	0	0	0
14	0	7	6	0	0	0	0	0	0	0	0	0	0
15	0	1	4	0	0	0	0	0	0	0	0	0	0
16	0	9	4	0	0	0	0	0	0	0	0	0	0
17	0	6	4	0	0	0	0	0	0	0	0	0	0
18	2	4	3	0	0	0	0	0	0	0	0	0	0
19	3	7	2	0	0	0	0	0	0	0	0	0	0
20	9	5	2	0	0	0	0	0	0	0	0	0	0
21	3	5	4	0	0	0	0	0	0	0	0	0	0
22	9	6	1	0	0	0	0	0	0	0	0	0	0
23	2	4	1	0	0	0	0	0	0	0	0	0	0
24	13	5	0	0	0	0	0	0	0	0	0	0	0
25	7	5	0	0	0	0	0	0	0	0	0	0	0
26	6	7	0	0	0	0	0	0	0	0	0	0	0
27	8	7	0	0	0	0	0	0	0	0	0	0	0
28	8	8	0	0	0	0	0	0	0	0	0	0	0
29	16	8	0	0	0	0	0	0	0	0	0	0	0
30	114	31	0	0	0	0	0	0	0	0	0	0	0

[a]Height above floor
[b]Visibility

E.4 Simultaneous variables

H(m)[a] / V (m)[b]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	1
6	0	0	0	0	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	0	0	0	0	7
8	0	0	0	0	0	0	0	0	0	0	0	4
9	0	0	0	0	0	0	0	0	0	0	0	2
10	0	0	0	0	0	0	0	0	0	0	0	2
11	0	0	0	0	0	0	0	0	0	0	1	4
12	0	0	0	0	0	0	0	0	0	0	0	1
13	0	0	0	0	0	0	0	0	0	0	1	3
14	0	0	0	0	0	0	0	0	0	0	4	4
15	0	0	0	0	0	0	0	0	0	0	3	2
16	0	0	0	0	0	0	0	0	0	1	1	2
17	0	0	0	0	0	0	0	0	0	1	5	5
18	0	0	0	0	0	0	0	0	0	0	0	2
19	0	0	0	0	0	0	0	0	0	0	5	8
20	0	0	0	0	0	0	0	0	0	2	5	4
21	0	0	0	0	0	0	0	0	2	5	2	5
22	0	0	0	0	0	0	0	0	0	0	3	11
23	0	0	0	0	0	0	0	0	2	5	4	6
24	0	0	0	0	0	0	0	2	1	9	2	7
25	0	0	0	0	0	0	0	2	6	4	4	7
26	0	0	0	0	0	0	3	2	4	4	12	11
27	0	0	0	0	0	3	2	7	11	3	12	3
28	0	0	0	0	3	3	8	9	7	12	13	4
29	0	0	2	4	7	9	14	11	12	23	20	18
30	200	200	198	196	190	185	173	167	155	131	103	76

[a]Height above floor
[b]Visibility

V (m)[b] \ H(m)[a]	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	2.4	2.5
1	0	15	49	103	123	136	146	149	159	160	160	163	163
2	12	21	54	53	52	48	43	41	33	33	34	32	32
3	6	27	24	19	17	11	7	9	7	6	5	4	4
4	3	15	25	15	4	4	3	0	0	0	1	1	1
5	4	17	13	2	3	0	0	1	1	1	0	0	0
6	5	10	10	4	0	1	1	0	0	0	0	0	0
7	4	9	2	3	1	0	0	0	0	0	0	0	0
8	6	8	9	0	0	0	0	0	0	0	0	0	0
9	8	8	5	0	0	0	0	0	0	0	0	0	0
10	9	10	1	0	0	0	0	0	0	0	0	0	0
11	10	4	1	0	0	0	0	0	0	0	0	0	0
12	5	8	1	1	0	0	0	0	0	0	0	0	0
13	5	4	1	0	0	0	0	0	0	0	0	0	0
14	5	9	1	0	0	0	0	0	0	0	0	0	0
15	7	3	2	0	0	0	0	0	0	0	0	0	0
16	5	1	1	0	0	0	0	0	0	0	0	0	0
17	6	0	0	0	0	0	0	0	0	0	0	0	0
18	3	3	0	0	0	0	0	0	0	0	0	0	0
19	4	3	0	0	0	0	0	0	0	0	0	0	0
20	5	1	0	0	0	0	0	0	0	0	0	0	0
21	5	0	0	0	0	0	0	0	0	0	0	0	0
22	5	4	0	0	0	0	0	0	0	0	0	0	0
23	4	3	0	0	0	0	0	0	0	0	0	0	0
24	8	5	1	0	0	0	0	0	0	0	0	0	0
25	6	0	0	0	0	0	0	0	0	0	0	0	0
26	6	3	0	0	0	0	0	0	0	0	0	0	0
27	5	1	0	0	0	0	0	0	0	0	0	0	0
28	9	1	0	0	0	0	0	0	0	0	0	0	0
29	9	2	0	0	0	0	0	0	0	0	0	0	0
30	31	5	0	0	0	0	0	0	0	0	0	0	0

[a]Height above floor
[b]Visibility