SCOPING STUDY ON THE SIGNIFICANCE OF MESH RESOLUTION VS. SCENARIO UNCERTAINTY IN THE CFD MODELLING OF RESIDENTIAL SMOKE CONTROL SYSTEMS

Danny Hopkin, Charlie Hopkin & Michael Spearpoint, OFR Consultants, UK
Ben Ralph, Foster + Partners, UK
Ruben Van Coile, Ghent University, BE

ABSTRACT

Computational fluid dynamics (CFD) modelling is a commonly applied tool adopted to support the specification and design of common corridor ventilation systems in UK residential buildings. Inputs for the CFD modelling of common corridor ventilation systems are typically premised on a ‘reasonable worst case’, i.e. no specific uncertainty quantification process is undertaken to evaluate the safety level. As such, where the performance of a specific design sits on a probability spectrum is not defined. Furthermore, mesh cell sizes adopted are typically c. 100 – 200 mm. For a large eddy simulation (LES) based CFD code, this is considered coarse for this application and creates a further uncertainty in respect of capturing key behaviours in the CFD model. Both co-existing practices summarised above create uncertainty, either due to parameter choice or the (computational fire and smoke) model. What is not clear is the relative importance of these uncertainties.

This paper summarises a scoping study that subjects the noted common corridor CFD application to a probabilistic risk assessment (PRA), using the MaxEnt method. The uncertainty associated with the performance of a reference design is considered at different grid scales (achieving different ‘a posteriori’ mesh quality indicators), with the aim of quantifying the relative importance of uncertainties associated with inputs and scenarios, vs. the fidelity of the CFD model. For the specific case considered herein, it is found that parameter uncertainty has a more significant impact on the confidence of a given design solution relative to that arising from grid resolution, for grid sizes of 100 mm or less. Above this grid resolution, it was found that uncertainty associated with the model dictates. Given the specific ventilation arrangement modelled in this work care should be undertaken in generalising such conclusions.

INTRODUCTION

Computational fluid dynamics (CFD) modelling is a commonly applied tool adopted to support the specification and design of common corridor ventilation systems in UK residential buildings, particularly those served by a single stair and / or featuring travelling distances that deviate from standard guidance (e.g. Approved Document B[1]). NIST’s Fire Dynamics Simulator[2] (FDS) is the de-facto tool applied by most within the fire engineering consultancy community to address this design challenge. FDS is a large-eddy simulation (LES) code for low-speed flows, with an emphasis on smoke and heat transport from fires. Due to its computational expense, a limited number of CFD simulations are completed to evaluate a given project and on the premise of defining a ‘reasonable worst case’. Where the worst case sits on a spectrum of possibilities is not typically evaluated. Also, aligned to computational demand, it is common for fire engineering consultants to operate at grid sizes of the order of 100 mm. Both co-existing practices create uncertainty, either due to parameter choice or the formulation of the model. What is not clear is the relative importance of these uncertainties. The objective of the scoping study is, therefore, to provisionally evaluate if priority should be given to further evaluating the impact of uncertainties in scenarios and parameters, versus improving model fidelity (i.e. refined grid resolutions), and under what circumstances.

UNCERTAINTY QUANTIFICATION IN FIRE SAFETY ENGINEERING (FSE)

Performance-based design (PBD) has gained significant traction as a means of satisfying statutory fire safety requirements, often in a more efficient manner, and with greater confidence when compared to prescriptive design. Traditional performance based fire safety design is deterministic in nature, requiring the selection of design inputs, scenarios, and performance criteria that are deemed appropriately conservative by the engineer. In such a process, the safety level associated with a given design is not evaluated as the full spectrum of consequences and their associated probabilities are not interrogated. Instead, it is assumed that an adequate, but unquantified, level of safety is attained based upon engineering judgement and on the pretence that: (a) real fire events have occurred, with performance observed; and (b) that society has not expressed dissatisfaction with the levels of performance witnessed. That is, the basis for acceptance of traditional performance-based design (or the safety foundation) is the experience of the fire safety profession, as proposed in Hopkin, et al.[3], and Van Coile, et al.[4].

Logically, this safety foundation can only be justified where there are sufficient real fire events to observe and guide design processes, which also offer society the opportunity to express views on their dissatisfaction (or otherwise) of the consequences witnessed. However, traditional fire safety design, and its associated safety foundation cannot be extrapolated to exceptional buildings, those with atypical consequences of failure, nor those adopting innovative materials, as it is likely that insufficient instances exist where fires have occurred and performance witnessed. For such complex cases, there is a need to explicitly evaluate the residual risk. This is only readily possible through probabilistic methods and creates technical challenges.

The generating of an unbiased estimation of the distribution (probability density function [PDF]) of an output variable from a model has typically required a very high number of model realisations, e.g. Monte Carlo simulations (MCS). In conflict, many fire engineering challenges are evaluated using computationally expensive models, such as CFD models for the quantification of fire and smoke spread, finite element models (FEM) for structural response and computational evacuation models (CEM) for occupant movement. CFD, in particular, does not lend itself to uncertainty quantification through traditional MCS based methods as each iteration can have a substantial simulation run time. For this reason, methods are been developed and employed, such as the MaxEnt procedure proposed in Van Coile, et al.[5], and Response Surface Modelling (RSM) as applied in Van Weyenberge, et al.[6]. The MaxEnt procedure, as adopted and discussed further herein, has already been successfully applied in the response of fire exposed structures, evaluated using finite element (FE) models[7].

CFD MODELLING AND COMMON CORRIDOR VENTILATION SYSTEMS

Under UK fire safety guidance for residential design, such as Approved Document B Volume 2 and BS 9991:2015[8], common corridors in multi-unit apartment buildings typically incorporate a means of natural ventilation as to minimise ingress of smoke into the stair during firefighting operations. Such systems are considered reasonable when corridor travel distances for single direction of travel are limited to either 7.5 m or 15 m (depending on the adopted guidance document and whether sprinkler protection is provided). These systems, in the form of either a natural shaft or an automatically openable vent (AOV) located within the corridor, are shown to provide a benefit, albeit limited, to corridor smoke clearance, often resulting in a prolonged period for the corridor to eventually clear[10]. Mechanical ventilation can be adopted when either the natural provisions recommended in guidance are not architecturally feasible or when travel distances within the common corridor extend beyond guidance recommendations. In the case of the latter, a fire and smoke modelling assessment, usually adopting CFD modelling tools, is typical. BS 9991 notes that the primary objective of this assessment is to “return the extended corridor and the associated stair enclosure to tenable conditions for means of escape and rescue purposes”. The expectation of returning the corridor to tenable conditions commonly results in mechanical ventilation systems which provide both a means of inlet and exhaust within the corridor. BS 9991 also refers to the Smoke Control Association (SCA) guidance[9] on smoke control to common escape routes in apartment buildings for further information on how to carry out an assessment.

The SCA Guide recommends that the CFD assessment consider two phases: means of escape and firefighting. The means of escape phase considers the development of a fire within an apartment and the initial occupant escape from this apartment, where the door to the apartment opens and smoke enters the common corridor for a brief door opening period (described as "generally…between 10 s and 20 s"). Once this occurs the ventilation system is expected to clear the corridor of smoke within a timeframe of "two to three minutes". For the firefighting phase, the assessment considers both firefighter tenability and the potential for smoke to enter the stair, where for a length of time both the apartment door and stair door are open with a fully developed fire in the apartment. In protecting the stair, BS 9991 notes that "provisions are necessary to ensure that the stairway(s) remain relatively free from smoke and heat". However, for the purpose of this paper, only the means of escape phase has been considered as this is the primary phase concerning life safety and also provides for a well-defined performance metric (corridor smoke clearance time – discussed later).

POST-SIMULATION MESH QUALITY METRICS

The quality of a CFD simulation is typically related directly to mesh resolution. A range of mesh quality metrics have been developed in an attempt to quantify errors in vector and scalar fields output by simulation.

Non-dimensional wall distance (y^+)

The adopted LES model uses a wall function to capture the near-wall flow structure, where viscous stresses are dominant over Reynolds stresses. The validity of this sub-model is dependent upon the distance between the wall and the computed velocity and therefore upon the grid resolution near the wall. Hence, the distance between the wall and the nearest resolved velocity vector is useful for verifying the validity of the wall function. To enable comparison of this distance across a range of cases, it is further useful to non-dimensionalise this parameter by a suitable length scale. Thusly, the non-dimensional distance from the wall, expressed in viscous lengths or 'wall units', is given by:

$$y^+ = \frac{y}{\max(\delta_V, s)} = \frac{\delta n/2}{\max(\delta_V, s)}$$

where δn is the wall-normal cell dimension, δ_V is the local viscous length scale, and s is the sand grain roughness for rough walls. The halving of the wall-normal cell dimension appears because, for the adopted fire model, the velocity is located at the centre of the cell face. The local viscous length scale is defined as[11]:

$$\delta_V = \frac{\mu/\rho}{u_\tau}$$

where μ is the viscosity of the fluid, ρ is the density, and u_τ is the friction velocity, defined as[11]:

$$u_\tau = \sqrt{\tau_w/\rho}$$

where τ_w is the viscous stress evaluated at the wall. The viscous stress at the wall is modelled by the wall function as:

$$\tau_w = \mu \frac{\partial |\boldsymbol{u}|}{\partial n}$$

where $|\boldsymbol{u}|$ is an estimate of the streamwise velocity component near the wall.

A target value for the non-dimensional distance from the wall of $y^+ = \mathcal{O}(100)$ is typically taken as being suitable for engineering LES applications[2]. Values of $y^+ > 1000$ are likely to be outside of the log layer and within the wake region and this would be expected to output highly uncertain results.

A weakness of this mesh quality metric is that wall functions are still under active development. Hence, it is difficult to set target metric values. General guidelines for wall functions in LES is that the first grid cell is within the log layer of the boundary layer[2]. However, a reliable method to define the log region for transient flows has not been established.

Wavelet error measure (WEM)

High variation or step functioning of an output quantity through a low number of consecutive cells can be an indicator of spurious variations or unresolved turbulence-induced fluid flow. Therefore, measurement of the magnitude of such phenomena can be used as a mesh resolution metric. This can be achieved by carrying out error analysis of a Haar[12] wavelet transform of output quantity data along a linear line of cells. A wavelet transform is analogous to a Fourier transform; but instead of a frequency domain decomposition, it uses a wavelet domain decomposition. A full description of wavelet transformations is outside of the scope of this paper; but the interested reader is referred to Schneider and Vasilyev[13].

Error analysis can be carried out on a Haar wavelet transform of output data captured in three spatial dimensions for two cells beyond the target cell in both directions. The errors are normalised against a step function. The maximum normalised value of this error in the three spatial dimensions is defined as the wavelet error measure (WEM). In this manner, a straight line gives a WEM of 0, a step function gives a WEM of 1 (by definition), and a triangle signal gives a WEM of 2. Based upon McDermott et al.[14] current good practice guidance is to maintain an average value of WEM of less than 0.5.

Measure of turbulence resolution (MTR)

The measure of turbulence resolution is a scalar quantity which is defined for a steady or quasi-steady state flow as:

$$M = \frac{\langle k_{sgs} \rangle}{\langle \mathrm{TKE} \rangle + \langle k_{sgs} \rangle}$$

where angled brackets denote suitable time-average values, k_{sgs} is the subgrid kinetic energy and TKE is the turbulent kinetic energy. The physical meaning of M is the proportion of kinetic energy in the flow field which is modelled using subgrid models. The value of subgrid kinetic energy can be estimated using the Deardorff turbulent viscosity model as[2]:

$$k_{sgs} \approx \left(\frac{\mu_t}{\rho C_v \Delta} \right)^2$$

where μ_t is the turbulent viscosity, C_V is the model constant (adopted as 0.1 from the literature[11]), and Δ is the filter width ($(\delta x \delta y \delta z)^{1/3}$). The time-dependent turbulent kinetic energy is output as the variance, or mean square error, between the velocity components and the time-averaged mean velocity components:

$$\mathrm{TKE} = \frac{1}{2}\left((\tilde{u} - \langle \tilde{u} \rangle)^2 + (\tilde{v} - \langle \tilde{v} \rangle)^2 + (\tilde{w} - \langle \tilde{w} \rangle)^2 \right)$$

where $\tilde{u}$, $\tilde{v}$ and $\tilde{w}$ are the resolved LES velocity components.

Pope[11] defines LES as $M < 0.2$ for canonical cases of isotropic turbulence and McDermott et al.[14] demonstrates that $M \cong 0.2$ provide numerical results within experimental uncertainties for a non-reacting buoyant plume. This value of M represents 80% of kinetic energy being resolved on the mesh.

STUDY DESIGN

Objective and methodology overview

The scoping study undertaken has been conceived to seek to understand the relative importance of model uncertainty versus scenario / parameter uncertainty when applied to the common application of CFD modelling in UK fire engineering practice, i.e. residential common corridor ventilation appraisals. In this paper, model uncertainty concerns the CFD approximation of the problem, with specific emphasis on the impact of mesh resolution and its role in boundary layer behaviours, turbulence resolution and heat transfer.

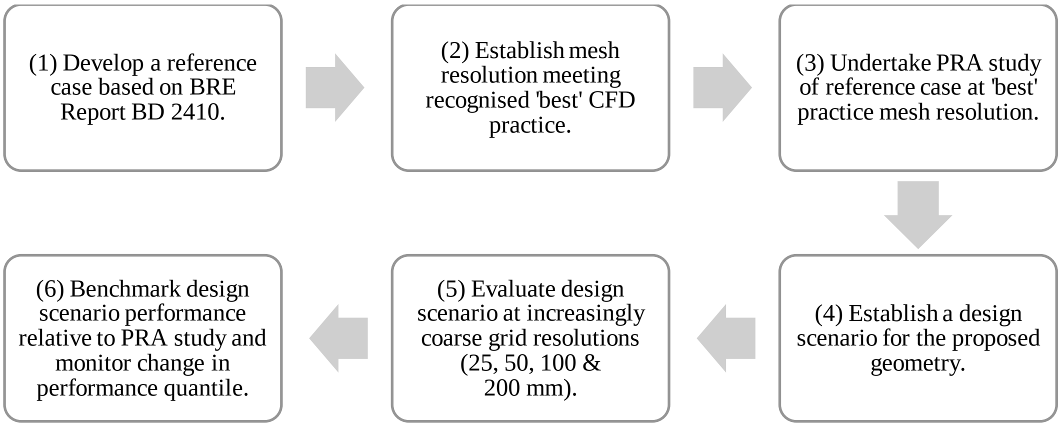


Figure 1. Overview of study methodology

Model geometry, ventilation systems and bounding surfaces

Figure 1 provides an overview of the study methodology. Each step is elaborated upon in the sections that follow. Step (1) in concerns the definition of an appropriate reference case. For this, a corridor layout aligned with that used in BRE report BD 2410[10] is adopted – see Figure 2. This comprises an apartment and a common access corridor (18 m in length). At one end of the corridor there is mechanical exhaust vent of 0.8 × 0.8 m and volumetric flow rate of 3.0 m^3/s. At the opposing end, there is a natural ventilator of 0.8 × 1.2 m. Both the natural ventilator and the exhaust vent operate upon activation of a smoke detector located centrally in the corridor. The exhaust ramps to the target volume flow rate over a 30 s duration, adopting a t-squared growth profile. Adjoining the corridor is a room intended to mimic a studio apartment. The room is 5 × 5 m on plan, with a low-level 2 × 1.4 m opening to outside to allow for provision of oxygen to sustain fire development. The corridor and room connect via an opening 0.8 × 2.0 m, representing a door. All floor to ceiling heights are 2.2 m. All walls are assigned thermo-physical properties consistent with that expected for plasterboard. Floors and ceilings adopt thermo-physical properties consistent with concrete. The geometry is divided into 4 meshes (for computational efficiency; all adopting the same cell size). The mesh is extended beyond openings into the fire compartment, with boundaries defined as ‘open’. Further elaboration on inputs is provided later in the paper.

A PRIORI ANALYSIS – BENCHMARKING AGAINST MESH QUALITY METRICS

Step (2) in Figure 1 concerns a series of provisional steady-state analyses which were conducted at differing mesh resolutions to establish cell sizes that might be considered best practice. This was through review of post-simulation mesh quality indicators (MQIs) as have been introduced previously (y+, WEM and MTR).

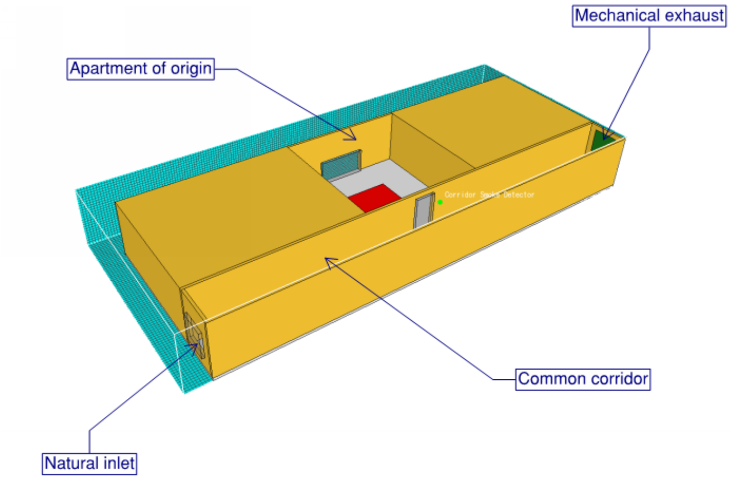


Figure 2. Reference model geometry

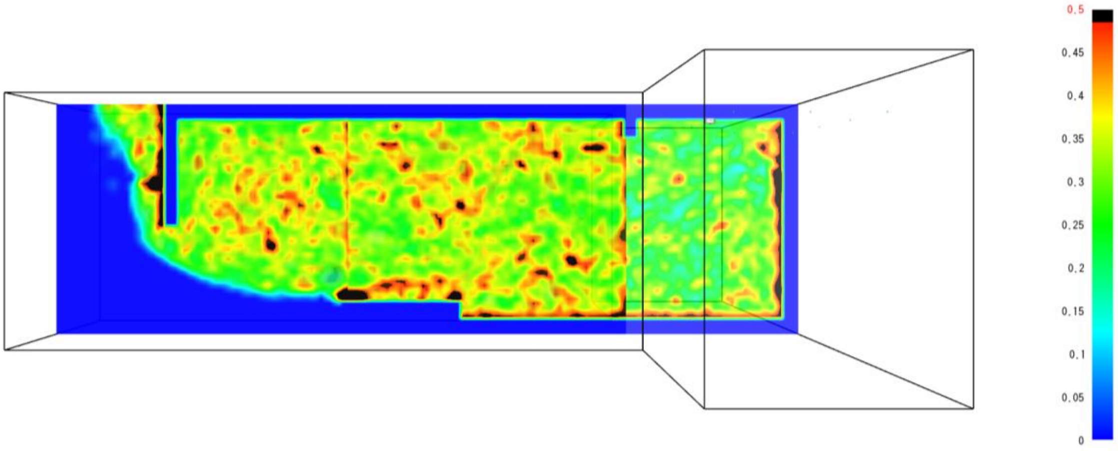
For the steady-state analyses, the door to the studio apartment was held open (i.e. no opening delay), with the ventilation system (forced exhaust and natural supply) fully operational. The fire size adopted was 2 MW, which might be broadly representative of the onset of fire service intervention (note: BD 2410 adopts 2.5 MW for the same purpose). Simulations were conducted at increasingly refined mesh resolutions, starting at 200 mm ($D^*/dx = 6.3$), decreasing through 100 mm ($D^*/dx = 12.7$), and 50 mm ($D^*/dx = 25.3$). MQIs were reviewed at each resolution interval to establish if a suitable resolution had been obtained. In the case of WEM, the soot mass fraction was monitored. This is because an output PDF in the PRA assessment for time taken for corridor visibility to return to 'tenable' conditions was sought. This is discussed further in the following sections.

Figure 3 (a) shows a contour slice of soot mass fraction WEM, (b) shows the y+ boundary contours, and (c) shows the MTR as computed through the centreline of the fire in the room of origin. All results relate to a cell size of 50 mm. The MTR is averaged at each coordinate over a 30 s duration of a pseudo steady-state analysis, i.e. in the time interval of 570 – 600 s.

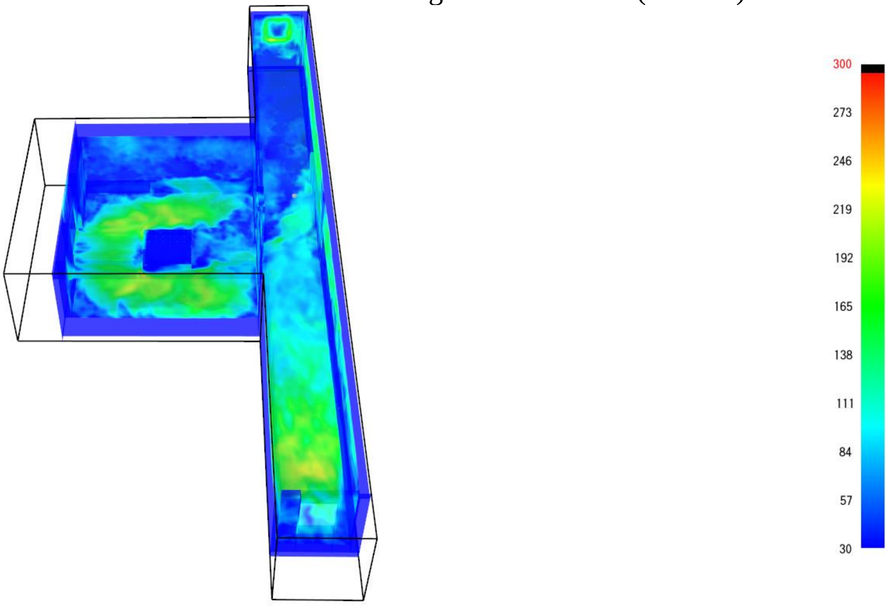
It is seen that the y+ is generally $\mathcal{O}(100)$, indicating wall functions are applied within the intended bounds. Soot mass fraction WEM is 0.5 or less. The MTR is generally below 0.4, implying more than 60% of the turbulent energy is resolved at the grid scale. Exceptions are in the near field region directly above the fire vent (3 to 5 m on the length scale) and above the door opening to the corridor (c. 2 m on the length scale). This is above the commonly adopted MTR recommendations given in McDermott, et al.[14] (i.e. not to exceed 0.2) and would imply at least one further mesh refinement would be justified. However, given the scoping nature and computational expense, 50 mm is adopted as the 'good practice' base-line for the purposes presented herein.

PROBABILISTIC ASSESSMENT AND RESULTS

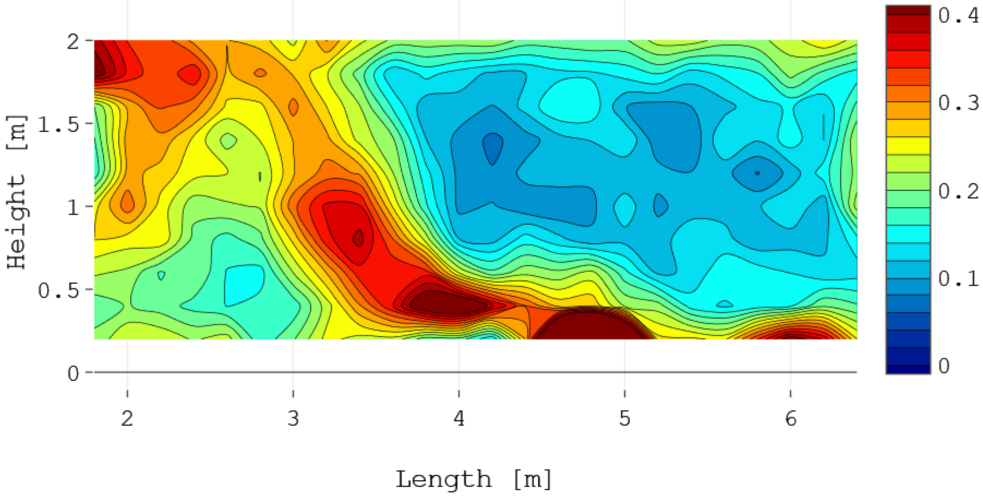
In common corridor ventilation system CFD studies, one of the primary performance objectives relates to the returning of the escape route to tenable conditions. Guidance on such studies[9] generally advocates that the visibility at head height (taken as 2.0 m herein) return to above 10 m within an appropriate timeframe relative to the escape of occupants in the apartment of origin. Herein, the probabilistic study focuses on the PDF concerning the time taken for the minimum visibility at head height to return to 10 m after occupants have escaped. This is measured relative to the door opening time. A 'KILL' routine is adopted within FDS whereby simulations are stopped once: (1) fire detection in the corridor occurs, and (2) the minimum visibility in a 2 m height corridor reference plane returns to 10 m. The KILL time is then adopted to compute a time offset relative to the apartment door opening time (defined as the clearance time herein).



(a) Soot mass fraction WEM – Slice through fire centreline (x = 9 m)



(b) y+ boundary contour



(c) MTR through fire centreline - contour

Figure 3. (a) soot mass fraction WEM; (b) y+ boundary contour; (c) MTR (50 mm cell size)

The previously highlighted ‘a priori’ steady-state analyses indicate that a 50 mm mesh size borders on satisfying all three of the chosen ‘a posteriori’ mesh quality indicators, with the exception of MTR. For scoping study purposes, the probabilistic analysis is undertaken at this grid resolution. It is acknowledged that it would be preferable to extend this to a further mesh refinement, i.e. 25 mm, in more detailed studies.

Overview of the MaxEnt procedure

The MaxEnt procedure makes an unbiased estimate of the PDF, f_A, for a scalar model output A of a numerical model (here: the corridor clearance time), while requiring only a limited number of model evaluations[5]. The methodology has been modified from a calculation procedure proposed by Zhang and Pandey, which relies on the principle of maximum entropy[15-16], i.e. a maximisation of uncertainty consistent with observed data when no prior knowledge on the shape of the PDF exists[17]. The concept presented by Zhang and Pandey takes advantage of the multiplicative dimensional reduction method (MDRM) and Gaussian interpolation to propose a very efficient calculation procedure (including sampling scheme). These calculation procedures however also introduce limitations, as the MDRM assumes the effects of stochastic input variables to be multiplicative, and Gaussian interpolation (with a standard integration order of five) is a numerical integration scheme. The MaxEnt method and has already been adopted in several structural fire engineering studies[7].

For each stochastic variable X_l, five realisations $x_{l,j}$ are calculated through the equation given below, with the five 'Gauss points' z_j given in Table 1. For each realisation $x_{l,j}$, the model is evaluated for the variable X_l, and using the median value (i.e. $x_{k,3}$) for all other stochastic variables X_k, resulting in the model realisation $y_{l,j}$. This implies five model realisations per stochastic variable, but as the model with all stochastic variables equal to their median value has to be evaluated only once (model realisation a_0), the total number of model realisations is $4n+1$ (where n is the number of stochastic variables).

$$x_{l,j} = F_{x_l}^{-1}\left(\Phi\left(z_j\right)\right)$$

where $F_{x_l}^{-1}(.)$ is the inverse cumulative distribution function (CDF) for variable X_l and $\Phi(.)$ is the standard normal CDF.

Table 1. Gauss points z_j and associated Gauss weights w_j

	1	2	3	4	5
z_j	-2.857	-1.356	0	1.356	2.857
w_j	0.011257	0.222076	0.533333	0.222076	0.011257

After each realisation of the model (i.e. a_0 to a_n) the MaxEnt optimisation procedure is applied to estimate the output PDF. The procedure is not described in further detail herein, with more information available in the literature[5,7], but results in the PDF estimate which maximises uncertainty and is consistent with the (fractional moments) resulting from the $4n+1$ model evaluations. As will be presented as the case herein, adopting three stochastic variables for the chosen problem thus results in a need for 13 CFD computations, i.e. significantly less than would be necessary to generate an unbiased approximation of an output PDF when compared to more traditional methods such as MCS (typically 10^3 – 10^4 simulations).

Stochastic vs. deterministic inputs

Provisionally, three stochastic inputs are considered for the scoping analyses. These are: (1) the fire growth rate, assuming t-squared behaviour, (2) the apartment door opening time relative to ignition, and (3) the soot yield. All other parameters are fixed, i.e. the peak fire heat release rate, heat of combustion, the door opening duration, wall lining thermo-physical properties, etc. A summary of stochastic and deterministic parameters is given in Table 2. At this stage, given the scoping nature of the study, semi-arbitrary distributions are adopted for the three stochastic variables to elicit a broad range of responses.

Table 2. Stochastic and deterministic parameters

Input and units	**Distribution type**	**Mean**	**Standard dev.**	**Min.**	**Max.**
α - Fire growth rate [kW/s^{2}]	Uniform	N/A	N/A	0.00073	0.047
t_d - Door opening time after ignition [s]	Lognormal	180	30	N/A	N/A
γ_s - Soot yield [kg/kg]		0.027	0.03		
Peak heat release rate [kW]	N/A	2,000	N/A		
Door opening duration [s]		10			
Wall conductivity [W/m.K]		0.48			
Wall specific heat [kJ/kg.K]		0.84			
Wall density [kg/m^{3}]		1,440			
Floor / ceiling conductivity [W/m.K]		1.8			
Floor / ceiling specific heat [kJ/kg.K]		1.04			
Floor / ceiling density [kg/m^{3}]		2,280			
Exhaust volume flow rate [m^{3}/s]		3.0			

MaxEnt Sampling Combinations and Sample Results

For three stochastic variables and five gauss integration points, the MaxEnt sampling procedure results in the combinations given in Table 3. The corresponding time to clear, relative to door opening time, (t_{clear}) for each simulation is also given.

Table 3. MaxEnt sample combinations and CFD simulation results

Simulation	**α [kW/s^{2}]**	**t_d [s]**	**γ_s [kg/kg]**	**t_{clear} [s]**	**Simulation**	**α [kW/s^{2}]**	**t_d [s]**	**γ_s [kg/kg]**	**t_{clear} [s]**
1	0.02386	177.5	0.0201	81.1	8	0.02386	222.2	0.0201	74.4
2	0.00082	177.5	0.0201	7.7	9	0.02386	284.9	0.0201	74.8
3	0.00478	177.5	0.0201	45.1	10	0.02386	177.5	0.0023	38.0
4	0.04294	177.5	0.0201	74.1	11	0.02386	177.5	0.0072	68.8
5	0.04690	177.5	0.0201	76.3	12	0.02386	177.5	0.0568	86.4
6	0.02386	110.6	0.0201	46.9	13	0.02386	177.5	0.1788	73.2
7	0.02386	141.8	0.0201	66.7					

Generally, results show a logical trend, i.e. increasing growth rate, door opening time or soot yield results in a prolonged time to return visibility at head height to below 10 m. The exceptions are simulations 1 and 13. Upon reviewing the results of both simulations, the combination of inputs results in a higher proportion of soot particulate accumulating at the lower levels of the corridor, i.e. the chosen reference plane at 2.0 m is not an ideal point at which to evaluate if the corridor is clear. In further studies, this would be better addressed through the termination of simulations at the point at which the corridor volume below a 2 m reference height returns to a minimum of 10 m visibility.

The output probability density function and cumulative probability density function

The MaxEnt[5] optimisation procedure is applied to the results in Table 3 to evaluate the output PDF and CDF for t_{clear}. An estimation order of four is adopted. Results are shown in Figure 4. The left indicates the PDF and the right the CDF /complementary CDF (cCDF). Alongside the MaxEnt estimation (indicated with suffix m4), a biased estimated of the PDF, CDF and cCDF is shown assuming a lognormal distribution.

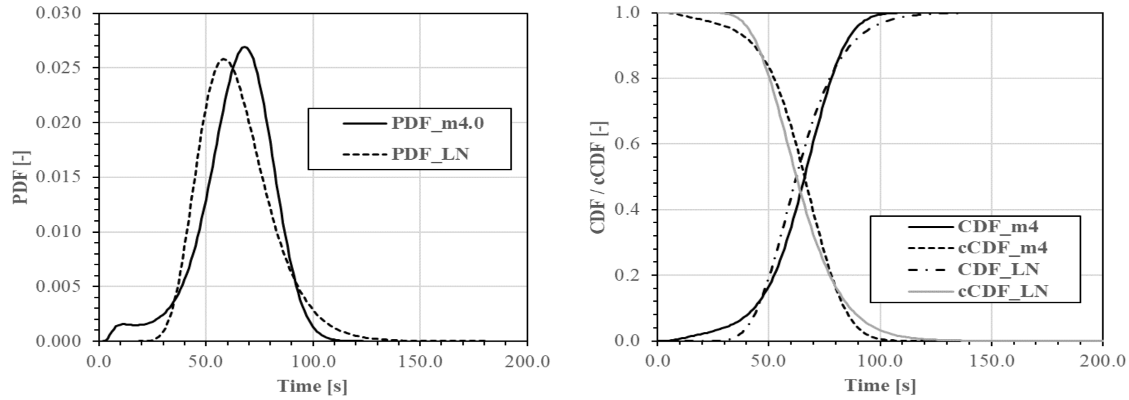


Figure 4 – (left) PDF for t_{clear}, (right) CDF and cCDF for t_{clear}

SENSITIVITY STUDY – THE IMPACT OF MESH RESOLUTION ON CONFIDENCE

To evaluate the relative importance of mesh size vs. input uncertainty, a design scenario for the geometry (Figure 2) and ventilation provisions outlined previously is conceived. This constitutes: α = 0.0.12 kW/s^2 (i.e. a medium growth rate – typical for residential applications), t_d = 300 s (recommended in the SCA Guide[9]) and γ_s = 0.07 kg/kg (the 95th percentile proposed in Robbins & Wade[18] – based on furniture fires). All other parameters are as defined in Table 2. The design scenario is evaluated at mesh resolutions of 50, 100 and 200 mm. For each grid size iteration, t_{clear} is benchmarked against the CDF given in Figure 4, with the likelihood of exceedance observed. From this, the trend in likelihood of exceedance vs. grid size is evaluated, as per Table 4.

Table 4. Sensitivity study – Grid size vs. likelihood of exceedance

Grid size [mm]	**t_{clear} [s]**	**Likelihood of exceedance [-]**	**Deviation likelihood of exceedance relative to 50 mm [-]**
50	86.4	0.074	N/A
100	85.6	0.081	0.007
200	68.8	0.427	0.353

Table 4 highlights a significant difference in the likelihood of exceeding t_{clear} as a function of the mesh resolution when transitioning between a 100 mm to 200 mm cell size. There is a marginal change in the likelihood of exceeding t_{clear} when transitioning between a mesh size of 50 mm to 100 mm. A more complete picture of the influence of mesh size could be achieved through comparisons of the full CDF at each grid size interval, i.e. repeating the MaxEnt study across a range of grid scales.

DISCUSSION

The level of safety achieved by a fire safety design can only be quantified through the application of PRA. This creates a potential incompatibility where: (i) on the one hand - there is a reliance on high-fidelity (computationally expensive) models, such as CFD, to analyse complex behaviours, and (ii) on the other – producing an unbiased output PDF for a variable has typically involved a high number of model realisations. Further, also for reasons of computational expense, CFD models are in practice applied at mesh resolutions that would generally be considered coarse when reviewed against mesh quality indicators. In both the context of a lack of uncertainty quantification and a model's ability to estimate relevant physics (i.e. model uncertainty), this creates ambiguity as to the quality of designs that are delivered. The relative importance of these two sources of uncertainty has been subject to limited research to date, particularly in relation to the most common application of CFD in UK fire safety engineering practice.

Firstly, an a priori steady-state simulation has been conducted at a 50 mm grid size. From this, it is observed that some, but not all, 'a posteriori mesh' quality indicators are satisfied. This indicates that a further mesh refinement could be warranted, considering these indicators in isolation of other uncertainties. Further mesh refinement is a significant deviation from standard practice. The issue of incompatibility of model fidelity and the number of model realisations has been efficiently addressed herein through the application of the MaxEnt method. From this, a PDF of smoke clearance time for a common corridor ventilation scenario has been evaluated (at a 50 mm grid size) which demonstrates scatter with mean of 64.5 s, 5th percentile of 34 s, median of 66 s and 95th percentile of 89 s. It should be noted that the input distributions have not been selected from specific literature sources but were intended to elicit a range of corridor clearance times, whilst adopting inputs in the ranges commonly applied by practitioners. It follows that the percentiles noted are indicative only and would vary subject to differing inputs.

Subsequent to the probabilistic aspect of the study, design scenario evaluations have been conducted at differing mesh resolutions, with the likelihood of the noted clearance times estimated through benchmarking against the MaxEnt output PDF and CDF in Figure 4, with results summarised in Table 4. At a 50 mm grid size the corridor clearance time was 86.4 s and through benchmarking against Figure 4, there is a c. 0.07 likelihood of the clearance time being longer. At a 100 mm grid size the corridor clearance time was 85.6 s and through benchmarking against Figure 4, there is a c. 0.08 likelihood of the clearance time being longer, i.e. a change in percentile of only 1% (relative to 50 mm). In transitioning from a grid size of 50 mm to 100 mm, this would imply that the uncertainty of the inputs / scenario are more influential than any model uncertainty arising from the grid size. Markedly, at a 200 mm grid size the corridor clearance time was 68.8 s and through benchmarking against Figure 4, there is a c. 0.43 likelihood of the clearance time being longer. Relative to a 50 mm grid size, this equates to a change in percentile of c. 35.5%, reducing to 34.5% relative to a 100 mm grid size. This would indicate that significant uncertainty can arise from the modelling process, when adopting grid sizes in exceedance of 100 mm (i.e. model uncertainty dominates).

CONCLUDING REMARKS

The paper presents 'a posteriori' MQIs, which for the given application to the CFD modelling of common-corridor ventilation systems suggests 50 mm is a reasonable cell size. This is adopted as a base-line for uncertainty quantification. A design scenario is conceived which is evaluated at mesh sizes of 50, 100 and 200 mm. Relative to the 50 mm case, there is a nominal deviation in corridor clearance time when increased to 100 mm. This implies input uncertainty is dominant. At a further mesh size increase (to 200 mm), there is a significant change in corridor clearance time, implying uncertainty associated with the model (where MQIs are significantly poorer) governs. Care, however, should be taken in generalising any such conclusions, as, without further research, such conclusions may be unique to the ventilation arrangement modelled herein. In undertaking the study, several other observations have been made which warrant further investigation as part of a more detailed future study:

- The sourcing of distributions from the literature for soot yield, fire growth rate and door opening times is necessary – this will serve to give a more definitive quantification of the distribution of corridor clearance times for the case investigated;
- Further uncertainties exist that should be incorporated into the study, this includes the apartment door opening duration and the thermo-physical properties of boundary surfaces. Increasing the stochastic variables to five would necessitate 21 CFD simulations to generate an output PDF;

- The output quantity of the simulation, i.e. time to clear the corridor, would be better estimated from the measuring of soot concentration throughout the entire corridor volume, not only at a 2 m reference height. Simulations indicate that, whilst a 2 m reference plane may be a visibility in exceedance of 10 m, less buoyant smoke with a high soot concentration can accumulate at lower levels;
- Provisional ‘a priori’ steady-state studies highlight that not all ‘a posterior’ mesh quality indicators are satisfied. This would imply a further mesh refinement is necessary, with the associated PDF generated at this resolution (instead of 50 mm);
- An improved quantification of the impact of model uncertainty vs. input uncertainty would be attained through the generating of the full PDF (using the MaxEnt method) at each grid size interval. These could then be directly contrasted; and
- There would be merit in evaluating more complex corridor geometries and ventilation arrangements, e.g. including dog-legs and similar, or push-pull ventilation systems.

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