Uncertainty of Tenability Times in Multiroom Building Fires

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Abstract
Analysis of fire risk for building occupants is generally based on the comparison of the required safe egress time (RSET) and the available safe egress time (ASET) after which the conditions in the rooms or evacuation path become untenable due to the buildup of hot smoke layer affecting people and impeding their evacuation. Any fire scenario includes uncertain parameters which are translated into the uncertainties in the critical times. These uncertainties have to be taken into account to determine credible safety margins in building design. In this paper, CFAST zone model is applied to the simulation of fire development and smoke propagation in multiroom buildings, with the aim of studying the sensitivity of tenability times to model parameters and uncertainties caused by the variability of scenario parameters. The building geometries include: i) a single room with a door and a window, ii) three rooms connected by a long corridor, and iii) two-level configuration with two rooms on the lower floor connected by a vertical vent to a room on the upper floor. Sensitivity indices of time to untenable conditions due to high temperature and smoke obscuration are analysed, after which the distribution functions of these times are presented and compared for different rooms of which the building is comprised.

Introduction
Fire safety for building occupants is commonly analysed in terms of the comparison of the required safe egress time (RSET) for building occupants, and the available safe egress time, ASET, the latter being the time after which untenable conditions build up in compartments or on egress routes used for the evacuation [1]. Building fire risk analysis often relies on the mathematical modeling of fire development, smoke propagation, evacuation of occupants, fire brigade intervention etc. The RSET and ASET times are determined from relevant mathematical models and the condition RSET < ASET is considered a basic requirement for safe evacuation of building occupants.

It is increasingly recognized that deterministic analysis of the RSET < ASET condition may not be sufficient, and uncertainties in the characteristic times have to be taken into account in the decision-making process. The sources of uncertainties are numerous, they involve, to name a few, intrinsic randomness and variability of physical processes, deficiencies of mathematical models, lack of input data etc. Quantification of model sensitivity and uncertainties is necessary to establish credible safety margins for building fire protection designs [2, 3].

A traditional approach to sensitivity analysis of fire models was to vary model parameters about some baseline scenario and see how significant the changes in the output functions (temperatures, toxic gas concentrations etc.) incurred by this variation are. Recently, more systematic approaches called global sensitivity analysis have been proposed which evaluate sensitivity over the whole parameters space, rather than at a single parameter space point [4]. In the field of fire safety, such methods were applied to the sensitivity analysis of CESARE-Risk smoke movement model [5]. A single room with a fire source was considered, and sensitivity of maximum temperature and time of untenable conditions to eight input parameters was studied. Note that CESARE-Risk is a single-zone fire model which assumes the gases to be well-mixed in the room, which is not the case in the pre-flashover stage of the fire where strong stratification into hot and cold gas layers exists.

From the life safety point of view, more appropriate at the initial stage of fire development are the zone models which take into account this stratification explicitly. Application of global sensitivity analysis to two-zone fire model to determine the effects of various parameters on the tenability times was carried out in [6]. Fire development and smoke movement in single and multi-compartment buildings was simulated by the CFAST zone model [7, 8]. Sensitivity studies (Morris diagrams, Sobol indices) were carried out by running CFAST under DAKOTA toolkit [9] which implements a number of sensitivity analysis and uncertainty quantification methods. The building geometries included: i) a single room with a door and a window, ii) three rooms connected by a long corridor (the experiments used as a validation case in CFAST documentation), and iii) two-level configuration with two rooms on the lower floor connected by a vertical vent to a room on the upper floor. The main output parameters studied were the times of untenable conditions due to high temperature and loss of visibility. It was shown in [6] that both times to untenable conditions are mostly sensitive to the rate of fire development. Also, the results obtained showed that in multiroom buildings the critical times for different rooms can be sensitive to different problem parameters, which must be taken into account for proper quantification of ASET times.

In this paper, the global sensitivity analysis performed in [6] is extended to study the uncertainties of the critical tenability times in multiroom building fires. Distribution functions for the critical tenability times are obtained and compared for different rooms. Safety boundaries corresponding to 95% probability of safe evacuation are determined. The building room geometries and fire parameters are taken similar to those used in [6], which enables us to use the results of global sensitivity analysis obtained therein.

Models and Solvers

Fire development and smoke movement in single and multi-compartment buildings was simulated by the CFAST zone model [7, 8]. In this model, each compartment is divided into two distinct zones, the upper (hot) and lower (cold) layers, each having its own temperature and gas composition. For each compartment, a system of four governing ordinary differential equations is solved, with the main unknowns being the total pressure P, volume of the upper zone V_U, temperature of the upper and lower zones T_U and T_L, respectively. Closure of the model is achieved by applying submodels for fire source, fire plume, as well as mass and energy exchange between compartments and heat transfer between the gas and structural elements (walls, ceiling, etc). CFAST [7, 8] was chosen as the main fire model solver because it is well-established, extensively tested and can be regarded as an industry-standard zone model. Note that in the above-mentioned work [5], the sensitivity analysis was performed for a response surface fitted by regression rather than for the CESARE-Risk model itself. In the current work, the CFAST solver was run for each set of parameters; this was found feasible because a typical run times on a modern workstation are from a fraction of second up to several seconds, at least for the building geometries studied (up to four interconnected rooms).

Coupling between CFAST [7] and DAKOTA [9] was achieved by developing pre- and postprocessor modules and interface scripts. The general interaction framework corresponds to the “black-box” model: DAKOTA generates samples for the input variables which are then pre-processed to generate CFAST input files; CFAST is run with each input file generating output files which are post-processed to extract the response functions of interest (times to untenable conditions for each room) which are fed back to DAKOTA for the statistical analysis.

Room Geometries

The room geometries originate from the full-scale experiments by Factory Mutual [10] which were used for validation of CFAST in [8], where reasonable agreement between predictions and measurements was demonstrated.

We consider three building geometries, also used in [6]: G1 is a single room; G2, three rooms connected by a corridor, all on the same level; G3, three rooms of which two are on the same level, with the third room above them (two-level configuration). Details of all geometries are shown in Figs. 1*a*-*c*, with the rooms denoted as geometry-room number pairs (e.g., G3-R2 stands for geometry G3, room No.2; the fire rooms are denoted as FR).

Geometry G1 contains a single room G1-FR, 3.64×3.64×2.45 m, window size 0.85×0.85 m, sill at 1.26 m, door size 0.92×2.05 m. Geometry G2 exactly corresponds to the experiments by Factory Mutual [10], including room and opening sizes, as well as material properties. The fire room G2-FR is the same as G1-FR, room G2-R2 is 3.64×3.65×2.45 m, room G2-R3 is 3.53×3.53×2.43 m, corridor is 2.43×18.89×2.43 m, doors to rooms G2-R2 and G2-R3 are 0.88×2.02 m. Finally, geometry G3 includes three rooms in two levels, the fire room G3-FR is the same as G1-FR, rooms G3-R2 and G3-R3 are 4.0×3.64×2.45 m, the vertical vent area is 1m^2. Note that geometry G1 uses the same fire room (G1-FR) as in G2-FR, but it connects to the outside through the door. Geometry G3 also uses the same fire room, but it connects by a door to a larger room which, in turn, is connected to an upper room via a vertical vent. The walls and ceiling were assumed to be made of ½ inch gypsum board, the floor was of 6 inch concrete.

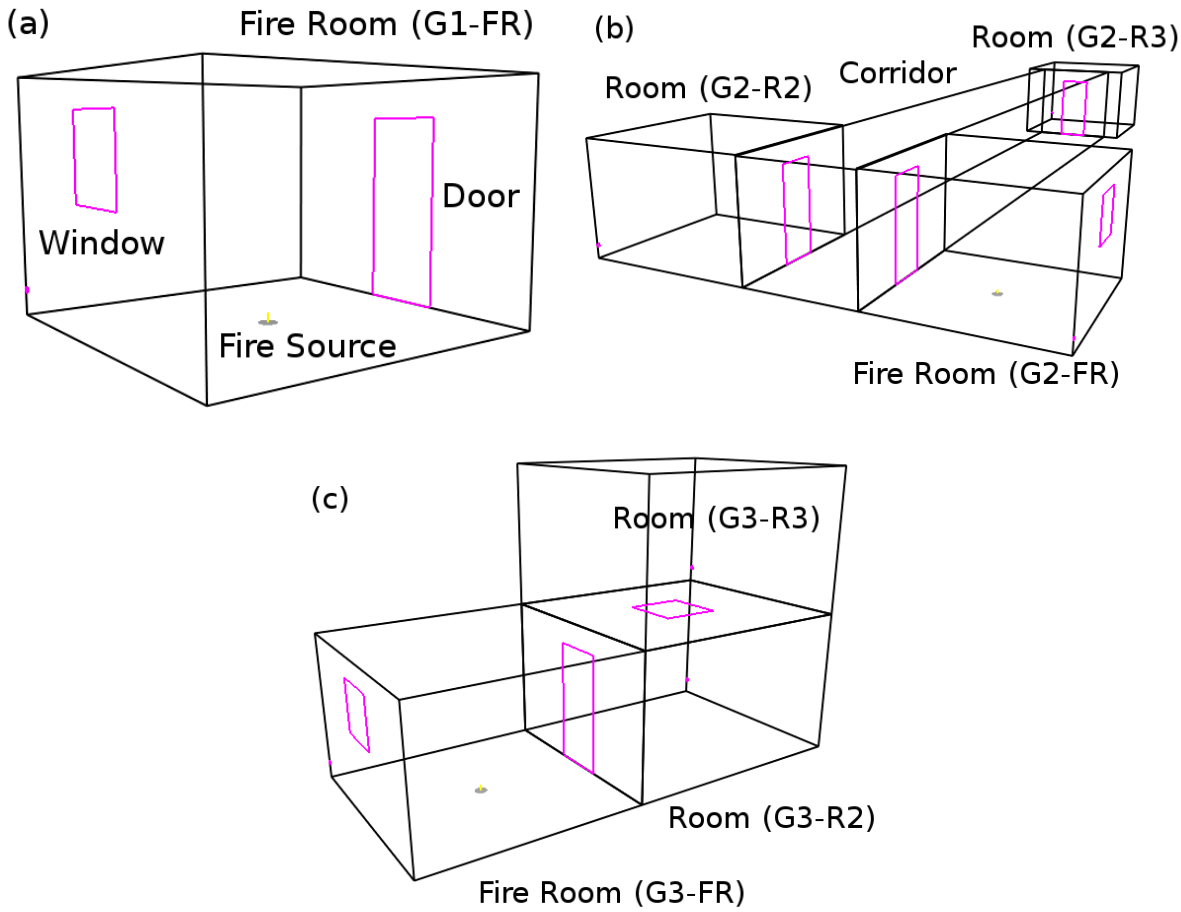

Figure 1. Building geometries used in sensitivity analysis: a) single-room; b) three rooms connected by corridor; c) three rooms in two levels.

Fire Source and Uncertain Parameters

Similar to the previous work [6], a t^2-fire was assumed in this study, rather than a steady fire used in the experiments [10]. Transient fire is more relevant to life safety evaluation because building occupants must be evacuated during the first several minutes into fire development, when steady burning has not yet been achieved. The heat release rate is assumed to grow as $Q(t) = at^2$ until it reaches the maximum value of $Q_{\max}$ and then stays constant (fire decay not considered). The fire growth parameter a can be expressed conveniently in terms of the time $t_{1\text{MW}}$ necessary for the fire power to reach 1054 kW.

The parameters considered as uncertain are listed in Table 1, uniform distributions in the ranges given in the last column are assumed for each of them [6]. Among these are the both fire source parameters depending on fire load specifics ($Q_{\max}, t_{1\text{MW}}$), fire room and vent geometry (L , h, x_w), as well as combustion properties (x_R, Y_s).

Table 1. Uncertain input parameters.

No.	Parameter	Description	Baseline Value	Range
1	$Q_{\max}$	Maximum fire power, [kW]	800	700-1000
2	$t_{1\text{MW}}$	Time to 1054 kW fire power, [s]	200	175-225
3	L	Length of fire room between wall without vents, [m]	3.64	3.5-4.0
4	h	Window height, [m]	0.85	0.75-0.95
5	x_W	Window opening fraction, [m]	1	0-1
6	x_R	Radiative fraction, [-]	0.3	0.25-0.35
7	Y_s	Soot yield C/CO_2, [-]	0.01	0.0075-0.0125

Critical tenability times

The values of interest in this study were the times at which untenable conditions were reached at a level of 1.7 m. Tenability was assessed with respect to gas temperature at that height exceeding the critical value of 70ºC (thermal impact), or the optical density exceeded the value of 0.119 m^{-1}(loss of visibility). These times were extracted by the post-processor from the CFAST output files; depending on whether the smoke layer interface height was more or less that the reference height of 1.7 m, the values from the lower or upper layers were used to determine the critical time. Note that the same response functions were used in the sensitivity analysis [6].

Results for Single Room (Geometry G1)

In the single room (geometry G1, see Fig. 1*a*), rapid room filling by smoke occurs. In Fig. 2*a*,*b*, the time histories of the upper layer temperature and smoke interface height are presented for the baseline scenario, the corresponding thresholds used for tenability criteria are shown by the horizontal dashed lines. For the baseline scenario, the times to the critical tenability conditions determined from the temperature and visibility are, respectively, t_T = 62 s and t_V = 34.4 s. Evidently, loss of visibility may be the main threat for people in the fire room which fills rapidly with smoke, while temperature impact becomes dangerous later on.

In Fig. 3, the calculated cumulative distribution functions CDF (*a*) and probability density functions PDF (*b*) are shown for the critical tenability times t_T and t_V. One can see that the PDF function for visibility loss time has two peaks (corresponding to rapid changes in the slope of CDF function), the reasons for these, either physical or due to the model behavior, need further study.

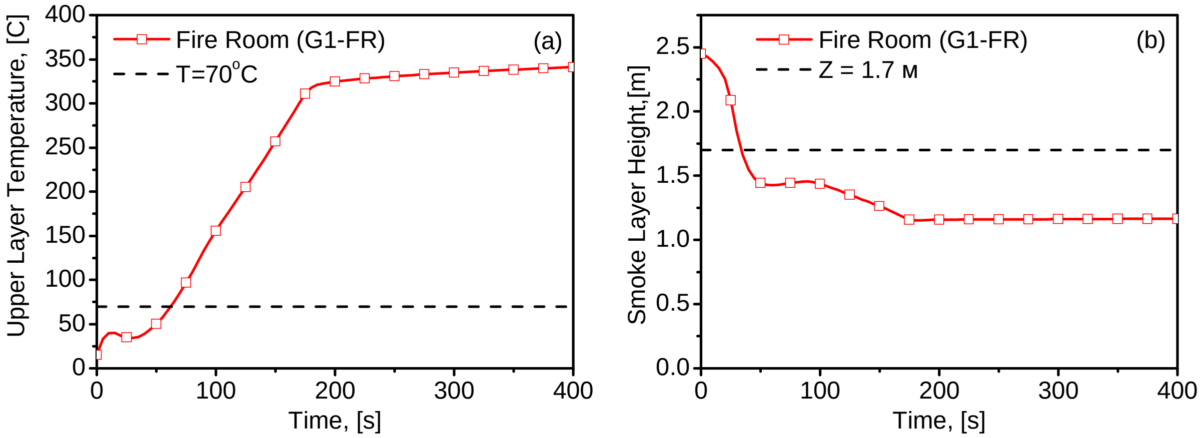

Figure 2. Time histories of the upper layer temperature (*a*) and smoke layer interface height (*b*) for the baseline fire scenario.

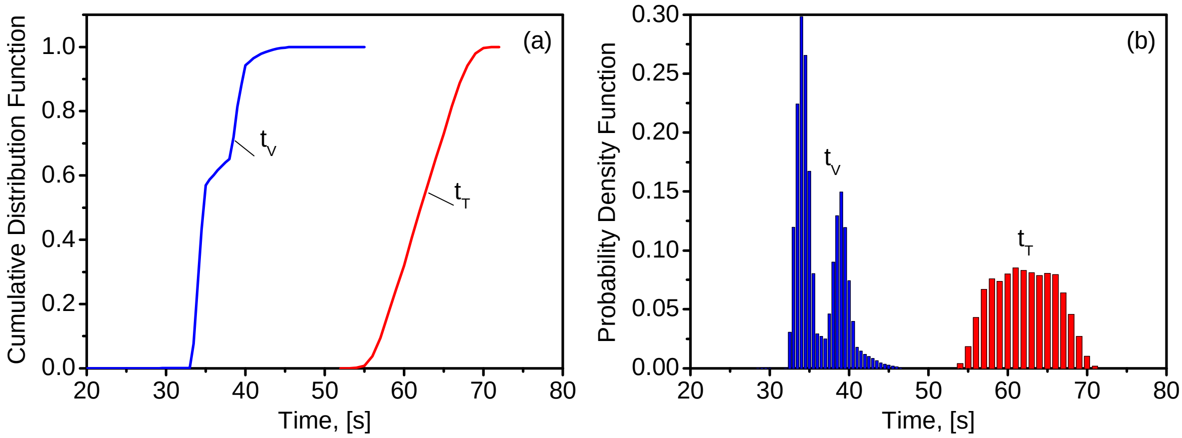

Figure 3. Cumulative distribution functions (*a*) and probability distribution functions (*b*) for geometry G1.

The input of each uncertain parameter into the critical times variance is quantified by the Sobol total sensitivity indices [11] (see also [4, 9]) presented in Fig. 4. The index S_{Ti} gives the fraction by which the output function variance would be reduced if the uncertainty of *i*-th input variable would be eliminated. The most influential parameters are the rate of fire growth (presented in terms of the time to reach 1 MW); for the time t_T the next most influential is the radiative fraction x_R, while for t_V it is the soot yield Y_s.

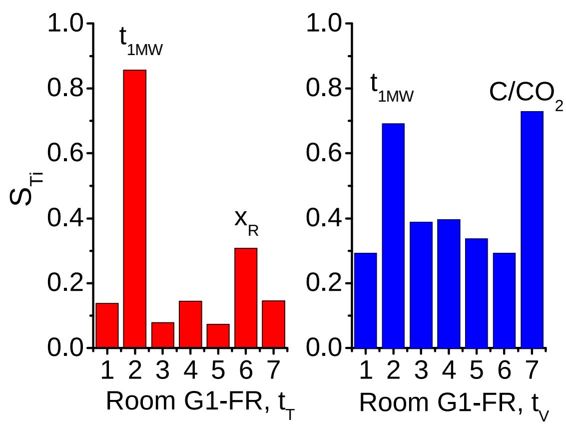

Figure 4. The Sobol total sensitivity indices for the times to untenable conditions due to high temperature (*left*) and loss of visibility (*right*); variables 1-7 are listed in Table 1.

Results for Three Rooms with a Corridor (Geometry G2)

In this case (geometry G2, see Fig. 1*b*), the analysis is focused on the conditions in the fire room as well as in Room G2-R3, the most remote from the fire room. In Fig. 5*a*,*b*, the upper layer temperatures and smoke layer interface heights calculated for the baseline set of parameters (see Table 1) are presented for the fire room, corridor, and the remote room.

In Fig. 6, the cumulative distribution functions CDF (*a*) and probability density functions PDF (*b*) are shown for the critical tenability times t_T and t_V in the fire room (G2-FR) and remote room (G2-R3). One can see that in all the rooms, critical conditions due to loss of visibility are attained quicker than those due to high temperature, similar to the case of a single fire room (geometry G1). The statistical properties of the critical times for the fire room G2-FR are very close to those for the single fire room (G1-FR), which means that the feedback from the presence of other rooms is rather weak.

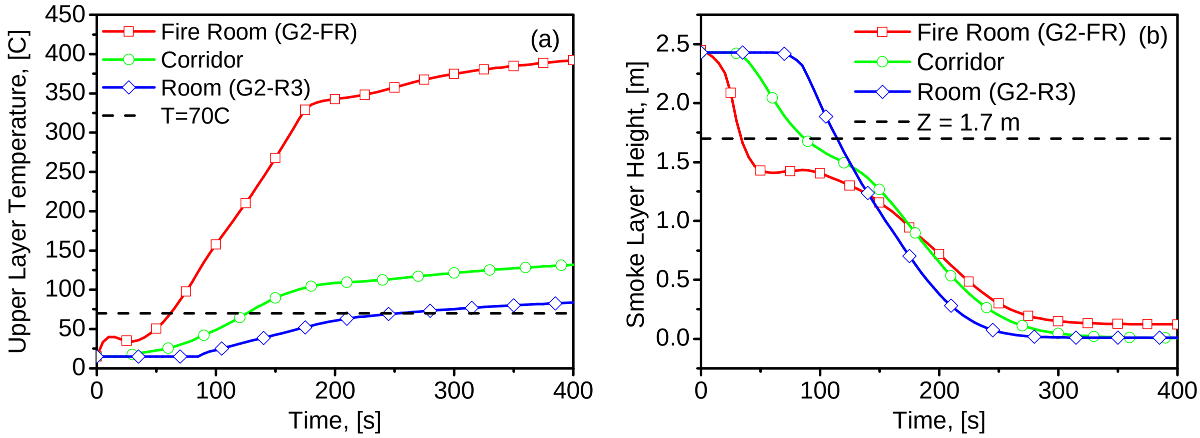

Figure 5. Time histories of the upper layer temperature (*a*) and smoke layer interface height (*b*) for the baseline fire scenario.

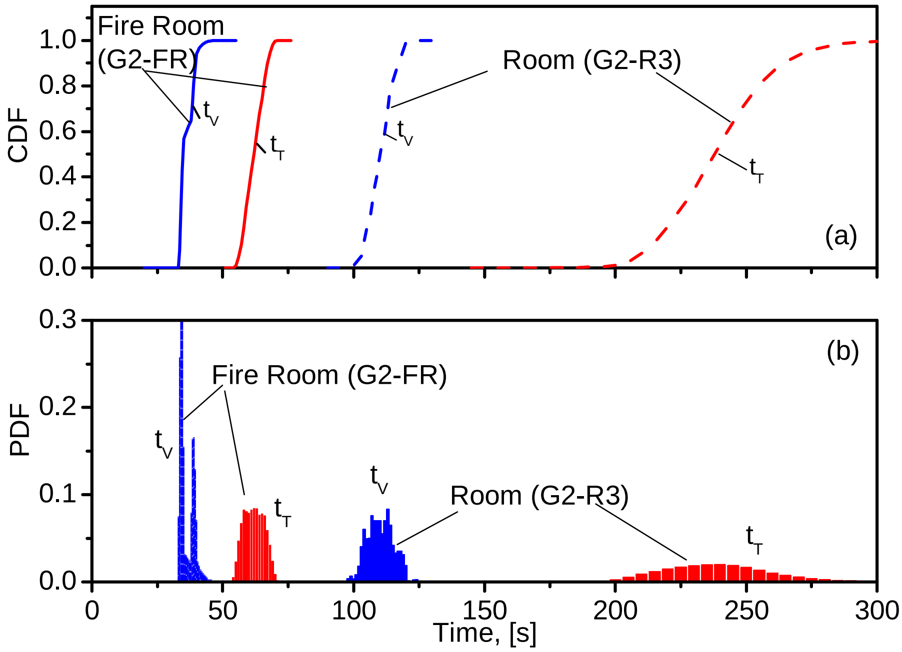

Figure 6. Cumulative distribution functions (*a*) and probability distribution functions (*b*) for geometry G2.

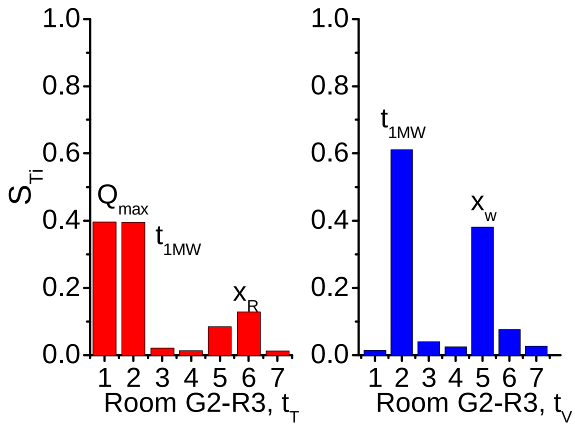

Figure 7. The Sobol total sensitivity indices for the times to untenable conditions due to high temperature (left) and loss of visibility (right); variables 1-7 are listed in Table 1.

The probability density function for t_T in room G2-R3 is much wider than the other ones, which is explained by the temperatures in the upper layer developing in this room (see Fig. 5*a*) being very close to the critical threshold, so that the critical condition is poorly defined, and small variation in the input parameters cause large variation in the respective critical time. The Sobol total sensitivity indices for the remote room G2-R3 are presented in Fig. 7. Similar to the case of fire room (see Fig. 4), the most important parameter is the time to reach 1 MW. For t_T, the maximum fire heat release rate becomes important, because for the remote room the temperatures are rather close to the critical threshold (70C), and the time to reach the tenability time becomes sensitive to gas heating. In contrast to this, in the fire room the hot layer temperatures are much higher than the threshold value, and the critical time is determined simply by the descent of hot layer boundary, irrespective to the particular temperature of the hot layer gas.

Results for Three Rooms in Two Levels (Geometry G3)

For the baseline scenario in geometry G3, the upper layer temperatures in all rooms, as well as the interface heights are plotted in Fig. 8*a,b*. The distribution functions for the critical tenability times are presented in Fig. 9*a,b*, while the Sobol total sensitivity indices for room G3-R3 are shown in Fig. 10. Comparison with the previous cases (G1 and G2) show similar trends in the data obtained: fire development in the fire room proceeds similarly in all three cases, albeit the maximum temperatures of the smoke layer are somewhat higher in the current case than in the geometry G2 (at t = 400 s the maximum temperature is higher by about 40 degrees). Noticeable is also that the temperature in room G3-R3 grows slowly and is close to the threshold level, which explains high variation of the predicted critical time.

Another effect of the temperature in room G3-R3 being close to the threshold was that for some combination of parameters generated by random sampling, the temperature did not reach the critical level at all. In the post-processor which extracted the times to critical condition from CFAST output files, this situation was processed by setting the critical time to 600 s (arbitrary large value). For this reason, the corresponding CDF function in Fig. 9*a* does not reach the level of 1, rather, it saturates at the level 0.725. This means that 27.5% of samples were for non-critical situation. The probability distribution function in Fig. 9*b* was obtained by differentiating the CDF, it does not include the rightmost point (at 600 s) where the remaining non-critical cases are concentrated.

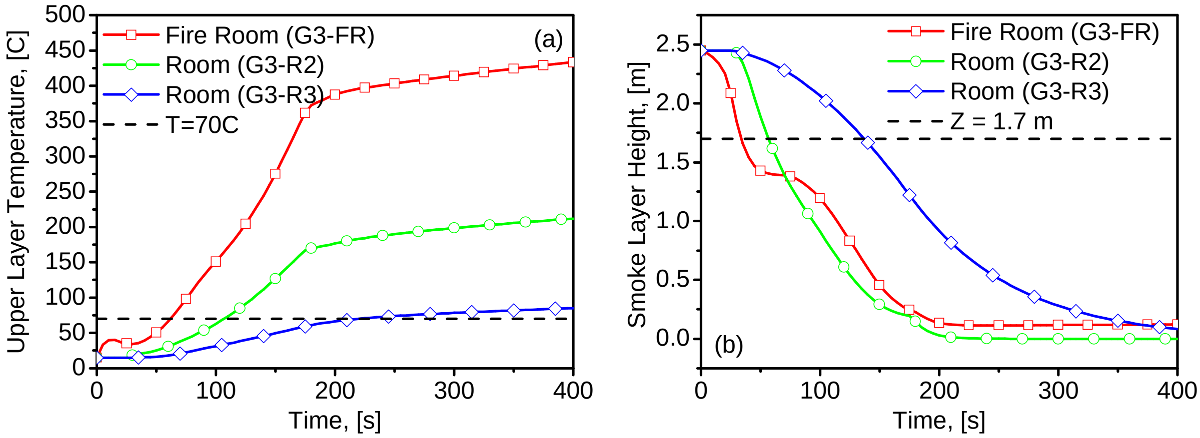

Figure 8. Time histories of the upper layer temperature (*a*) and smoke layer interface height (*b*) for the baseline fire scenario.

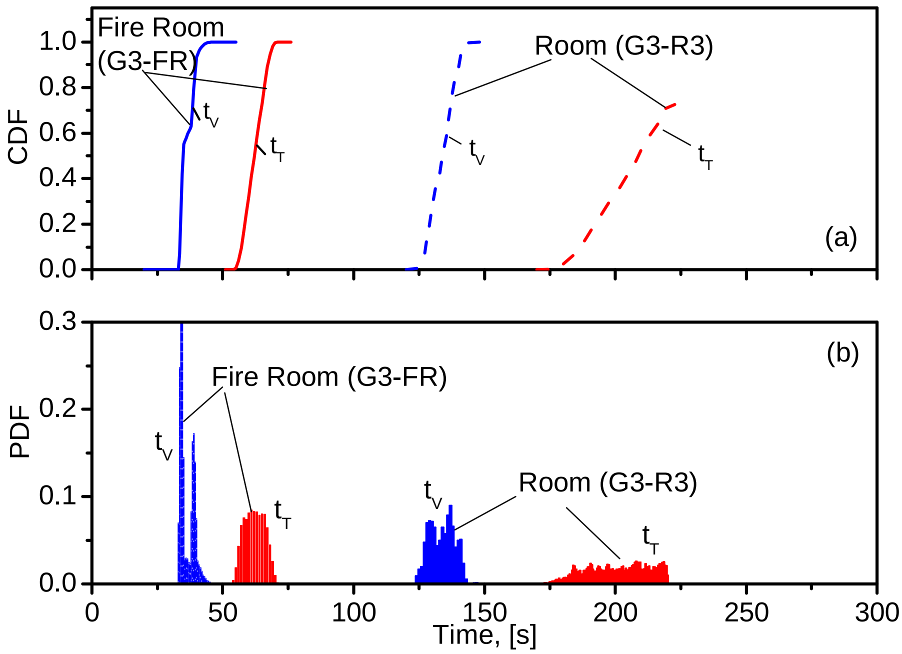

Figure 9. Cumulative distribution functions (*a*) and probability distribution functions (*b*) for geometry G2.

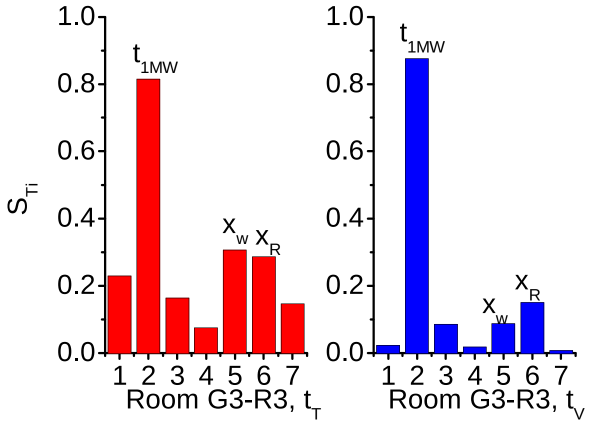

Figure 10. The Sobol total sensitivity indices for the times to untenable conditions due to high temperature (left) and loss of visibility (right); variables 1-7 are listed in Table 1.

Summary of critical times

The distribution functions of critical times obtained above allow us to obtain, for each geometry and room, the mean values of critical tenability times $\bar{t}_T$ and $\bar{t}_V$, as well as their standard deviations σ_T and σ_V characterizing the respective uncertainties. Also, from the safety point of view, of interest are the lower boundaries of both critical times corresponding to the CDF equal to 5%, $t_T^{5\%}$ and $t_V^{5\%}$ respectively. These can be regarded as the safety limit times for people evacuation: with 95% probability the untenable conditions will develop in the respective room later than these limit times. The results obtained in the calculations are summarized in Table 2. Note that the values for room G3-R3 shown in italic are estimates based on the functions presented in Fig. 9, due to the cases where the critical temperature was not attained.

The data in Table 2 illustrate in the quantitative way the findings mentioned in the discussions to each scenario. The fire room fire development and tenability timing is almost insensitive to the presence of other rooms (of course, this is due to the fire room having an independent ventilation through the window; otherwise, the dependence of fire development on the geometry and room connectivity in the whole building might be stronger). The critical conditions due to loss of visibility are the first to be reached for all the rooms involved. The uncertainties in the critical tenability times are increasing with the increase in the distance from fire source, not only for the modeling reasons (accumulation of model uncertainties), but also because the temperature of smoke layer is decreasing with distance, approaching the critical threshold, so that the time at which the threshold level is attained becomes poorly defined, unlike the fire room where critical conditions are attained instantly upon the descent of smoke layer interface to the prescribed height.

Table 2. Critical tenability times and their uncertainties.

Geometry	Room	$\bar{t}_T$, [s]	σ_T, [s]	$t_T^{5\%}$, [s]	$\bar{t}_V$, [s]	σ_V, [s]	$t_V^{5\%}$, [s]
G1	FR	62.2	3.8	56.2	36.1	2.8	33.4
G2	FR	62.1	3.8	56.3	36.2	2.7	33.4
G2	R3	239	21.5	208	110.6	5.0	103
G3	FR	61.9	3.7	56.1	36.2	2.7	33.3
G3	R3	*200*	*20*	183.2	134.9	4.4	126.5

Conclusions

Uncertainty quantification is payed increasing attention in building fire analysis because it allows one to establish credible safety margins in building fire protection design. The results presented in this paper shown that sensitivity analysis and uncertainty quantification of zone model is feasible with modern uncertainty quantification methods, using the zone model of fire development and smoke movement as a core solver run repeatedly for large number of input data samples. For more computationally intensive calculations (e.g., based on CFD models), direct application of these method may be hindered by the prohibitively large computational overhead incurred. In this case, a way forward may be in developing surrogate models (response surface approximations) and running them instead of the full model for the purpose of uncertainty analysis.

The results obtained in this paper show that the times to untenable conditions due to high temperature and loss of visibility are mostly sensitive to the rate of fire development. In multi-room buildings the critical times for different rooms can be sensitive to different problem parameters, which must be taken into account for proper quantification of ASET times. Also, the uncertainty in the prediction of critical tenability times increases for rooms which are more remote from the fire source.

Acknowledgments

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