Coupling of Evacuation and Fire Modelling through Soot Level Analysis

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ABSTRACT

When assessing evacuation from a building fire, computational fluid dynamics (CFD) models of fire can aid with the calculation of available safe egress time (ASET), and evacuation and crowd dynamic simulation can help estimate the required safe egress time (RSET). Some existing models and simulation environments directly couple the fire and evacuation models for a holistic assessment. These, however, often use the measure of incapacitation in terms of fractional effective dosage (FED) or fractional irritant concentration (FIC) to quantify tenability condition and to affect the walking speed of the agents. Much fewer models use the measure of visibility to predict the walking speed and exit/route selection of the agents. Even when visibility is taken into consideration, often the local level at the position of the agents are used, especially when the exit door is not within the line of sight. This paper presents a new and computationally resourceful method of analyzing visibility along the entire line of sight for each agent through the consideration of soot level. The method is tested on the agent-based crowd simulation tool, Oasys MassMotion version 10, using its software development kit (SDK). A simple geometry of 50 m by 50 m floor with walls is used to test evacuation in three ways: 1) without any coupling with the fire model, 2) using local visibility values, and 3) through the consideration of soot level analysis along the line of sight for each agent. The results are compared to show how the new method can provide a more realistic coupling of CFD and evacuation models and can affect the overall RSET.

INTRODUCTION

The growing shift from prescriptive to performance-based design of buildings requires analyses of relevant fire and evacuation scenarios. These analyses typically consist of assessments of Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET). ASET is the available time from fire ignition to loss of tenability and is evaluated through fire models, and RSET is the time required for escape and is assessed through evacuation simulation. Averill (2011) identified as one of the five grand challenges in pedestrian and evacuation dynamics to be the integration of evacuation models with fire models to support performance-based design. There are a number of simulation packages and previous research within the field to address this challenge, where fire and evacuation assessments are carried out within the same environment to understand the impact of fire and smoke on particularly the movement time, as displayed in Figure 1.

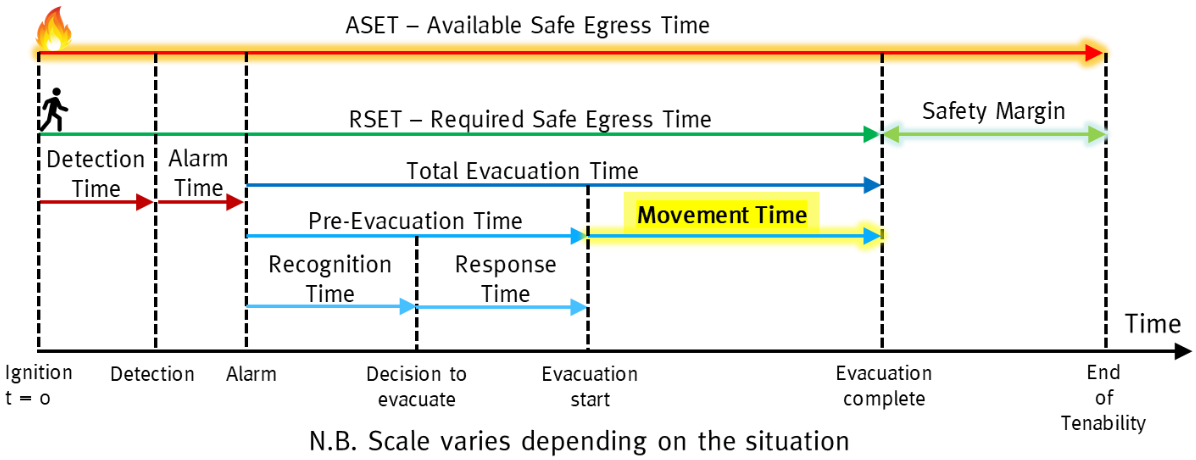

Figure 1 - ASET/RSET timeline (based on Lovreglio, 2016)

The coupling of dynamic fire and evacuation models is conducted via the assessment of the tenability conditions and the resulting impact on the evacuees. Often, computational fluid dynamics (CFD) forms the basis of the fire simulations, and agent-based models allow the modelers to set individual agents' properties and decision-making processes. The tenability criteria are typically assessed in terms of the following: 1) Visibility, 2) air temperature, and 3) fractional effective doses (FED).

Much of the coupling work considers the carbon monoxide, carbon dioxide and oxygen levels, as well as irritant gas levels caused by incomplete combustions. They evaluate the dynamic FED levels that each agent faces throughout the evacuation process rather than the impact on the walking speed or the exit selection (Rådemar et al, 2017; Sargant et al, 2014).

Coupling work that considers visibility utilizes just local values to influence the walking speed of the agent (Thunderhead Engineering, 2020; Fridolf et al, 2016; Galea et al., 2008; Korhonen, 2018; Rådemar et al, 2017; Ronchi et al, 2012; Sargant et al, 2014). The local visibility is the distance an agent can see within the control volume of the fire model at the location of the assessed agent. The reason for using the local visibility values is because the smoke layer in a fire scenario is often a heterogeneous mixture (Wegrzynski & Vigne, 2017). Most of the coupling work has been carried out using Fire Dynamics Simulator (FDS) for the fire model and Pathfinder, STEPS, or FDS+Evac for the evacuation model.

However, Wood's (1972) experiment indicates that over 70% of evacuees changed their direction when faced with smoke. Initially, out of the 70%, only 40% turn around, but after 10 yards (9.144 m) into the smoke, a further 30% of evacuees turned around, and after 15 yards (13.716 m), more people changed their exit selection. However, Wood (1970) also concluded that while smoke directly at the exit showed negligible impact on the exit selection, when the smoke started to spread extensively throughout the building, the frequency of using other doors than their normal exits increased (Wood, 1972). These findings show that visibility does not impact just the walking speed but also the exit selection.

This paper, therefore, presents a new methodology of a one-way coupling of fire and evacuation model where the overall soot levels impact not just the walking speed but also the exit selection of the agents.

The rest of the paper is organized as follows: the next section covers the literature review related to the effects of visibility on human movement, the impact of soot yield on visibility, and other previous methods to have considered non-local visibility values. The section following the literature review presents the proposed methodology. Subsequently, the modeling scenario is outlined, and the penultimate section of the main body presents the results. The final section prior to the conclusion provides a discussion of the results.

LITERATURE REVIEW

Definition of visibility

Visibility is defined as the local value that is inversely proportional to the extinction coefficient, as presented in Equation 1. The constant depends on the type of light source and its value from 5-10 for light-emitting lamps and 2-4 for reflecting signs (Society of Fire Protection Engineers, 2019).

$$Visibility = \frac{Constant}{Extinction\ coefficient} \tag{1}$$

Effects of visibility on human movement

One of the first studies and a rare experimental study involving evacuation in an environment with a real fire was conducted by Jin (1970). Jin showed a relationship between the extinction coefficient and walking speed, variable depending on whether the is moke is an irritant or not, see Figure 2.

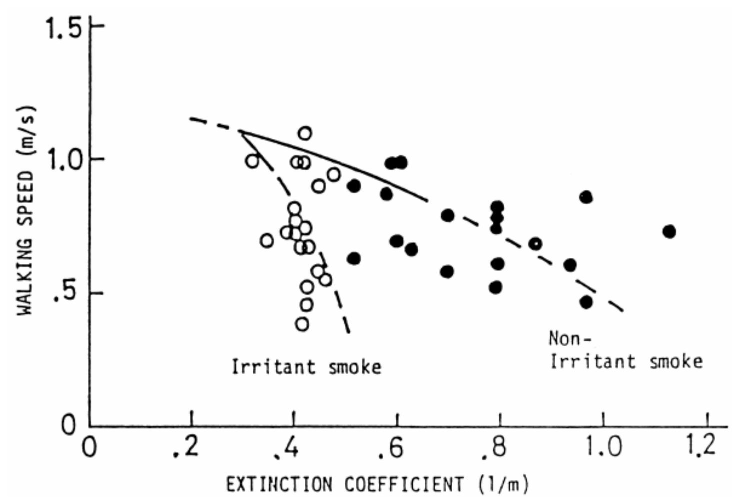

Figure 2 - Walking speed vs extinction coefficient based on real fire experiment (Jin, 1970)

In recent years, other researchers have evaluated the impact of the extinction coefficient on walking speed in white smoke with smoke generators in tunnels (Seike et al, 2016; Boer, 2002). Figure 3 shows that their findings contradict the results from Jin and that the evacuees walk faster in a smoke-filled environment.

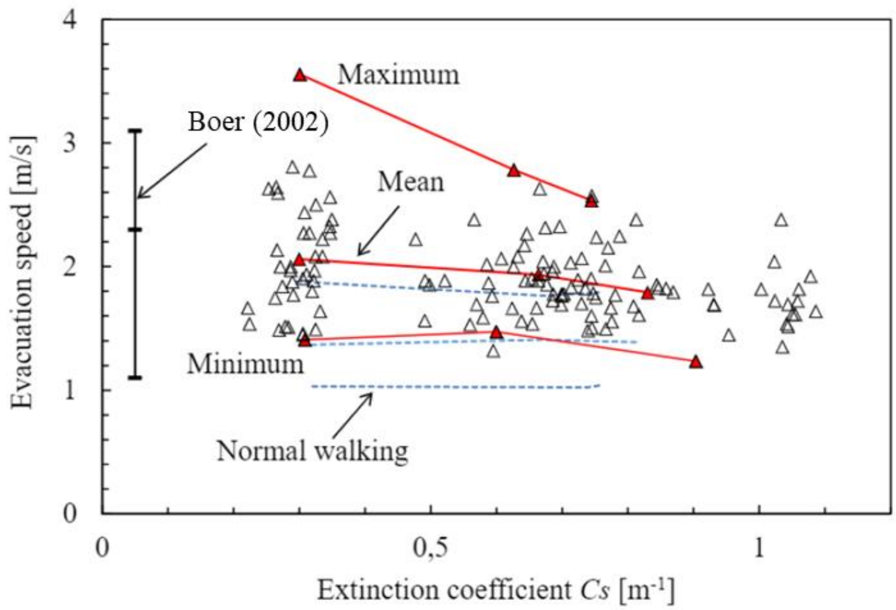

Figure 3 - Walking speed based on extinction coefficient in white smoke (Boer, 2002; Seike, 2016)

However,for Seike et al.'s (2016) experiments only male university students were recruited, and therefore, the findings may not reflect the impacted walking speed of a diverse demographic.

While Jin, Seike et al, and Boer (1970, 2016, 2002) evaluate the relationship between the extinction coefficient and walking speed for lower extinction values, i.e. a visibility of above 1.6 to 9.3 depending on the characteristics of the exit signs, Frantzich and Nilsson (2003) in contrast conduct evacuation analysis through dense smoke with higher extinction coefficients, as shown in Figure 44. Their results show that the walking speed drops significantly at lower visibility values (higher extinction coefficients).

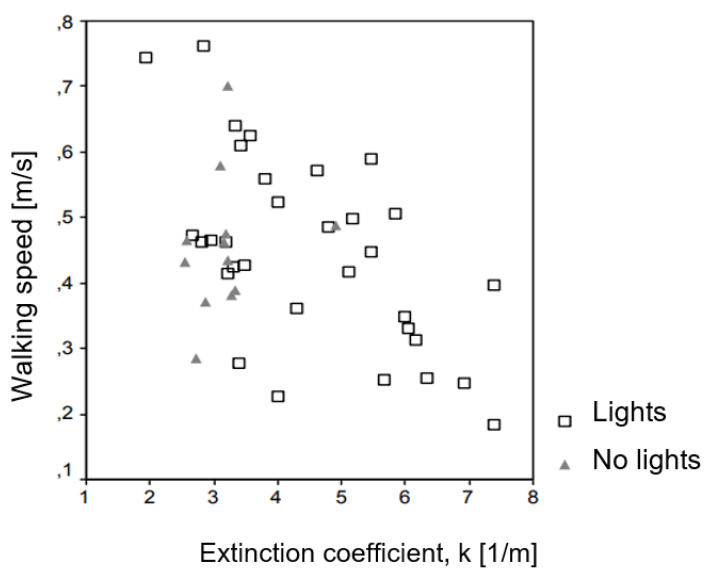

Figure 4 - Extinction coefficient vs walking speed for extinction coefficients higher than 1 (Frantzich & Nilsson, 2003)

The findings then have been formulated into a single equation by Fridolf et al (2018), as shown in Equation 2.

$$v = \min\left(v_{smoke-free}; \max\left(0.2, v_{smoke-free} - 0.34 \times (3 - visibility)\right)\right) \quad (2)$$

Because the walking speed is calculated as the minimum of unimpeded speed and an impacted speed, Seike et al and Boer's findings (2016, 2002) showing higher walking speed is excluded in the walking speed analysis. For the purpose of this study, Fridolf's equation has been used.

Effects of soot yield on visibility

Wegrzynski & Vigne (2017) have undertaken experiments and simulations to understand the relationship between the soot yield and visibility. One of their findings was that the obscuration density (which is a representation of the mass concentration of smoke) is proportional to soot yield, and in their example scenario, the mass density of smoke in the middle of the room grew with the increasing soot yield, as expected. These are shown in Figure 5.

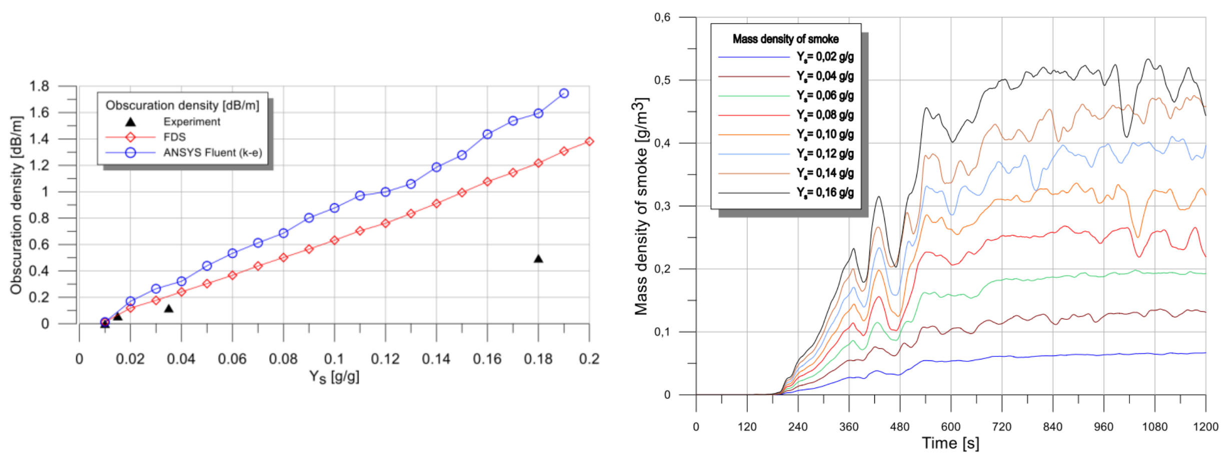

Figure 5 – a) Obscuration density vs soot yield
b) Mass density of smoke varying with soot yield based for a given open room
(Wegrzynski & Vigne, 2017)

Other previous methods considering non-local visibility values

Kang (2005) proposed a multi-ray tracing method by setting up a camera from each agent's location to cast rays and simulate how they propagate through space. A raster image is then created and the pixels that are dim are considered to have been affected by smoke. Using the Bouger-Lambert-Beer Law, as shown in the discretized form in Equation 3, visibility is deduced based on obscurity levels.

$$I = I_0 \times \exp\left(-s\alpha_m \sum_i \rho_i \omega_{s,i}\right) \quad (3)$$

where s is the smoke aerosol, α_m is the mass specific extinction coefficient in m²/g, ρ_i is the fluid density in g/m³ and $\omega_{s,i}$ the mass fraction in g/g.

However, Bouger-Lambert-Beer Law assumes a homogenous mixture of smoke and casting multiple rays are computationally demanding. Therefore, He (2009) developed a method using virtual visibility where a single line of sight is used from the agent to the exit sign, and an average extinction coefficient is calculated. However, averaging values neglects pockets of high extinction coefficients.

PROPOSED METHODOLOGY

The proposed methodology for one-way coupling using soot level analysis relies on two streams. Using the same inputs of room geometry and fire location, the fire simulation will run independently from the evacuation model. An additional input is required just for the fire simulation, which is the chemical components of the fuel, or the fire source, which determine the overall fire size in terms of heat release rate and the combustion (by-) products. A separate set of inputs are required for the evacuation model, which are the building occupancy and the normal distribution of the occupant walking speed. Prior to coupling, the evacuation simulation is run for 1 minute to have a developed crowd movement in the room to have the agents spatially distributed.

As shown in Figure 6, at the start of the movement time, the visibility and soot mass fraction outputs from the fire model are imported for every x, y, and z coordinates where there is an agent. The coupling module, we call Visibility-Soot algorithm, then determines the agent's direction and calculates the walking speed for the next time step.

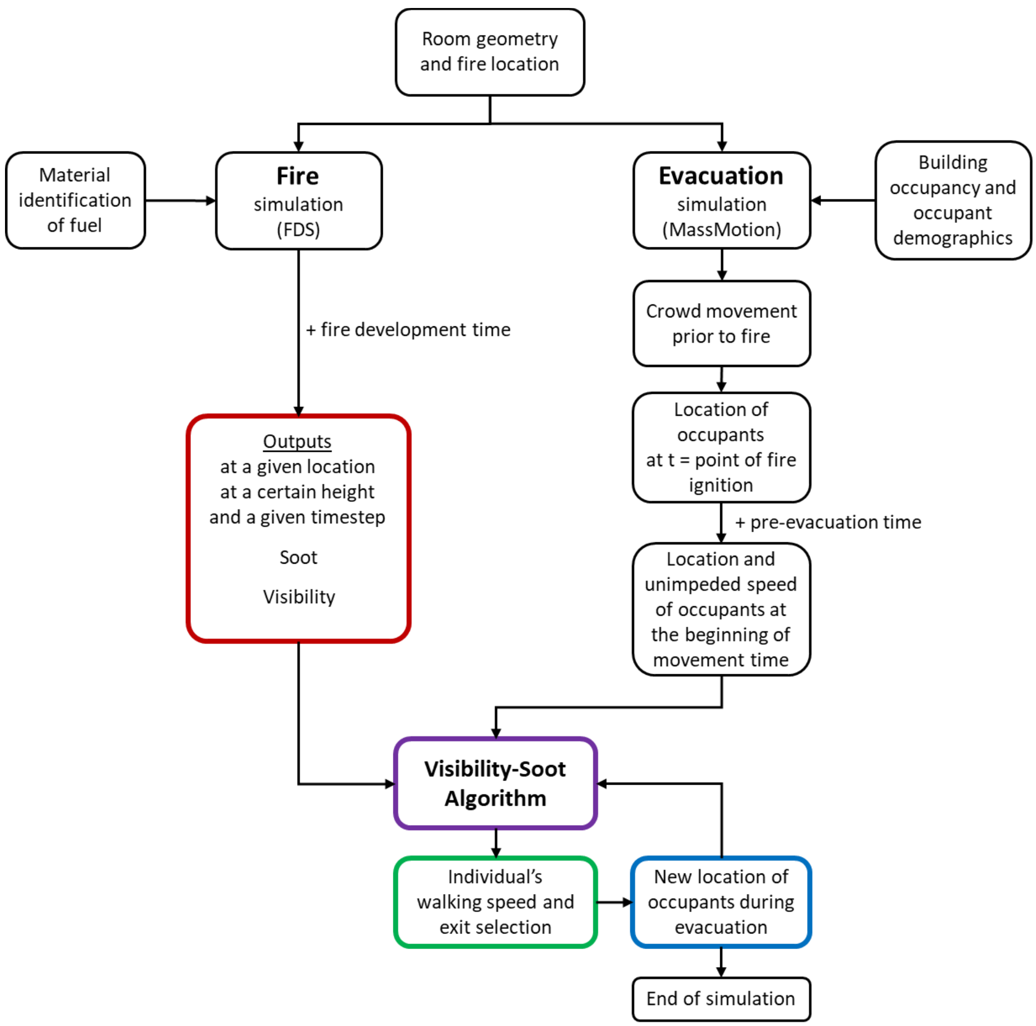

Figure 6 - Overall coupling methodology

The visibility-soot algorithm consists mainly of two steps:

Step 1. Calculate the agent's walking speed based on the local visibility as per the relationship developed by Fridolf et al (2016, 2018).

Step 2. Determine the individual agent's exit selection based on the maximum soot mass fraction along the line of sight to all the exits.

The maximum soot mass fraction is compared to a threshold. As a reference, the work from Wegrzynski & Vigne (2017) is used to set to 0.1 g/g.

A detailed flowchart describing the visibility-soot methodology is illustrated in Figure 7 for the example scenario with two exits studied in this paper.

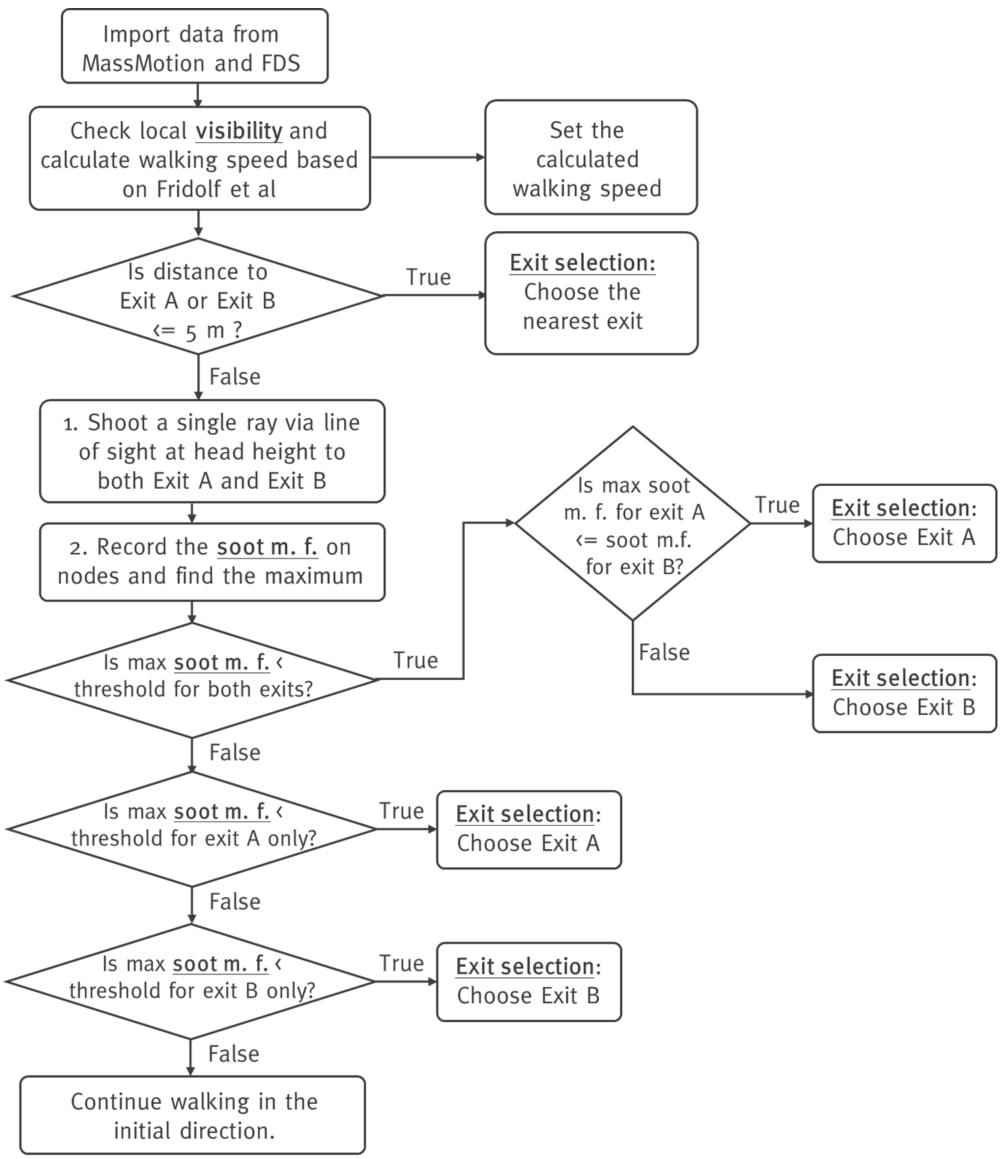

Figure 7 - Visibility-soot algorithm for the example of two exits, A and B

MODELLING SCENARIO

Simulation tools

For this paper, Fire Dynamics Simulator (FDS) version 6 is used for the fire model. FDS is an open-source 3D computational fluid dynamics (CFD) tool provided by the National Institute of Standards and Technology (NIST) of United States Department of Commerce. It is a large-eddy simulation code for low-speed flows solving Navier-Stokes equations numerically. For this paper, devices are set in 0.25 m intervals on the horizontal plane in both the x- and y-directions and at a head height of 2.5 m. 2.5 m is chosen based on National Fire Protection Association (NFPA) 305, which states that to account for current precision of modeling method, a height of at least 2.5 m should be used (NFPA, 2020).

For evacuation modeling, MassMotion version 10.5 is used. It is a verified 2D agent-based tool from Oasys for the use of evacuation modeling (Kinsey, 2017). The advantage of MassMotion is its software development kit (SDK) feature to allow for customized coding to control the agents by the user using one of the common programming languages. For this project, Python is used. Through the SDK feature, the output of the FDS can be imported into MassMotion, and the visibility-soot algorithm can be applied.

Geometry

The geometry follows the layout approximately of one from Fang et al (2010), who applied a multi-grid method to FDS+Evac using a 50 m by 50 m open-plan room with two exits. The room studied in this paper has the exits at opposite diagonal ends with widths of 2 and 4 m, respectively, to introduce asymmetry.

The fire represents a sofa with a fire potential of 3 MW and of polyester fabric and flexible polyurethane padding with soot yield of 0.073 g/g as determined by Robbins & Wade (2008) with chemical compositions outlined by Gann et al (2003). The fire development is set to follow an ultra-fast growth rate to show a conservative scenario.

In terms of the demographics of the evacuees, 30 homogenous agents are introduced from 7 different locations throughout the room. The agents' unimpeded walking speed have been set to be a mean of 1.35 m/s with a standard deviation of 0.25 m/s and a minimum of 0.65 m/s and maximum of 2.05 m/s, as prescribed by Fruin (1971).

The FDS model and the MassMotion models are shown in Figure 8.

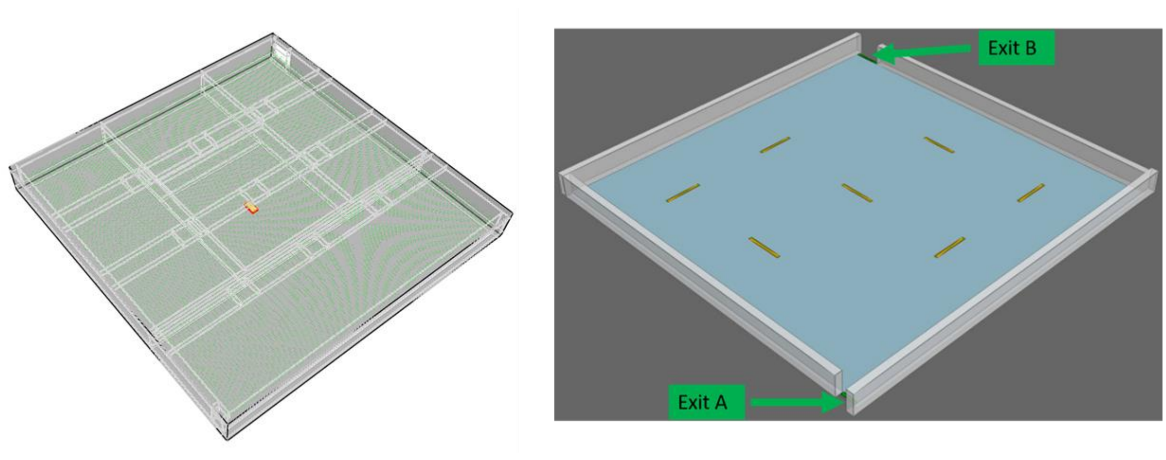

Figure 8 - FDS and MassMotion models

RESULTS

The evacuation model is run three times using the same random seed: Once without any coupling, which forms the base model, the second model considers only the effect of visibility on the walking speed as described by Fridolf et al (2016), and the third model is coupled using our visibility-soot method. The results are summarized in Table 1.

Table 1 - Summary of results

Key areas	**Base model**	**Visibility only**	**Visibility-Soot Method**
Computational runtime	2.574 seconds	111.863 seconds	166.549 seconds
Total movement time	46.6 seconds	176.7 seconds	137.0 seconds
Exit selection	47% choose exit A 53% choose exit B	47% choose exit A 53% choose exit B	43% choose exit A 57% choose exit B
Density analysis	Smaller high-density areas at the exits with higher densities experienced on the paths	Larger high-density areas at the exits.	Largest high-density areas at the exits.

When considering the paths that the agents have taken in the 3rd model, when visibility-soot algorithm is applied, the agents avoid the center of the room where the fire is, located whereas in the other methods, agents walk through heavy smoke. The paths are shown from the plan view of the room in Figure 9.

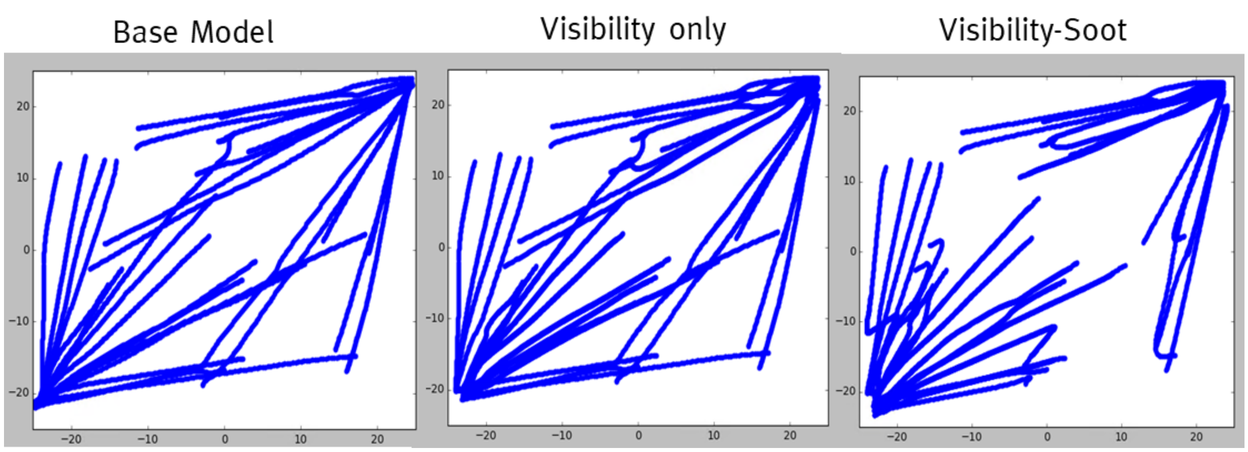

Figure 9 - Agent paths on plan view

The maximum densities throughout the room are shown in Figure 10 in terms of the level of service (LOS).

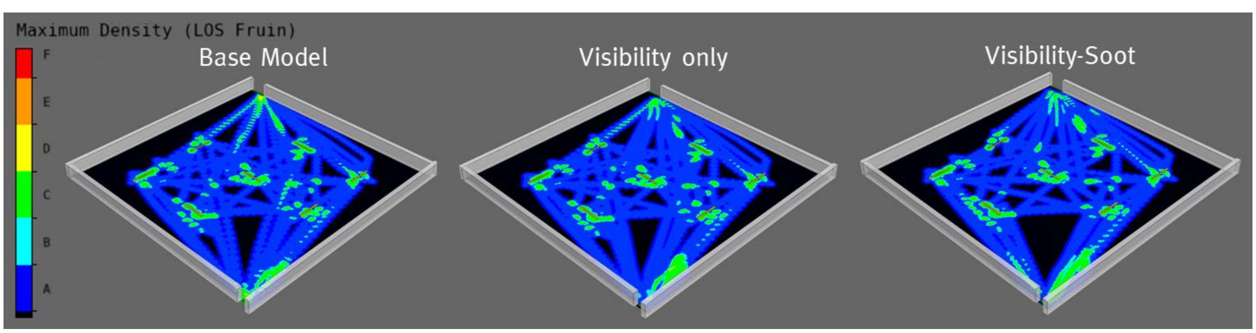

Figure 10 - Densities along the floor based on Fruin LOS levels

The results show that when evacuation is run on its own, the paths show a high level of service with congestion experienced at the exits as the agents are walking fast. When the impact of visibility is applied to the agents' walking speeds, the throughput through the exits are shown to be steadier due to the lower walking speeds. When the change of exit selections due to the soot levels are applied in addition to visibility, the exits show a larger area of LOS level C.

DISCUSSION

When the visibility-soot algorithm is applied, the results show a different evacuation dynamic. Due to the changes in the exit selection, the total evacuation time is calculated to be lower by 39.7 seconds than when only incorporating the visibility factor for this particular set-up. Because of the different paths taken by the agents, the density levels around the room also varied.

One other result output considered for this paper is the runtime. One of the disadvantages of coupling fire and evacuation modeling is the increased runtime. However, the results show that the run time for the model still has been less than 3 minutes on a Windows 10, Intel Xeon 3.5 GHz CPU with 6 physical cores and 64GB RAM. The set-up time of the coupling would have been the other time-consuming activity, but as this is now automated, the set-up time is negligible in the future. The largest bottleneck is the fire modeling part of the coupling, which would have to be run anyway, even in non-coupled scenarios, to assess tenability conditions for the evacuees.

NEXT STEPS

The most critical parameter that will need to be further investigated is the soot mass fraction threshold, as that will vary when the agents choose a different exit. In addition, this model will need to be verified and validated, beyond just verifying against underlying theories, by using NIST's guide on verification and validation of evacuation models (Ronchi et al, 2013). Thirdly, the evaluation of different geometries with obstacles covering the line of sight to the exits needs to be considered.

Outside of the consideration of visibility and soot level, the evacuation model needs to incorporate heterogeneous demographic and stochastic analysis as well as FED or FIC levels.

CONCLUSION

A new visibility-soot algorithm has been developed to influence the direction of the agents as well as their walking speed during a fire evacuation simulation. The method has been tested using FDS 6 and Oasys MassMotion. The results show a different evacuation dynamic compared to when the soot level analysis along the entire line of sight is neglected. When incorporating the soot levels across the room, the agents avoid clouds of dense smoke and go to the clearest exits. The soot level threshold will need to be investigated further in the next phase of the research.

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