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Representation of the Impact of Smoke on Agent Walking Speeds in Evacuation Models

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Abstract. This paper addresses the problem of reproducing the effect of different visibility conditions on people's walking speed when using evacuation models. In particular, different strategies regarding the use of default settings and embedded data-sets are investigated. Currently, the correlation between smoke and walking speed is typically based on two different sets of experimental data produced by (1) Jin and (2) Frantzich and Nilsson. The two data-sets present different experimental conditions, but are often applied as if equivalent. In addition, models may implement the same data-sets in different ways. To test the impact of this representation within evacuation tools, the authors have employed six evacuation models, making different assumptions and employing different data-sets (FDS + EVAC, Gridflow, buildingEXODUS, STEPS, Pathfinder and Simulex). A simple case-study is simulated in order to investigate the sensitivity of the representation of two key variables: (1) initial occupant speeds in clear conditions, (2) extinction coefficients. Results show that (1) evacuation times appear to be consistent if models use the same data-sets and interpret the smoke vs speed correlation in the same manner (2) the same model may provide different results if applying different data-sets or interpretations for configuring the inputs; i.e. default settings are crucial for the calculation of the model results (3) models using embedded data-sets/assumptions require user expertise, experience and understanding to be employed appropriately and the results evaluated in a credible manner.

Keywords: Evacuation modelling, Human behaviour in fire, Emergency evacuation, Visibility, Evacuation simulation

1. Introduction

The increasing capabilities of evacuation models [1–4] are leading to a high number of new model users. One of the consequences is that the application areas are becoming more diverse as the community of evacuation model users is growing

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[5, 6]. This has not necessarily been accompanied with the required increase in expertise and experience. To increase the number of evacuation model users, model developers are also constantly working on improving the usability of models, making them more accessible and embedding more behavioural sophistication. The number of embedded default settings is growing; to accommodate model ease of use, given increasing model complexity. In fact, default settings often permit the models to be applied without prior configuration [7, 8].

Evacuation modelling can be a peripheral activity, leading non-expert users to apply these tools without the same level of expertise as they may have in their primary area of expertise (e.g. fire modelling). These, evacuation modellers, may not have a deep understanding of the model capabilities and limitations due to a limited knowledge on default settings, embedded data-sets employed, range of applicability, validation and verification, etc. The situation is made worse by the multi-disciplinary nature of the field [9]. In brief, the lack of specific academic or professional credentials relating to the use of evacuation models can affect the accuracy and credibility of the simulation results produced.

Numerous simulation packages are available that can be applied as part of the performance-based approach (i.e. the comparison between ASET—Available Safe Egress Time—and RSET—Required Safe Egress Time) by simulating fire and evacuation processes within the same environment. In this context, one of the main aspects to be reproduced is the simulation of the smoke effects on human performance [10]. Smoke affects the process of way-finding in a building producing impacts on occupant walking speeds.

This paper presents the application of different data-sets and their subsequent interpretations for reproducing the impact of smoke on occupant walking speeds. The case-study refers to the evacuation of a corridor, providing a sensitivity analysis of the two main variables affecting this issue; i.e. the visibility conditions (often measured by extinction coefficient) and the initial occupant speeds in clear conditions. Many other correlations and constructs are used within evacuation modelling; however in this case-study, a single (relatively simple) problem is investigated in order to minimise the influence of any other factors.

The study of the smoke/speed correlation is currently based on two main data-sets. The first is a set of experiments performed by Jin [11] more than 30 years ago. The experimental data collected has been used for providing the correlation between the extinction coefficient and walking speeds, visibility levels and cognitive abilities when exposed to smoke. The second correlation currently in use is based on the more recent studies conducted by Frantzich and Nilsson [12] who performed tunnel experiments for studying the influence of different visibility conditions on individual walking speeds. The two data-sets employed different experimental conditions (i.e. types of irritant gases, population characteristics, structural configuration, etc.), but are frequently used within evacuation models as if interchangeable. Another issue that may affect the impact of these data-sets is the way evacuation models interpret the two data-sets. Currently, there are two main methods to apply the smoke/speed curves to simulate the impact of smoke. The first method to reproduce the impact of smoke on walking speeds requires a fractional reduction of the initial speed. The speed achieved is affected by two variables: the visibility conditions and the initial speed in clear conditions. The second method considers an absolute reduction of the speed; i.e. agents reduce their speed all in the same way regardless of their initial speed in clear conditions. In this case the only variable affecting the derived speed in smoke is then the visibility conditions experienced.

There are significant differences between the two data-sets and their interpretations. Models that are relatively easy to use and require less user configuration (i.e. have pre-determined default settings) are particularly susceptible to misuse if the user is inexperienced and inexpert—as less user expertise is required to configure them and subsequently produce results.

The authors have selected six models to examine the impact of default settings, embedded data-sets and their interpretation upon results produced. These models have been selected to address two different points: (1) the impact of default embedded data-sets on evacuation results, and (2) the impact of different interpretation of the data-sets on the results produced. The following six models—applying different default settings/embedded data—have been used and the results presented: FDS + Evac [13], Gridflow [14], buildingEXODUS [15], STEPS [16], Pathfinder [17], Simulex [18]. They were selected because they present different assumptions with regards to the representation of the impact of smoke on agents; i.e. they may or may not have default settings, and/or embed either Jin's or Frantzich and Nilsson's data-set.

Conclusions are presented focussing on the different ways in which these selected evacuation models reproduce the impact of smoke on occupant walking speeds. Considerations on the use of default settings/embedded data are provided as well as suggestions on how to model the impact of smoke on occupant speeds.

2. The Impact of Smoke on Occupant Walking Speed

The presence of smoke during an emergency may have different impacts on evacuees' behaviours [19–22]. These impacts could be psychological, physiological or physical. Different occupant behaviours may be caused by contacting with smoke, including: (1) the evacuee's initial response, (2) redirection of movement, (3) reduction of the efficiency of evacuee movement (i.e. reduced speed, crawling, etc.). [11]. This paper investigates the available literature/data-sets for modelling the impact of smoke on occupant speeds and the manner for interpreting this information within evacuation models.

2.1. Available Data-Sets

The current literature includes two main experimental data-sets based on Jin [11] and Frantzich and Nilsson's studies [12]. The experiments made by Jin [11] were performed more than 30 years ago and they are currently available in the Society of Fire Protection Engineering Handbook [23], while Frantzich and Nilsson's [12] experiments were performed more recently. These experiments are often considered (especially in engineering practice) as equivalent data-set to reproduce the impact of smoke on evacuee movement speeds during an evacuation. They both provide a correlation between extinction coefficient (i.e. the visibility conditions within the considered infrastructure) and occupant speeds. Jin's experiments also provide information on the occupants' cognitive abilities when exposed to smoke [24].

Jin studied the effect of two types of smoke: (1) irritant and (2) non-irritant. Experiments were performed in a 20 m-long corridor that was filled with smoke corresponding to an early stage of fire. The experimental population consisted of 17 females and 14 males, ranging from 20 years to 51 years in age. Irritant smoke was produced by burning wood cribs, while less irritant black smoke was produced by burning kerosene. Test subjects were instructed to walk into the corridor. In the case of irritant smoke both smoke density and irritation affect the walking speed. The speed decreases rapidly from 1.0 m/s to 0.3 m/s as extinction coefficient increases from 0.1/m to 0.5/m (see Figure 1). With relatively dense irritant smoke, the participants were not able to keep their eyes open, causing a zig-zag movement or using the wall as an aid to guidance.

The case of non-irritant smoke showed a slower decrease in the walking speed (see Figure 1), with a range of ~0.5 m/s to 1.0 m/s. The range of extinction coefficient investigated in these experiments was 0.2/m to 1.0/m. In this case, if the smoke concentration is higher than 0.5/m (see Figure 1) the ability to walk at desired speed was seriously affected, although to a lesser degree than with the irritant smoke. The subjects continued to walk with a minimum speed of approximately 0.3 m/s, behaving as if in darkness and feeling their way along the walls.

Frantzich and Nilsson performed their experiments in a tunnel that was approximately 37 metres long. It was filled with artificial smoke and acetic acid was used to simulate irritation. A total of 46 people took parts in the experiments. A broader range of extinction coefficient was examined than in Jin's experiments (see Figure 1). The range of extinction coefficient was ~2.0/m to 8.0/m. Two different experimental conditions were considered during these trials: participants walked through the tunnel (1) with the tunnel lighting on and (2) with the tunnel

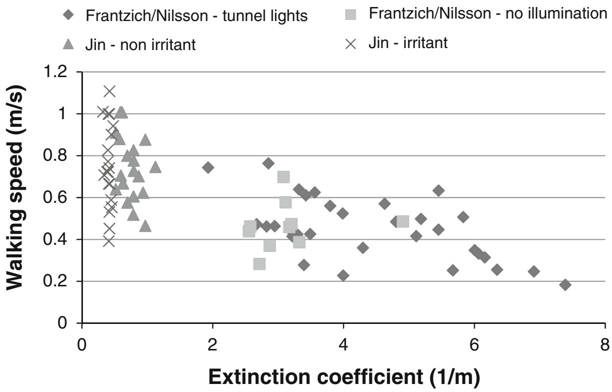

Figure 1. Walking speed as a function of extinction coefficient obtained in Jin's experiments (with irritant and non-irritant smoke) and Frantzich and Nilsson's experiments (with tunnel lights on and no illumination and people using or not using the wall along their path).

lighting turned off (see Figure 1). The analyses were performed separately for the two sets of data and only the data with illumination were used to derive the correlation between extinction coefficient and walking speeds in the analysis performed here. This choice was made because it reflects the current interpretation of this data-set made by the model developers [13].

The walking speed range in Frantzich and Nilsson's experiment was ~0.2 m/s to 0.8 m/s. A scattered data set was produced making it hard to derive a representative occupant walking speed for an assigned extinction coefficient. This is a consequence of differences in participant characteristics/skills and the exact conditions experienced. Another key aspect of the experiments is that occupants seem to walk faster when in close proximity to a wall (the data-set showed in Figure 1 includes both people using the wall or not using it along their path). This finding reproduces observations made by Jin. Also, while Jin's work involved a simple corridor, the Frantzich and Nilsson experimental environment was more complex, involving some way-finding around obstacles. The comparison between the two data-sets can be made by comparing the speed decreasing trend.

Further behaviours may be observed in relation to the occupant's actions when moving through smoke. With regard to minimum walking speed there are two issues: physical ability to move through dense smoke and decision-making about whether to continue or redirect. For non-irritant smoke Jin found a minimum speed of ~0.3 m/s at high smoke densities where subjects moved as if in darkness, with similar findings in the Frantzich and Nilsson experiments [12]. In fire incidents some people are known to have moved through very dense smoke; however, studies by Bryan have shown that the proportion of people turning back rather than entering smoke increases with the smoke density [19]. This depends somewhat on the situation (and the options available), so that people in a relatively clear space may turn back rather than attempting to move through dense smoke, while those engulfed in dense smoke in the enclosure of origin may continue to move through very dense smoke. For tunnel fires some people have walked for several hundred metres in dense smoke [25]. For dense, irritant smoke the conditions may become so severe that people are unable to continue walking due to eye pain and breathing difficulties. Possible relationships between walking speed and effluent composition in terms of irritants have been proposed by Purser [26].

2.2. Data-Set Interpretations

The current knowledge on occupant behaviour in a smoke-filled environment and the manner in which the available data is interpreted is reflected in the manner in which different evacuation models apply this information to simulate occupant performance in smoke.

Currently, there are two methods adopted within evacuation models when representing reduced movement due to the presence of smoke (See Section 2.1):

(A) The smoke produces a fractional reduction of the speed; i.e. the final speed in smoke is dependent on the individual's walking speed in clear conditions, which is then reduced in accordance with some function relating travel speed to smoke conditions.

(B) The smoke effect is interpreted as an absolute reduction of the speed; i.e. the final speed in smoke of each person relies only on the smoke conditions (e.g. extinction coefficient, derived visibility, etc.), regardless of the individual's initial walking speed in clear conditions;

The consequence is that the use of Method (A) will produce *n* curves of speed reduction in relation to the initial unimpeded walking speeds of the single individual. Method (B) produces a single curve of speed reduction that is valid for all the agents, i.e., the final speed is not affected by the initial speed in clear conditions.

With regards to the minimum speed in smoke, there are three different methods currently adopted to bound the impact of the smoke upon occupant movement:

(1) No minimum speed. Each person reduces their speed in relation to the decreasing extinction coefficient.
(2) Constant minimum speed. Each person reduces their speeds in relation to the decreasing extinction coefficient until they reach a constant minimum speed in very dense smoke.
(3) Variable minimum speed. Different minimum speeds are assumed based on the individual.

These three methods reflect three different behavioural hypotheses related to the behaviour of people in poor visibility conditions (i.e. almost complete darkness) and the definition of a threshold of minimum speed. Method (1) relies on the hypothesis that walking speeds are affected by the smoke in any condition. In this case, the extinction coefficient represents the main factor affecting the speed of the individuals. Method (2) is based on the hypothesis that people will not reduce their speed beneath a particular threshold. The entire population of evacuees have therefore a minimum speed corresponding to their speed in complete darkness. This limit, in accordance with Jin studies [11] and Frantzich and Nilsson researches [12] is generally 0.3 m/s to 0.4 m/s (See Figure 1). Method (3) is instead based on the hypothesis that the individual characteristics of the evacuee determines their performance in smoke. Different people may therefore have different minimum speeds in relation to their skills.

The five combinations of these interpretations (there are not six combinations as an absolute reduction in speed does not include the possibility of not having a minimum speed) are:

$$v_i^s = v_i^0 c(K_s) \tag{1}$$

$$v_i^s = Max\{v_{i,min}, v_i^0 c(K_s)\} \tag{2}$$

$$v_i^s = Max\{v_{i,min}(i), v_i^0 c(K_s)\} \tag{3}$$

$$v_i^s = Max\{v_{i,min}, v_i(K_s) \pm \Delta\} \tag{4}$$

$$v_i^s = Max\{v_{i,min}(i), v_i(K_s) \pm \Delta\} \tag{5}$$

(1) Fractional/no minimum speed: the walking speed in smoke v_i^s of occupant i is a fraction $v_i^0 c(K_s)$ (i.e. $0 < c \leq 1$) of the walking speed in clear condition v_i^0 depending on the extinction coefficient K_s. n smoke/speed curves are produced in accordance with the characteristics of n individuals under consideration and there is no limit in the individual minimum (see Figure 2). There is no lower boundary limiting the travel speed that might be reached given the conditions faced.

(2) Fractional/constant minimum speed: the walking speed in smoke v_i^s of occupant i is a fraction $v_i^0 c(K_s)$ (i.e. $0 < c \leq 1$) of the speed in clear condition v_i^0 depending on the extinction coefficient K_s; In dense smoke, all occupants end up at the same minimum speed $v_{i,min}$($\sim$0.3 m/s to 0.4 m/s). n smoke/speed curves are produced in accordance to the characteristics of n individuals, but the curves present all the same minimum speed (see Figure 3).

(3) Fractional/variable minimum speed: the walking speed in smoke v_i^s of occupant i is a fraction $v_i^0 c(K_s)$ (i.e. $0 < c \leq 1$) of the speed in clear condition v_i^0 depending on the extinction coefficient K_s; in dense smoke there is a considerable scattering of speeds i.e. $v_{i,min}$ depends on the characteristics of the occupant i.e. $v_{i,min} = v_{i,min}(i)$. n smoke/speed curves are produced in accordance with the characteristics of n individuals, and the minimum speed is dependent on the characteristics of the individuals. For example, some models (e.g., FDS + Evac) can calculate the minimum speeds as $v_{i,min}(i) = 0.1 v_i^0$. Occupants, even in dense smoke, keep walking with n different minimum speeds depending on their individual skills (see Figure 4). A minimum threshold is applied for each individual below which their travel speed will no fall.

(4) Absolute/constant minimum speed: the walking speed in smoke v_i^s depends on the extinction coefficient K_s (absolute reduction), within a certain range Δ of speeds around the average i.e. speed reduction is independent from the occupant speed in clear conditions v_i^0. In dense smoke, all occupants walk at a minimum speed $v_{i,min}$ ($\sim$0.3 m/s to 0.4 m/s). A single smoke/speed curve is produced for all the occupants. The final speeds for all the individuals are

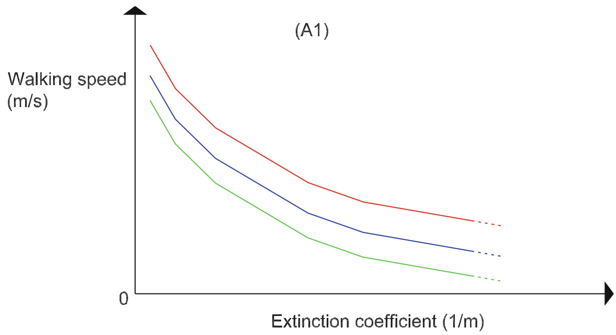

Figure 2. Schematic representation of the fractional/no minimum speed interpretation (1).

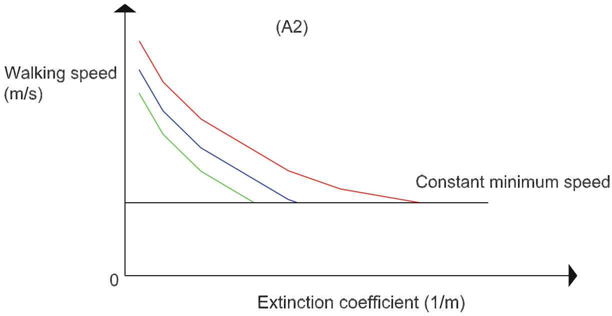

Figure 3. Schematic representation of the fractional/constant minimum speed interpretation (2).

along the line of the single curve employed, including a fixed minimum speed within a certain range Δ (see Figure 5).

(5) Absolute/variable minimum speed: the walking speed in smoke v_i^s depends on the extinction coefficient K_s (absolute reduction), within a certain range Δ of speeds around the average i.e. speed reduction is independent from the initial walking speeds v_i^0. In dense smoke, speed reduction is variable among the occupants i.e. $v_{i,min}$ depends on the characteristics of the occupant i.e. $v_{i,min} = v_{i,min}(i)$ within a certain range Δ. A single smoke/speed curve is produced for all the occupants, with the exception of the last part of the curve where n minimum values are available in accordance with the individual skills of the evacuees (see Figure 5).

Three interpretations [(1), (3) and (4)] have been identified in existing evacuation models and examples of models applying them are selected and discussed in Section 3. The exact type of curve(s) employed will be dependent on the data-set in use and the type of correlation employed (whether it is linear, non-linear, etc.).

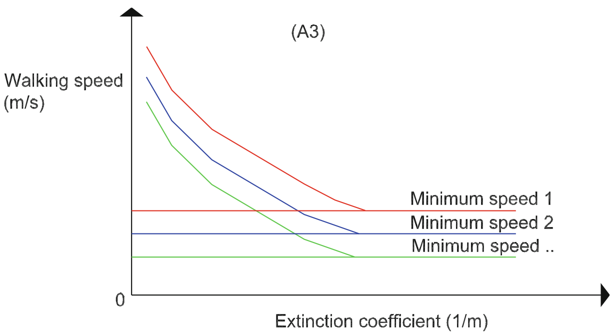

Figure 4. Schematic representation of the fractional/variable minimum speed interpretation (3).

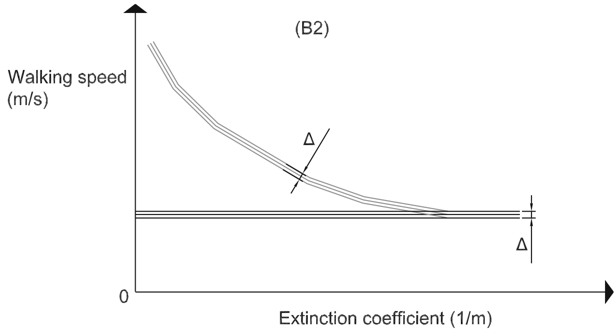

Figure 5. Schematic representation of the absolute/constant minimum speed interpretation (4).

Another important point to be considered is the lighting conditions during an evacuation. The first consideration is the general illumination conditions enabling occupants to see their surroundings in order to avoid obstacles and navigate towards a desired objective such as an exit or a safe escape route. Models are often based upon the assumption of a generalised diffuse illumination, so that a subject's surroundings are viewed by reflected light [27], attenuated depending upon the smoke density. In practice the source of illumination is very important. In a situation such as a tunnel, if illumination is by ceiling lighting then it is necessary to consider the extent to which the illumination and contrast of the surroundings is attenuated by the smoke, in addition to the extent to which there is further attenuation of the appearance of illuminated objects to evacuating subjects. In addition it is necessary to consider the effects of systems such as low level emergency lighting and illuminated exit signage. If a subject is in total darkness due to the combined effects of obscuration of general lighting and visual attenuation by smoke, but can see the glow of an illuminated exit sign, this can give purpose and direction to their escape movements, but may not enable them to see other objects in their surroundings in order to walk forward safely and efficiently. The value of extinction coefficient may vary over a wide range according to the combustion environment and illumination conditions, thus causing considerable uncertainty when selecting the extinction coefficient as an input parameter to visibility models [28]. To some extent these problems can be addressed by gradually incorporating more environmental conditions and/or the individual skills for orientation in smoke into models.

The general lack of theoretical understanding on human performance in smoke makes it difficult to provide a definitive interpretation of the available data-sets. This affects the current evacuation models which use different data-sets and can lead to the models being applied by inexpert users as if the data-sets and the interpretations are equivalent. To explore this problem, this paper provides a case-study where an extensive range of possible scenarios has been investigated varying the two key variables i.e. occupant walking speeds in clear conditions v_i^0 and extinction coefficient K_s.

3. Case Study

Six evacuation models have been selected to test their capabilities to reproduce the impact of smoke on occupant walking speeds. Table 1 shows their different strategies about default settings and embedded data-sets.

3.1. Scenarios

A simple straight corridor (100 m of length and 3.5 m of width) with a single exit located at one end is modelled to test the impact of the different model assumptions on the results produced. The scenarios required a number of further assumptions to be made which were applied across all of the models employed:

- A single agent was simulated to remove agent interaction from influencing the results.
- Smoke was represented (if possible) within the model as being at a constant extinction coefficient throughout the simulation. Visibility conditions were therefore considered as constant in each scenario, although different extinction coefficients were examined between scenarios. No influence of external sources of lights is taken into account.
- The toxic effect of smoke was not considered (i.e. FED [26] is always equal to 0).
- Free-flow conditions were assumed at the final exit and no influence of signage is taken into account.
- Two different environmental conditions were considered during the application of the Jin's data-set [11]: irritant and non-irritant smoke. During the application

Table 1
Evacuation Models Employed and Corresponding Default Settings/ Embedded Data-sets

Model	Embedded data-set	Smoke/speed curve default interpretation
FDS + Evac 2.3.1	Frantzich and Nilsson	(3) Fractional/variable minimum speed
Gridflow 3.03	Any data-set	No default settings
buildingEXODUS 4.1	Jin	(1) Fractional/no minimum speed[a]
STEPS 4.1	Jin/any data-set	(4) Absolute/constant minimum speed
Pathfinder 2011	No embedded data-set	No default settings
Simulex 5.8	No embedded data-set[b]	No default settings[b]

[a] This assumes the scenarios being investigated here. Other aspects of the buildingEXODUS behavioural model in relation to smoke is bounded (e.g. crawling speeds and when the extinction coefficient falls outside the Jin range for irritant and non-irritant smoke conditions)

[b] The feature of a Smoke/Speed correlation is currently under development; i.e. it is available for beta testing but it is not embedded in the model. It is not used in this paper

of the Frantzich and Nilsson's data-set, [12] irritant and non-irritant smoke is not differentiated; i.e. only one correlation to simulate the impact of smoke on speed is provided for both cases. This is based on the fact that the irritant effect in Frantzich and Nilsson's experiment is much less severe than in Jin's experiment [22].
- Jin's data-set is used only within its range of applicability (that is an extinction coefficient within 0.2/m to 1.0/m for non-irritant smoke and 0.2/m to 0.5/m for irritant smoke).
- The smoke influence on speed coming from Frantzich and Nilsson's data-set is derived only from the data where the tunnel lights were on (See Section 2.1) in accordance with model developer's interpretation of the data-set [13].
- Walking speeds were specified at the beginning of the simulations, i.e., random distributions are not used.
- Default agent body dimensions were used, where required.
- Hand calculations of the occupant walking speeds in smoke are used for the models which do not allow the smoke conditions to be represented directly (Pathfinder and Simulex).

Five different initial walking speeds were considered (ranging from 0.25 m/s to 1.25 m/s). Agents with these initial travel speeds were exposed to five different visibility conditions (i.e. extinction coefficients) for irritant and non-irritant smoke. This produces a total of 35 scenarios. A three place naming convention is used for these scenarios. The first place indicates the assumed initial speed of the agent (either 1.25 m/s, 1.0 m/s, 0.75 m/s, 0.5 m/s, or 0.25 m/s). The second place shows the extinction coefficient (10/m, 7.5/m, 3.0/m, 1.0/m, or 0.5/m). The final place indicates whether the smoke represented was irritant or non-irritant (either I or NI). Scenarios where there are no differences about irritant and non irritant gas are represented as I/NI. For instance, Scenario [125_10_I] represents an agent with initial speed 1.25 m/s, in irritant smoke with extinction coefficient 10/m.

3.1.1. Model Input Configuration

3.1.1.1. FDS + Evac. The visibility conditions in FDS + Evac are reproduced using its associated fire model FDS, the Fire Dynamics Simulator [27]. The corridor visibility conditions have been simulated by defining the initial conditions of the environment. This method is based on the assumption of fixed visibility conditions in space and time and no external sources of light. Thus, the calculation of the ratio between the mass of soot and mass of air (Mass fraction—kg/kg) has been provided for obtaining the desired visibility conditions. In FDS, this parameter is the command line &INIT MASS_FRACTION(2) and the input value has been calculated for the 5 different extinction coefficients by simulating a fictitious fuel made of 100% soot. The variables generating toxic gases in FDS are set equal to 0 (i.e. the command line CO_YIELD = 0). Initial walking speeds are inserted as a constant value in each scenario. The random fluctuations within the movement model have been set equal to 0. The current version of the model reduces by default the walking speeds of the agents along a linear correlation produced by the model developers interpreting the experimental data-set provided by Frantzich and Nilsson [12]. The model by default interprets the Frantzich and Nilsson curve as Fractional/variable minimum speed (Interpretation (3) in Section 2.2). The minimum speed is depending on the characteristics of the single agent, i.e. its walking speed in clear conditions, where $v_{i,min}(i) = 0.1v_i^0$. Experimental data give the standard deviations of the experimental parameters employed by the model, but only mean values of reduced speed are used by FDS + Evac for each agent.

3.1.1.2. Gridflow. Each occupant is assigned an unimpeded walking speed—the speed at which they will travel across open floor-space when there are no other occupants causing an obstruction. This can be defined as a single number (for an individual or a group of occupants), or as a distribution (such as normal or log-normal positively skewed). A wide range of observed travel speeds have been reported, depending on factors such as individual differences, sex and environmental conditions. Default walking speeds are assigned from a theoretical normal distribution (mean of 1.19 m/s and a standard deviation of 0.3 m/s, subject to a minimum of 0.3 m/s). The distribution and minimum can be re-set by the used by selecting desired minimum, mean and standard deviation values. In smoke the unimpeded values assigned by the distribution are reduced by the user-defined factor. Inputs are provided by the user through the use of a spreadsheet. FED values are set equal to 0 in this case (i.e. the toxic effect is not considered in these scenarios). In order to test the models against each other, two different sets of speed factors have been used in Gridflow for simulating the scenarios considered. The first is derived from the FDS + Evac approximation of Frantzich and Nilsson's experimental data (fractional/variable minimum speed—Interpretation (3) in Section 2.2) while the second set of speed factors comes from the buildingEXODUS representation of Jin's data-sets (Fractional/no minimum speed—Interpretation (1) in Section 2.2). Hand calculations have been completed for calculating the speed factors according to these two different data-sets and the described interpretations. The speed factors are then inserted into the input spreadsheet for each time step. The susceptibility set for each agent to speed factors was 1, so that every agent will have exactly the selected speed reduction (although it is possible to set varying levels of susceptibility for different individual agents).

3.1.1.3. buildingEXODUS. The agent was generated with an initial *Fast Walk Speed* set to the values indicated in Section 3.1. Within buildingEXODUS an agent can have a range of initial *Fast Walk Speeds* that can either be randomly generated or set by the user. This acts as a base value. This is the speed typically adopted by an agent when traversing horizontal space in a clear environment. The agent was then positioned at the far end of the geometry. An environmental zone was set across the entire geometry and the extinction coefficient within the zone was set to the values of the scenarios examined (as described in Section 3.1). In this case, the toxic impact of the gases present is not represented. The model was configured to either use the embedded Jin irritant curve or the embedded Jin non-irritant curve (with no narcotic or irritant gases explicitly modelled in either case). The model interprets these correlations according to the definition provided in

Interpretation (1) (see Section 2.2), assuming the crawling behaviour is not enabled and the extinction coefficients fall within the Jin ranges (as they are assumed to do here). The Jin curves are applied. The extinction coefficient is then established and the impact derived from the Jin curves and converted into a mobility factor (a *Mobility* attribute within the model) that is used as a coefficient of the *Fast Walk Speed*. Typically, this *Mobility* is set to 1.0; i.e. has no impact on the resultant travel speed adopted. In accordance with the Jin curves, the *Mobility* is kept constant up to a point after it reduces given detected extinction coefficients. buildingEXODUS is also able to represent the impact that smoke has on the initial response of the agent (i.e. whether the presence of smoke causes the agent to respond more quickly than otherwise), the route adopted (e.g. the potential of redirecting away from smoke or passing through it), the potential for crawling (i.e. whether the upper layer of smoke leads the agent to attempt to crawl beneath it), the presence of agent staggering and boundary use for guidance. The first two behaviours were not relevant in this case study as they are not related to the scenario represented. Crawling behaviour is disabled as in buildingEXODUS this is only activated beyond the Jin data ranges. It would not then have been activated in this case given that the smoke conditions examined using the buildingEXODUS matched the Jin data-sets to allow comparison with the other models; i.e. up to 0.5/m for the irritant conditions and 1.0/m for the non-irritant conditions. The impact of staggering within the smoke and wall adherence is included in the simulations as these behaviours were specifically derived from the Jin experiments—buildingEXODUS attempts to represent both the quantitative impact and the qualitative factors from the Jin experiments. However, given the nature of the geometry used, these two qualitative behaviours are expected to cancel each other out somewhat (i.e. the narrow corridor allows agents to find their way and reduce the staggering that might otherwise have occurred) producing a small net effect.

3.1.1.4. STEPS. The visibility conditions in STEPS have been reproduced by importing the fire data simulated with the FDS tool [24]. The geometry was then directly imported from the FDS input file. The method to simulate the smoke is then the same as employed in FDS + Evac. The model permits the smoke concentrations to be represented at a certain height within the computational domain and then employs Jin's smoke vs speed correlation by default, while customised correlation can be used too. Smoke concentrations were homogenous in the considered scenarios. Consequently the definition of the height of the slice file imported from FDS was not relevant; i.e. the slice file would provide the same information about smoke concentrations at any height. The default Jin's curves are then employed (irritant or non-irritant) to simulate the impact of smoke on occupant walking speeds, applying an absolute reduction with a minimum walking speed; i.e. as described in interpretation (4) (See Section 2.2). Also, in this case, the speed reduction is represented in the model through a mobility attribute, that is in this case an absolute value for all the agents. This parameter is kept constant until a minimum smoke concentration threshold, after which the model employs a correlation approximating the data-set of Jin. In line with interpretation (4), all the evacuees slow their speed until they reach the minimum speed threshold. No toxic effects of smoke have been simulated in the model.

3.1.1.5. Pathfinder/Simulex. These models do not permit the impact of smoke on occupant speeds to be directly represented; i.e. no embedded data-sets are provided within the models. Thus, evacuation modellers need to calculate the impact of smoke beforehand, and then reduce the initial occupant speeds in accordance with a pre-defined speed factor to manually represent the impact of the environmental conditions. In order to test the model capabilities and compare models against each other, two different data-sets have been employed by configuring the input as described in interpretation (3) for Frantzich and Nilsson data-set and interpretation (1) and interpretation (4) for Jin's data-set (see Section 2.2).

3.1.2. Results. The results produced with the six models are shown in Table 2. The predicted evacuation times are in line with the correlations provided by Jin and Frantzich and Nilsson. As expected, evacuation times increase with higher extinction coefficients and lower initial walking speeds (Figure 6).

The evacuation times produced appear to be consistent if the same data-set is employed based on the same assumptions; i.e. the smoke impact on speeds is interpreted in the same manner. An example of the consistency of the results has been provided in Figure 7, where Frantzich and Nilsson's data-set has been applied as in Interpretation (3) in four different models (where this data-set is applied by default i.e. FDS + Evac or where a default data-set is not available; i.e. Gridflow, Pathfinder and Simulex) in the case of four different extinction coefficients—respectively 10/m, 7.5/m, 3/m and 1/m.

The analysis of scenarios within the range of applicability of the Jin's curve (that is an extinction coefficient of 0.2/m to 1.0/m for non-irritant smoke and 0.2/m to 0.5/m for irritant smoke) allows us to compare the results of the six models in relation to different default settings employed; i.e. embedded data-set and their interpretation.

Also in this case, results appear to be consistent when applying the same data-set/assumptions. When employing Jin's data-set and interpretation (1), the Gridflow, buildingEXODUS, Pathfinder and Simulex models provide consistent results. The same consistency appears evident when applying Frantzich and Nilsson's data-set for FDS + Evac, Gridflow, Pathfinder and Simulex models. The STEPS model employs, by default, the absolute interpretation of the Jin's data-set (interpretation (4)) different from buildingEXODUS (interpretation (1)). This leads to significant differences among the results. In fact, buildingEXODUS provides, by default, more conservative results (see Figures 8, 9, 10) because of the fractional interpretation of the Jin's curve without imposing a minimum speed in the extinction coefficient range examined (as happens in STEPS model).

Differences also arise when applying different data-sets. Figure 8 shows the results for the case with irritant smoke and an extinction coefficient = 0.5/m. The

Table 2
Evacuation Times Produced by the Six Models Employed

Model:	F	G	G	bX	ST	P	P	P	S	Sim	Sim
Data-set:	F/N	F/N	Jin	Jin	Jin	F/N	Jin	Jin	F/N	Jin	Jin
Interpretation:	A3	A3	A1	A1	B2	A3	A3	B2	A3	A3	B2
Scenario	Evacuation times (s)										
125.10.I/NI	419	417	/	/	/	416	/	/	417	/	/
125.75.I/NI	203	205	/	/	/	204	/	/	205	/	/
125.3.I/NI	107	105	/	/	/	105	/	/	103	/	/
125.1.I	87	87	/	/	/	87	/	/	88	/	/
125.1.NI	87	87	174	175	176	87	176	173	88	174	174
125.05.I	84	83	227	223	209	84	228	208	84	227	207
125.05.NI	84	83	96	97	98	84	98	99	84	96	97
100.10.I/NI	526	527	/	/	/	526	/	/	526	/	/
100.75.I/NI	255	257	/	/	/	257	/	/	258	/	/
100.3.I/NI	133	132	/	/	/	132	/	/	132	/	/
100.1.I	109	109	/	/	/	108	/	/	108	/	/
100.1.NI	109	109	217	218	176	108	220	173	108	219	174
100.05.I	105	104	283	279	209	103	285	208	105	285	207
100.05.NI	105	104	120	121	99	103	121	99	105	121	97
075.10.I/NI	711	713	/	/	/	715	/	/	716	/	/
075.75.I/NI	339	332	/	/	/	333	/	/	331	/	/
075.3.I/NI	177	175	/	/	/	176	/	/	176	/	/
075.1.I	146	145	/	/	/	144	/	/	145	/	/
075.1.NI	146	145	289	290	176	144	291	173	145	293	174
075.05.I	139	140	377	372	209	140	381	208	139	383	207
075.05.NI	139	140	160	162	132	140	162	133	139	161	134
05.10.I/NI	998	1000	/	/	/	999	/	/	999	/	/
05.75.I/NI	509	500	/	/	/	499	/	/	500	/	/
05.3.I/NI	266	263	/	/	/	263	/	/	264	/	/
05.1.I	217	217	/	/	/	216	/	/	217	/	/
05.1.NI	217	217	435	436	199	216	440	201	217	439	199
05.05.1I	208	208	567	557	209	208	570	208	207	570	207
05.05.NI	208	208	241	242	199	208	242	201	207	243	199
025.10.I/NI	1998	2000	/	/	/	1999	/	/	1998	/	/
025.75.I/NI	1005	1000	/	/	/	1001	/	/	999	/	/
025.3.I/NI	529	527	/	/	/	526	/	/	526	/	/
025.1.I	434	433	/	/	/	435	/	/	435	/	/
025.1.NI	434	433	877	872	399	435	876	399	435	878	398
025.05.I	415	417	1143	1115	399	417	1142	399	417	1140	398
025.05.NI	415	417	487	484	399	417	488	399	417	486	398

"Interpretation" refers to the type of interpretation of the smoke impact as described in Section 2.2

FDS + Evac = F, Gridflow = G, buildingEXODUS = bX, STEPS = ST, Pathfinder = P, Simulex = S, F/N = Frantzich and Nilsson data-set employed, Jin = Jin data-set employed

use of Jin's data-set through interpretation (1) (i.e. fractional/no minimum speed) produces evacuation times that are ~170% greater than Frantzich and Nilsson's data-set.

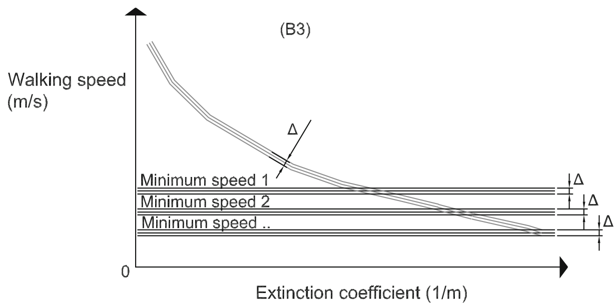

Figure 6. Schematic representation of the absolute/variable minimum speed interpretation (5).

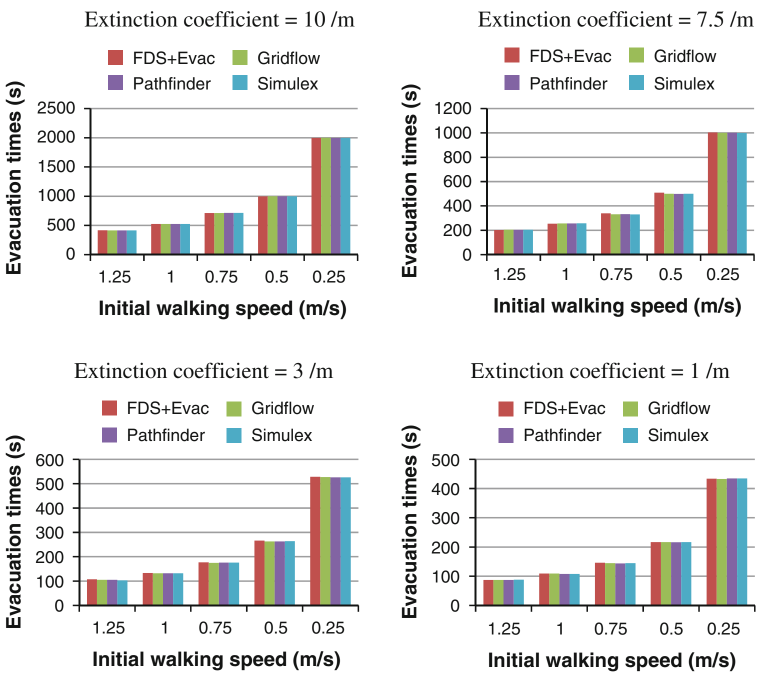

Figure 7. Evacuation times produced by four different models (FDS+Evac, Gridflow, Pathfinder and Simulex) when applying Frantzich and Nilsson's data-set through interpretation (3).

The next scenarios examines walking speeds when extinction coefficients of 1.0/m (see Figure 9) and 0.5/m are simulated (see Figure 10) for the case of non-irritant smoke.

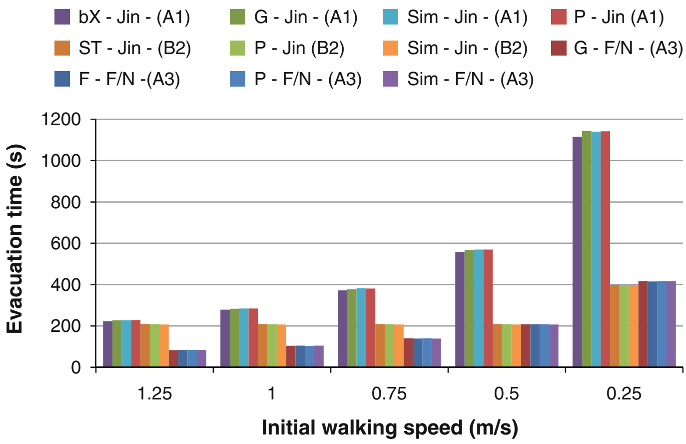

Figure 8. Evacuation times for scenarios with extinction coefficient = 0.5/m and irritant smoke using six models. *X* – *Y* – (*Z*): *X* is the model employed: [FDS+Evac = F, Gridflow = G, buildingEXODUS = bX, STEPS = ST, Pathfinder = P, Simulex = Sim]; *Y* is the data-set employed: [F/N = Frantzich and Nilsson is the data-set employed, Jin = Jin is the data-set employed]; (*Z*) = the type of interpretation of the smoke impact on speeds as described in Section 2.2.

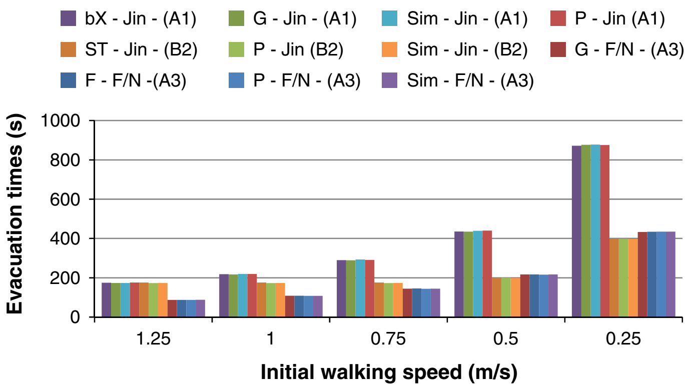

Figure 9. Evacuation times for scenarios with extinction coefficient = 1/m and non-irritant smoke using six models. X – Y – (Z) is following the same representation of Figure 8.

Results show that the use of Jin's correlation assuming interpretation (1) leads to an increase of evacuation times; it consists of approximately a 97% to 107% increase when the extinction coefficient is 1.0/m and 14% to 19% increase when the extinction coefficient is 0.5/m. As expected, the differences in the evacuation times are again higher where lower walking speeds are initially assumed.

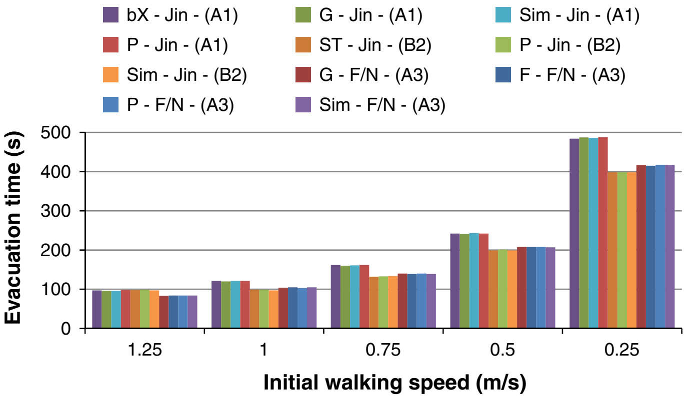

Figure 10. Evacuation times for scenarios with extinction coefficient = 0.5/m and non-irritant smoke using six models. X – Y – (Z) is following the same representation of Figure 8.

4. Conclusions and Discussion

This paper focused on the potential issues that arise when employing evacuation models to simulate the impact of smoke on occupant walking speeds. The impact of model settings, embedded data and user/model interpretations on evacuation modelling results were investigated as part of this effort. The case-study presented covers the basic variables affecting agent performance in response to this scenario; i.e. initial occupant walking speeds in clear conditions and smoke environments with different extinction coefficients. This case study was deliberately simple in order to limit the number of factors that might influence the outcome. Numerous other behavioural factors (crawling, redirection, etc.) have therefore been excluded from this analysis.

Two data-sets have been analysed in detail: Jin's and Frantzich/Nilsson's experimental data. Six models have been compared (FDS + Evac, Gridflow, buildingEXODUS, STEPS, Pathfinder and Simulex) and categorised according to how they embed and interpret these data-sets. A total of 35 scenarios have been examined to test the sensitivity of the results produced, given the embedded relationship between the smoke conditions (i.e. extinction coefficient) and the speed reduction. Models were therefore tested to identify the causes of differences in the results produced; differences that might be produced through the uninformed use of the model.

The results produced show that (1) the application of different data-sets/interpretations or assumptions produced different results irrespective of the models being employed; (2) the results produced were comparable when the same assumptions were employed (i.e. data-sets/interpretations were the same among different models). Result (2) may allow some cross-validation between the models to be conducted; however, result (1) further highlights the importance for the user to understand the data-sets employed within the models and the underlying assumptions made.

The differences in the model results were caused by two factors: (1) the different data-sets embedded in the models and (2) the type of correlation used by the model developers to interpret a specific data-set. Both data-sets can be considered to be equivalent by model users; instead, model users should carefully evaluate the conditions of the scenario of interest before selecting or applying the data-set and/or the associated behavioural assumptions. Model users should be aware of these differences and the potential implications that they might have on the analysis at hand. Similarly, the manner in which these data-sets are implemented differ between models, further complicating the results produced.

The results here have highlighted the need for the user to understand the assumed settings and their impact, to ensure that the settings are credible and appropriate for the application at hand. It is critical that the data-sets embedded and the assumptions employed are sufficiently documented to allow the user to identify and understand these key factors. As has been shown in this paper, if model users do not understand these factors then they may misinterpret the results produced or misattribute the performance levels produced. However, this alone does not ensure credible use of the model. Embedding deliberately conservative estimates or ensuring that the model cannot be used without user intervention (e.g. fewer default data-sets) may provide an additional safeguard against inappropriate (and optimistic) use of the model given its default settings. Although it may make the model initially more difficult and time-consuming to configure, when adopted in conjunction with the necessary model documentation, it may reduce the accidental misapplication of the model.

It should be noted that different applications may have different definitions of conservative values and that it is not always possible for model developers to provide default values that are conservative for all applications. A designer should therefore re-evaluate the appropriateness of the default values provided by model developers in relation to the intended application scenario.

The issues highlighted here arose from a deliberately simple case study. These issues become more complex once the numerous other modelled factors are included.

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