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A new method for assessing the application of deterministic or stochastic modelling approach in evacuation scenarios

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ABSTRACT

The utilisation and importance of evacuation simulation models have grown due to their capabilities in the prevention, management and subsequent analysis of emergencies, and their contribution to protecting human life. Although several evacuation models for different types of scenarios exist in the field of fire safety engineering, it should be noted that most of these employ a deterministic approach. However, the evacuation process is a highly random phenomenon that is subject to the variability of human behaviours and other risk factors pertaining to an emergency.

This paper studies the effect of using a deterministic instead of a stochastic approach in evacuation modelling. In this sense, two methods are proposed: (1) an exact method, which analyses the relative error when a deterministic approach is used and also offers acceptance or rejection criteria and (2) an a priori method, which predicts when a deterministic approach can be accepted or rejected by considering the independent variable characteristics of the corresponding model. Both methods are applied to two evacuation scenarios: 1) passenger trains and 2) road tunnels. These application cases show the usefulness of these two methods. Furthermore, this paper shows the necessity of continuing to study the influence of diverse factors in deterministic or stochastic modelling for evacuation analysis.

1. Introduction

During the last decades, the use of egress models for managing emergency situations in different situations and scenarios has grown [1–4]. These models overcome the difficulties or impossibility [5,6] of performing realistic and expensive evacuation drills for different environments (building types, facilities, transport types, etc.) that would allow preventive and management strategies for human safety to be obtained. Evacuation modelling allows different scenarios to be simulated by considering the physical characteristics of the scenario, people involved and emergency conditions. These models have been applied [7] mainly for the following purposes.

Performance-based analysis: this is applied mainly for new and existing buildings in order to evaluate the design and evacuation procedures [8,9].

Forensic analysis: this allows an evacuation process that occurred in the past to be reconstructed in order to analyse possible failures and inefficiencies.

Management: this use of models allows real-time simulations in order to establish rapid and efficient management during evacuation procedures.

The literature includes a few evacuation model reviews [1,3,4]. These reviews show that, apart from their use in the field of transportation (ships, aircraft, and trains) [10,11], most egress models have been employed mainly for application to buildings and they have also been used (adapted) for other kinds of scenarios.

The evacuation is a highly random phenomenon, due to the uncertainty of both human behaviour and the development of the emergency itself [12]. In some cases the uncertainty can be associated with the early stage of the experimental research as well. Models use distribution laws to treat the randomness of human actions and decision inputs; however, they essentially use a deterministic approach for outputs, since they produce only one sample of possible results.

The importance of a stochastic approach in evacuation analysis was expressed by Jason Averill in [12]. However, it is clear that this approach is more complex than deterministic modelling in terms of data collection and processing, computational sophistication and run times, output processing, etc.

The purpose of this study is to investigate how a deterministic and a stochastic approach each affect one of the main results in evacuation modelling (total evacuation time or the time in which the last person reaches a safe area).

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A priori and exact methods are presented to analyse the impact of using a deterministic instead of a stochastic approach. Furthermore, criteria for selecting the appropriate approach for application scenarios are proposed. Finally, the application of these methods to two stochastic models, EvacTrain 1.0 and EvacTunnel 2.0, is studied. The challenge is to obtain equilibrium between the accuracy of the results and the efficiency of the model.

2. Determinism or randomness: exact method

All the processes of nature are essentially random [13], because they are based on a set of unpredictable factors that cause the results to vary according to chance. However, in some cases this influence can be minor or even imperceptible. We can obtain the mathematical representation of this circumstance. Let us consider the phenomenon's result as a set of variables:

$$Y = \{\overline{y}_i + \varepsilon_i\} | i = 1, n \tag{1}$$

where $\overline{y_i}$ is the mean value of variable y_i, ε_i the random fluctuation of variable y_i and n the total number of variables that characterise the phenomenon or process.

For practical purposes, if we assume a deterministic approach, the phenomenon would be defined by average characteristic variables. Therefore, a relative error $\tilde{\delta}$ would be assumed:

$$\tilde{\delta} = \{\delta_i\} = |\varepsilon_i| / \overline{y}_i | i = 1, n \tag{2}$$

In order to assume a deterministic approach, we should consider an acceptable relative error $\tilde{\delta}$. It should be noted that the acceptable $\tilde{\delta}$ can be different for each of the parameters that characterise an evacuation process.

However, we assume the same acceptable $\tilde{\delta}$ for all these variables. It should be noted that the acceptable error is strongly influenced by the type of analysis and the application scenario. Therefore, the deterministic approach is accepted if

$$\forall \delta_i \to \delta_i \le \tilde{\delta} \big| \; i = 1, n \tag{3}$$

Nevertheless, we cannot ignore that ε_i is a random parameter. This implies that the inequality (3) has a casual character and its probability of occurrence should be considered:

$$Pr[\forall \delta_i \to \delta_i \le \tilde{\delta}] = p_o \big| \; i = 1, n \tag{4}$$

where p_o is the probability of occurrence (a high probability is assumed like 0.9, 0.95, 0.99,…).

By considering the deterministic character of $\overline{y}_i$ and $\tilde{\delta}$, Eqs. (2) and (4), we can obtain that

$$Pr[\delta_i \le \tilde{\delta}] = Pr\left[\frac{|\varepsilon_i|}{\overline{y}_i} \le \tilde{\delta}\right] = p_o \Rightarrow \frac{\max_{p_o}|\varepsilon_i|}{\overline{y}_i} \le \tilde{\delta} \tag{5}$$

where $\max_{p_o}|x|$ is the maximum value with probability p_o of x.

The maximum value of ε_i may be represented by

$$\max_{p_o}|\varepsilon_i| = \begin{cases} P_{p_o}(y_i) - \overline{y}_i & \text{if} \quad \varepsilon_{i_{crit}} > 0 \\ \overline{y}_i - P_{1-p_o}(y_i) & \text{if} \quad \varepsilon_{i_{crit}} < 0 \end{cases} \tag{6}$$

where P_p is the percentile of random variable x and $\varepsilon_{i_{crit}}$ the critical value for random fluctuation of variable y_i. Based on the variable application, the effectiveness of the phenomenon is improved when $\varepsilon_{i_{crit}}$ increases, or vice versa.

Eqs. (5) and (6) indicate that the acceptance of a deterministic approach depends on the equation compliance.

$$\begin{aligned} &\frac{P_{p_o}(y_i) - \overline{y}_i}{\overline{y}_i} \le \tilde{\delta} \text{if} \quad \varepsilon_{i_{crit}} > 0 \\ &\frac{\overline{y}_i - P_{1-p_o}(y_i)}{\overline{y}_i} \le \tilde{\delta} \text{if} \quad \varepsilon_{i_{crit}} < 0 \end{aligned} \tag{7}$$

In evacuation modelling, one of the output variables that characterise the evacuation process and modelling result is the total evacuation time T_{evac} [14] or the time when the last person reaches a safe area.

This variable permits us to define whether people are able to leave the area safely in a reasonable time in a specified scenario and hazard situation. The acceptance or rejection of a deterministic approach in this kind of process has critical consequences for the saving of lives. From the previous equations and by considering that for this modelling purpose, if T_{evac} increases, the situation is more unfavourable (condition $\varepsilon_{i_{crit}} > 0$). We assume that a deterministic approach can be acceptable if

$$\delta(T_{evac}) = \frac{P_{p_o}(T_{evac}) - \overline{T}_{evac}}{\overline{T}_{evac}} \le \tilde{\delta} \tag{8}$$

where $\overline{T}_{evac}$ is the mean value of evacuation time and $P_{p_o}(T_{evac})$ the p_o percentile of evacuation time.

Eq. (8) permits us to define whether or not a deterministic approach can be used for a specific evacuation model in a particular scenario. In order to use Eq. (8), $\tilde{\delta}$ should defined; however, this acceptable error is commonly assumed to be 0.05, 0.10 or 0.15 for engineering applications. Furthermore, the mean and p_o(i.e. 0.99) percentile values of evacuation time should be obtained.

Several evacuation drills should be performed in order to obtain $\overline{T}_{evac}$ and $P_0(T_{evac})$ experimentally. Furthermore, these evacuation drills will obtain uncertain results, since it is unlikely that the real conditions of an emergency are represented. A stochastic model for the application scenario should be developed (or used) in order to obtain the mean and percentile of evacuation time. This requires mathematical and computational modelling of the dependency

$$\overline{T}_{evac} = f(x_j) \big| \; j = 1, m \tag{9}$$

There are different types of independent variables x_j in an evacuation model, depending on the selected modelling features (type of network, movement representation, behavioural characteristics, etc.), application scenarios and modelling purpose. The randomness of the variables x_j will define the randomness of dependent variable T_{evac}.

Eq. (9) allows one to obtain a stochastic evacuation model. The probability distribution laws of x_j (and its statistical characteristics) allow one to obtain a sample of evacuation times using Monte Carlo methods [15,16].

The statistical treatment of the results of the sample enables one to obtain its probability distribution law and statistical parameters (mean and percentile). Finally, Eq. (8) analyses the convenience of using a deterministic instead of a stochastic approach.

It should be noted that a stochastic model can be used as a deterministic model by considering the dispersion (variance of standard deviation) of independent variables near zero.

The hypothesis that the greater the randomness of independent variables x_j, the greater the randomness of dependent variable T_{evac} that can be assumed, and a stochastic approach should be considered for evacuation modelling.

Therefore, if we can evaluate the level of randomness of independent variables x_j, we will be able to define a priori the convenience of using a stochastic approach without obtaining the complete mathematical and computational models. This is explained in the following point.

3. Determinism or randomness: a priori method

The a priori method analyses the level of randomness of independent variables for a hypothetical evacuation model. This