Fire risk assessment with a stochastic approach – Model development and application to an auditorium

Samia Haouari Harrak, Philippe Fromy, Pascal Boulet, Rabah Mehaddi, Elizabeth Blanchard

FIRE RISK ASSESSMENT WITH A STOCHASTIC APPROACH – MODEL DEVELOPMENT AND APPLICATION TO AN AUDITORIUM

Samia Haouari Harrak*(1) (2), Philippe Fromy(1), Pascal Boulet(2), Rabah Mehaddi(2) & Elizabeth Blanchard(1)
(1) CSTB (Centre Scientifique et Technique du Bâtiment) - Université Paris Est, 84 avenue Jean Jaurès Champs sur Marne, 77447 Marne-La-Vallée cedex 2, France
(2) Université de Lorraine, LEMTA, CNRS UMR 7563, TSA 60604 Vandoeuvre-lès-Nancy, F-54518, France

ABSTRACT

A fire safety engineering code, SCHEMA-SI, was developed with the goal to design fire safety in buildings with a performance-based approach. The originality with the current practice is to associate dynamically human behaviour, human displacement, fire dynamics and features in interaction, thanks to coupled models and stochastic approach. This paper presents the associated principle and the code structure. We focus here on the differences with the first version already presented in Ref[1]. Then, this paper presents a case study in an auditorium. In this application, SCHEMA-SI allows to design a fire safety strategy combining soft and hard features, in other words organizational and technical features. It demonstrates that soft features have a strong impact on fire safety performance. Moreover, in the presented case study, isolated technical features may not lead to the required fire safety level, it is necessary to associate them to organizational features.

INTRODUCTION

Fire safety relies on a combination of features which can be technical (smoke detector, smoke exhaust system, sprinkler for instance) or organizational (e.g. to ensure safety staff role in particular). However, in most cases, building fire safety is studied with a performance-based approach by considering technical features only and even some of the features solely. Indeed, the integration of feature combination and the estimation of a consecutive global fire safety level are tricky problems.
Our research is conducted within the frame of fire safety engineering. It aims at developing a numerical tool capable to integrate all features cited previously and also human behavior. It is named SCHEMA-SI.

PRINCIPLE OF SCHEMA-SI CODE

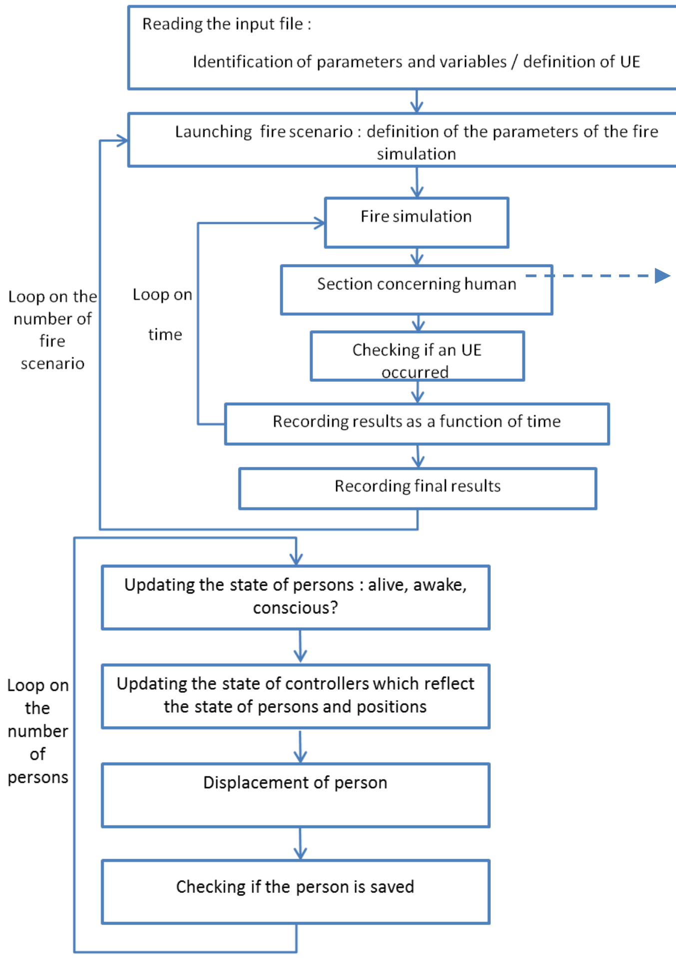
The SCHEMA-SI code is a stochastic hybrid model simulating dynamically continuous and discrete events. It is based on a two-zones fire model CIFI and a human evacuation model. The approach consists in simulating a large number of fire scenarios inside a building. In particular, the primary fire source, the way it burns and propagates, the door/window initial open state and also human decisions and displacements are defined stochastically (e.g.: evacuation way, time for evacuation, lethal conditions).
In each scenario, continuous phenomena are related to fire (fuel burning, smoke flow) and discrete events occur. These discrete events can be induced by the fire (e.g. window/door breakage) or by human intervention. For instance, when someone evacuates, he opens doors and can close the door after, he can open a window, he can himself help to evacuate people by warning …
The fire risk is quantitatively assessed by computing a level equal to the frequencies of "undesired-events" occurence. An undesired event gives a level of fire severity. Each undesired event (UE) is defined before the simulation. It could be associated to the death of one person, the death of several

people or even material damage. Furthermore, outputs can be analyzed to identify the inputs that lead to undesired events.

PRESENTATION OF SCHEMA-SI CODE

The SCHEMA-SI code in its first version was presented in Ref[1]. The version 2 is developed in Fortran 90. The code begins by randomly defining fire scenario parameters. Then, the simulation is conducted on a large number of fire scenarios in which the value of each random parameter changes, according to a probability distribution law on a given range. Five laws are available, uniform law, triangular law, x^2 law, normal law and the Weibull law (with a dispersion parameter, by default equal to 0.04).
Figure 1 illustrates the code structure. First, the input file is read. Then, before starting each fire scenario, and before launching the fire zone-model CIFI, the value of each random parameter is set. Next, fire is ignited. During the simulation, fire is growing, people evolve (become conscious of the fire, awake, die) and / or move in the building. At the end of the fire scenario, the code checks if an undesired event occurred and records it in a file. Then, a new fire scenario begins.
Interactions between fire and people are modeled using extensively controllers and Booleans. As an illustration, when a person moves from a room to another and opens a door which was initially closed, the door opening state changes, its controller moves from FALSE to TRUE. If the person closes the door after a while, the controller changes its state to become FALSE again, after the indicated lapse of time.

Figure 1: Structure of the code



Fire model

As previously mentioned, the fire model implemented in SCHEMA-SI is CIFI. The latter is a multi-compartment two-zones model. CIFI was developed at the CSTB from 1970 onwards and it was validated for different configurations including room fires[2]. The model predicts the effects of the development of a fire within a multi-storey building. CIFI is similar to the well-known CFAST model developed in the US by NIST. FORTRAN code related to fire model includes a time loop. At each time step, the model calls the different physical models to calculate mass and energy flows generated by the various components of the system (walls, openings, smoke extraction systems, fire sources, ...). Then, an ordinary differential equation systems solver is used. The variables describing each zone of each room are also updated.

Human evacuation model

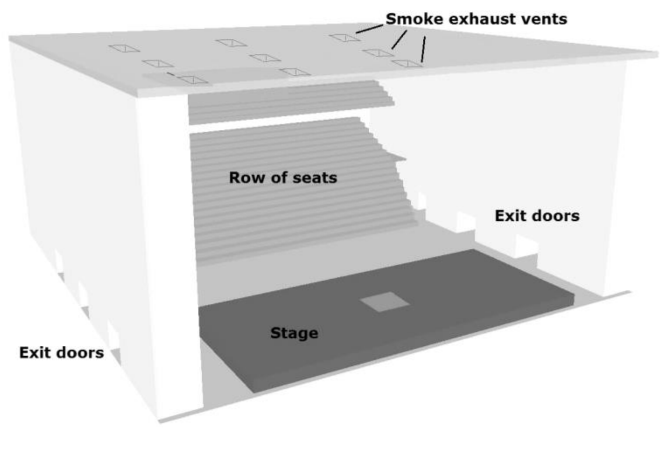
Each person is considered individually at each time step, considering its position and states. A person is characterized by four different states: alive or dead, conscious or unconscious of the fire, asleep or awake and saved or potentially at risk. For each state, the state transition is valid only in one direction: a living person becomes dead, an unconscious person becomes conscious, a sleeping person becomes awake, and person potentially at risk becomes saved.
A person state transition may depend on ambient conditions and also on the state or the position in the building of this person or another person. The transition conditions are defined in the input file.
The model of people displacement within the building is a very simple discrete model. A person moves from one room to another within a certain time. The decision of the person to move can be conditioned by the ambient conditions and by his state (conscious /unconscious, asleep / awake). It can also depend on other people (states, positions).
FORTRAN code related to human evacuation includes a loop on the number of persons (cf. Figure 1). For each person, the code updates his state (living, conscious, awake) according to the ambient conditions, the position and the state of this person or other persons. Then, the state of each controller which describes the person is updated. Next, the person is moved if the conditions of displacement are verified. Finally, the code checks if the person is saved.

APPLICATION TO AN AUDITORIUM

SCHEMA-SI code is applied to a case study that takes place in an auditorium. The objective is to design a smoke exhaust control system. Two different organizational strategies are considered.

Auditorium description

Figure 2: Sketch of the auditorium



The auditorium geometry is simple. It is parallelepipedic, 40 m large, 40 m long and 20 m high. Several doors allow people evacuating. They are located at the bottom of the auditorium. The costumer requires a natural smoke exhaust control system with vents located on the roof.
Here, in the scope of the present paper, the geometric surface area of the roof vents is set. It represents 60 m². The air supply is ensured by exit doors, which represent 54 m².

Fire scenarios

In the simulations, we consider several fire loads differing by HRR, growth time period, rate, and location (on the floor or on the stage). We consider two wind conditions, different exit door opening chosen in a given time period too. All smoke exhaust vents are opened when the fire starts burning. The exit doors are closed at the beginning of the simulation (t = 0 s), except two doors.

Combined to the smoke exhaust system, two different organizational strategies are studied. In the first strategy, the safety staff does not help people to evacuate. People evacuate by themselves. We also associate a long time period for people evacuation, between 5 and 20 minutes. Moreover, doors for air supply are only opened when people are evacuating. In the second strategy, the safety staff plays a large role in people evacuation, they have to open the exit doors and let them opened. Thus, people evacuate in a shorter time (2 to 10 minutes), and air is supplied sooner.

Undesired events

Six undesired events (UE) are defined. The first four UE characterize fire conditions within the auditorium regarding seat row height (smoke filled degree and thermal conditions) without considering people evacuation. The two last undesired events integrate in addition the time for people evacuation.

UE 1: Smoke layer height Z_{int} is below 15 m high (the height of the last row of bleachers increased by 2 m).

UE 2: Smoke layer height Z_{int} is below 12 m high (the high bleachers become in contact with smoke).

UE 3: Smoke layer height Z_{int} is below 10 m high (half the auditorium height).

UE 4: Smoke layer temperature exceeds 50 °C. This UE characterizes a critical thermal environment for the public in contact with the smoke.

UE 5: Smoke layer height becomes lower than 15 m, before the public leaves the auditorium.

UE 6: Smoke layer height becomes lower than 15 m and the upper layer temperature exceeds 50 °C before the public leaves the auditorium.

Result analysis

Our analysis is conducted in three stages. Firstly, the frequency of occurrence for each undesired event is compared for the two strategies. In the second stage, we analyze the time at which an undesired event occurs. In the third stage, we identify which input parameter induces a larger probability that an undesired event occurs.

– Frequency of occurrence

Table: Occurrence frequencies for each UE in 500 fire scenarios for both strategies

UE	1	2	3	4	5	6
Strategy 1	100 %	89 %	57 %	75 %	100 %	36 %
Strategy 2	80 %	2 %	0 %	67 %	46 %	9 %

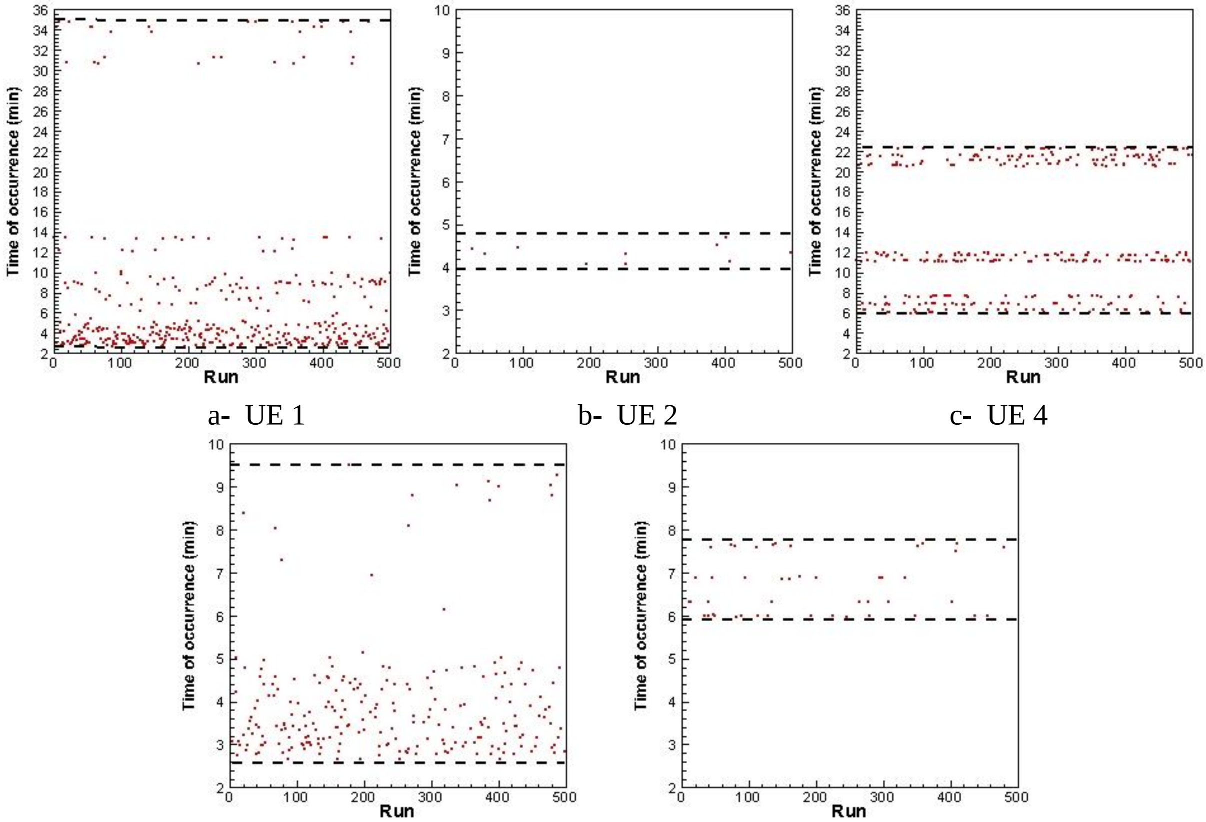
The results show that the second strategy induces a strong reduction of each UE occurrence frequency. In other words, each UE occurs less frequently in all simulated scenarios.
Thus, the auditorium is really less filled with smoke with the second strategy. In particular, the smoke layer height is never below 10 m from the floor in all simulated scenarios (corresponding to UE3 with a frequency equal to 0) whereas it is below 10 m in 57% of the cases with the other strategy. In addition, with the first strategy the smoke layer height remains below 15 m from the floor in all fire scenarios simulated (corresponding to UE 1 with a frequency equal to 100 %) whereas it is above 15 m in 20 % of the fire scenarios simulated with strategy 2.
According to the sole criterion of smoke layer height, our smoke control solution is not satisfactory, but if we also take into account the other criteria of smoke layer temperature and public evacuation time, our solution may be satisfactory if 9 % (UE 6 occurrence frequency) is considered as an acceptable value.
A second level of results involving the instants of occurrence of each UE, can contribute to decide if our solution can be satisfactory or not.

– Time of occurrence

The instant of occurrence of each UE is registered in 500 fire scenarios for the strategy 2. Figure 3 illustrates the distribution of the time of occurrence of each UE. This figure shows that the smoke layer height Z_{int} becomes lower than 15 m (UE 1) between 2 and 35 minutes, and mainly between 3 and 5 minutes. Moreover, it becomes lower than 12 m (UE 2) between 4 and 5 minutes. Furthermore, in case of fires for which the maximum heat release rate is equal to 7.2 MW or 14.4 MW, the smoke layer

temperature exceeds 50 °C (UE 4), between 6 and 8 minutes for a fast fire growth rate, between 11 and 12 minutes for a medium fire growth rate and between 2 and 22 minutes for a slow fire growth rate. In comparison, for the smallest fire (HRR= 3.6 MW), regardless of its fire growth rate, the temperature of the smoke layer never reaches 50 °C.
The figure 3-e shows that the people die between 6 and 8 minutes after the fire start (UE 6).

Figure 3: Distribution of the time of occurrence of each UE



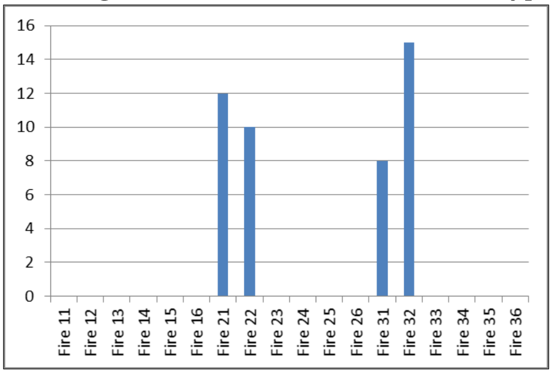
a- UE 1 b- UE 2 c- UE 4

d- UE 5 e- UE 6

– Influence of input parameters

The aim is to identify the fire characteristics in each fire scenario where people die (UE 6).
In the simulations, we consider 18 fire types: 3 heat release rates (3.6 MW, 7.2 MW, 14.4 MW), 3 growth rates (slow, medium, fast) and 2 fire positions (on the floor $Z_f = 0$ m or on the stage $Z_f = 2$ m). For each fire scenario, one fire type is activated.
Figure 4 shows the number of occurrences of the UE 6.

Figure 4: Number of times each fire type led to the occurrence of the UE 6

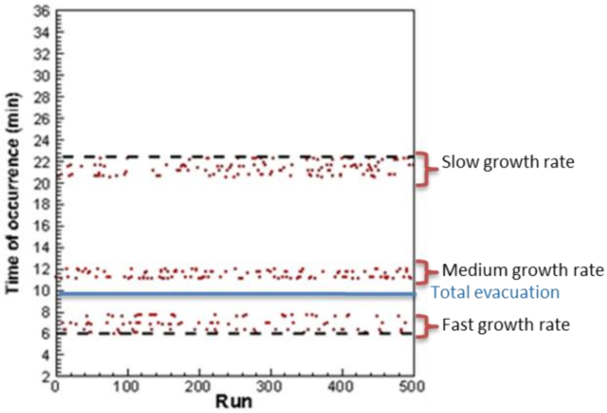


	Maximum HRR (MW)	growth rate	Fire position (m)
Fire 21	7.2	Fast	0
Fire 22	7.2	Fast	2
Fire 31	14.4	Fast	0
Fire 32	14.4	Fast	2

The UE 6 occurs when the value of the maximum heat release rate is equal to

Figure 5: Distribution of the instants of occurrence of UE 4

7.2 MW or 14.4 MW and the fire growth rate is fast. This is explained by the criterion of smoke layer temperature and the maximum duration of the evacuation. Indeed, according to figure 3-c, which represents the distribution of the time of occurrence of the UE 4, and taking into account the maximum duration of the evacuation (10 min), it appears that the fire types conducting to a temperature of 50°C before 10 min are those for which the value of the maximum heat release rate is equal to 7.2 MW or 14.4 MW and the fire growth rate is fast (cf. Figure 5).



Based on our analysis, the present case study shows that strategy based on technical and organizational features is better than the strategy based on technical features only. It illustrates that the technical features may (or may not) lead to the required fire safety level depending on its combination (or not) with organizational features. Indeed, it appears that fire safety strategy is greatly better when people evacuate while doors are opened in a short time after the fire starts burning. Moreover, this case study shows that organizational features have a stronger impact on fire safety.

CONCLUSION

The present paper presents SCHEMA-SI code developed with the goal to design fire safety in buildings with a performance-based approach. It allows to simulate continuous phenomena related to fire and discrete events induced by the fire (e.g. window/door breakage) or by human intervention. In other words, the tool is able to simulate a combination of features which can be both technical (smoke detector, smoke exhaust system, sprinkler for instance) and organizational (e.g. to ensure safety staff role in particular). It also involves human behavior. It is based on a generation of thousands of fire scenarios and on a statistic analysis. This statistical analysis helps to select acceptable strategies, and also to identify the factors that most influence the level of security of the building. For example, in the application case presented in this paper, the results show that the fire types with the maximum heat release rate equal to 7.2 MW or 14.4 MW and the fastest fire growth rate, can lead to the death of people. Moreover, it demonstrates that soft features have a strong impact on fire safety performance and that technical features solely may not lead to the required fire safety level. It is necessary to associate them to organizational features.

REFERENCES

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