# A Probabilistic Approach to the Analysis of Fire Safety in Hotels: MOCASSIN

**B. HOGNON and M. ZINI**
Centre Scientifique et Technique du Bâtiment
Champs sur Marne, BP 02
77421 Marne La Vallée Cedex 02, France

## ABSTRACT

After defining a quantifiable criterion i.e. the probability of a fire causing multiple victims, an explanation is given of the advantage of using event-oriented modelling, to which a simulation technique can be applied. The MINHOTAURE model, developed to represent the possible functioning of the system being considered, is a temporized, stochastic Petri net. After reviewing the rules which govern the operation of this type of network, the contents of the model, its possibilities and limits are briefly described. Scenarios are automatically created by a software package which uses a Monte-Carlo simulation to choose the valid transition delays. This software enables groups of scenarios to be simulated, different in both number and time. It supplies information concerning the marking of places and conditions reached during or at the end of scenarios. Finally, in order to illustrate the advantage of and the possibilities offered by this approach, the probabilities of 4 events are given, two of whic correspond to the presence of multiple victims at the end of the simulated scenarios. The results concern 6 projects which, for the same hotel, differ with regards to the safety equipment used.

**KEYWORDS** : *Fire safety analysis - Fire safety level - Deadly fire - Mutltiple victims - Probability - System - Simulation - Event-oriented modelling - Probabilist approach - Petri net - Place - Transition - Message - Marking - State - Action delay - Stochastic network - Monte-Calo simulation technique - Random variable.*

## INTRODUCTION

The need for an analysis method to predict the fire safety level of buildings open to the public is largely sahred by the public authorities, architects and engineers in numerous countries. This is a particulary so in France where the Department of Civil Defence (DSC) would like to eventually complete the current regulations based on obligation of means, by new regulations based on obligation of results.

The success of this approach should satisfy an urgent demand expressed for a number of years now by the designers of buildings for public use. To do this, the

DSC has asked the CSTB (Centre Scientifique et Technique du Bâtiment) and CEPS (Contrôle et Prévention Systèmes) to conduct a feasibility study and produce a model for hotels, based on the hypothesis of a fire breaking out in a guest room.

## FIRE SAFETY LEVEL

### Choice of a qualitive criterion

The expression "level of safety" is a convenient term to use but it must be formally defined in order to be determined quantitatively. In the case of hotels, what the public authorities are concerned with is preventing deadly fires causing victims other than the occupants of the room in which the fire originated, which is considered to be a private space and does not concern collective safety. During a hotel fire, the death of several people indicates the insufficiency or failure of the safety measures applied to the establishment. With regards to the aim of collective safety, regulated by the public authorities, it is an unwanted event the occurrence of which can be used as a criterion for evaluating the safety level. It is the use of this type of criterion which directed us towards the choice of event-oriented modelling.

### Quantitative definition of criterion

With regards to the safety analysis practice, the statement that absolute safety does not exist is a basic assumption. Thus, we will try and determine, by calculation, the probability of unwanted events occurring. By transposing this type of approach to our problem, the fire safety level of a hotel can be defined by calculating the propability of occurrence i.e. the probability that a fire, having been declared, will lead to multiple victims. The lower the probability of this critical event occurring, the higher the fire safety level of the establishment.

It should be noted that this approach does not include calculating the probability of a fire occurring in a hotel room, since it is considered a private area and is thus not covered by preventive measures of a regulatory order.

Working out a methodology for calculating the probability of a fire causing multiple victims and its application to various types of public establishments, will eventually provide the public authorities with the possibility of determining an obligation of result, expressed in the form of a maximum value which must not be exceeded, so that an establishment can be considered reasonably safe for the people in it.

## METHODOLOGY USED

### Simulation

In order to determine the probability of an unwanted event occurring during the functioning of a system, it must be possible to study a large number of developments for the system concerned. The system which we are concerned with here is a hotel, in one of the rooms of which accidental ignition occurs for an undetermined reason. This leads to incorrect functioning of the system, to varying degrees.

Since it is impossible to examine in real world a large number of examples of incorrect functioning, either by observation or by testing the system itself, a simulation technique must be used. Simulation is a method used to study complex systems and phenomena which consists in replacing them with a simpler model with similar behaviour, on which the experiment is carried out and not on the system.

Simulation can be applied to either an existing system or a system still being designed. It can therefore be perfectly incorporated into the different stages of building design and the examination of building permits. It means that a prediction analysis of the effectiveness of measures designed to protect users from deadly fires can be carried out, thus meeting the demand of the public authorities.

## Event-oriented modelling

The system to be studied here is far too complex to derive proper equations on the physics of all its aspects which include the following :

- the development of fire and the propagation of produts of combustion and smoke inside a hotel,
- the behaviour of the occupants of the hotel, both guests and staff,
- triggerring of fire safety equipment and the effect thereof,
- the contribution of external aid - fire fighting, rescuing of occupants who were not able to leave the premises and are in danger from the fire, etc.

The computer mathematical models wich are available today do not cover all these aspects. Due to their elaborate forms, these models are too unwieldy to use for them to be currently incorporated into a coherent set of programs. Also, since these models are of the deterministic type, they can only produce a single scenario, based on an given initial situation, and a single end result. The calculation time required using work stations currently available to the engineer is often far longer than the actual physical time of the simulated scenario. This is a considerable deterrent to using the probabilistic approach, since it means increasing the number of scenarios, based on the same initial condition of a system, in order to arrive at various end results, some of which can include the unwanted event - the presence of many victims in the hotel after the fire.

We must therefore direct our attention towards methods for modelling the dynamic behaviour of discrete systems. CEP Systèmes has thus examined the possibility of representing the problem with methods conventionally used for the safety of systems. This has led to selecting an event-oriented model of all the aspects of the system using the temporized stochastic Petri net.

## Temporized stochastic Petri net

This type of model consists in describing the system and its potential functions using four sets of objects - places, transitions, arcs and messages. Places represent the basic possible states of the various components of the system. Tokens are used to demarcate the finished set of places. The places marked at any given time define the state of the system at that time. Logic and graphic representation of the network consists in linking together certain places and transitions using valuated arcs, which diagrammatically represent possible fractions of scenarios. The valuation of weight of the arc indicates the number of tokens associated with crossing the corresponding transition. This results either in withdrawing token(s) from the upstream place, or adding token(s) to the downstream place.

The messages are Booleans which take on a true or false value. They are used so that crossing the associated transitions which appear in the different parts of the network, that is, in the representation of the various subsystems, can be synchronized or made possible. Transitions correspond to events whose occurrence changes marking of the network and therefore the condition of the mock-up system. Crossing certain transitions is accompanied by the issuing of a change in the Boolean value of certain messages ; as a result, certain other transitions, frozen up until then, become valid.

Crossing a given transition is only possible if three rules are satisfied.

*First rule* : the entrances places, linked to the transition in question by an upstream arc, must be marked with the necessary number of tokens. For example, if the weight of the upstream arcs is equal to 1, crossing the transition is accompanied by the removal of one token from each upstream place. A token is then added to each place linked to the transition by a downstream arc given a value of 1 ; this called an exit place. To model our problem, only arcs with a weight or value of 1 have been used, to simplify management of the tokens.

*Second rule* : If one or more messages associated with the upstream arcs are of prerequisites for crossing the transition, the Boolean value of these messages must be checked. If one of these messages does not have the Boolean value required, the transition is not valid and therefore cannot be crossed.

If, on the other hand, these first two rules have been satisfied, the transition is said to be valid or passable. Generally speaking, at any given moment, several transitions in a network are valid at the same time ; a third rule must then be applied, which is specific to temporized stochastic Petri net, and determines which of the transitions will be crossed first and causes a change in the state of the system.

*Third rule* : In a temporized stochastic Petri net, a crossing delay is associated with each transition. A transition which is valid at time t will only be crossed at a later instant t + δ, where δ is the crossing delay for the transition in question. If, at time t, the network has n valid transitions, that whose moment of crossing occurs first i.e. T j, must be identified by comparing the delays t + δ i, and that transition must be crossed at t + δ j. The action delays δ i, associated with the transitions, can be eitheir constants or variables corresponding to given distribution functions. In the last case, befor applying the third rule, after each crossing, the time-delays to be attribued to the transitions which have become valid at the instant in question must be determined.

It is at this stage that chance is taken into account in order to represent the large variety of real cases possible. By associating a random value generated by a Monte-Carlo simulation with each time-delay assigned to a valid transition, a random character is also assigned to the chaining of crossings, which is what happens during a scenario. Thus, by launching the generation of several scenarios, based on the same initial marking of the network (or initial state of the system) various paths are obtained leading to different final states. All these states can then be treated stastistically which gives the probability of states occuring which include multiple victims after a fire.

## MINHOTAURE

Minhotaure is a hotel probabilistic fire model for event-oriented networks of the temporized stochastic Petri net type, which uses two types of laws to determine action delays - the constant law and uniform law. In the second case, the transition crossing time is chosen randomly between two boundaries defined with regards to the action or phenomenon concerned. The choice of these boundaries is based on knowledge of the data supplied by three main sources :

-reading of fire reports,
-direct full scale experimentation,
-physical modelling and numerical simulation of fire on a computer.

CSTB is active in all these fields.

The event-oriented model means that, based on a primary seat of fire, which, for the model, is assumed to be in a guest room, all the possible degrees of development of the fire can be simulated as well as the progress of all the physical, material and human events which come into play at the same time as the fire is developing, including fire-fighting and intervention of the fire brigade.

Minhotaure takes into account the presence and operation or the absence and non-functioning, of automatic detection, alarm and smoke control equipment. It also considers the presence or absence of extinguishing equipment, as well as its possible use by the occupants of the hotel. Similarly, it also incorporates all the factors likely to impede development of fire and smoke, thus encouraging the evacuation of people before outside rescue teams arrive on the scene of the fire. Fire-fighting and rescue operations carried out by the fire brigade are thus described as well as the behaviour of hotel guests and staff in response to both localized and general alarms. Only evacuation of the floors on fire or filled withe smoke and their escape routes are considered. These are areas in which firemen could find victims. Jumping out the window, before this becomes necessary, and which is the result of individual perception of a danger assumed to be immediately fatal, is not described in the model, due to lack of sufficient data in this respect.

The initial optimum state of the system, which the first version of the model simulates, corresponds to the safety level of hotels which, because they can accommodate more than 99 guests, totally satisfy the fire equipment regulations currently in force in France (decrees of 25th june 1980 and 21th june 1982). The various aspects taken into account are summed up in figure 1 whose explanation is given in the appended table. A more recent version of the model enables more extensive use of automatic fire detection and fire extinguishing installations to be considered than that required by the regulations. These extensions to the basic model have been made at the request of those concerned by fire protection.

By changing the initial state of the system, due to the absence of one or more types of safety equipment, for example, the safety level of the hotel is downgraded, as demonstrated by the experiments carried out on the model (first version). This type of change is easy to make since it consists in purposely omitting the use of certain network modules ; this is achieved by leaving empty the corresponding entrance places. Similarly, certain changes can result in the suppression of messages or by using them as invariables. These two types of manipulations, carried out when defining the inital state, which precedes launching of simulation, enable different fire safety systems to be described, which lends itself well to the comparison of either various options in the same project, or of different establishments which already exist or are to be built.

## NUMERICAL EXPERIMENTATION

The simulator used is a software package which generates scenarios using Monte-Carlo simulation technique for the time delays associated with the transitions. This type of simulation brings us closer to reality, which itself is based on chance. A network input file in textual language enables the network initially entered to be changed easily, so that different variants can be described and evaluated. The chain of programs includes a module for the statistical processing of simulated groups of scenarios, which gives the passage rates during the scenarios, or the rates for reaching terminal individualized places or final defined states (combination of place markings). The first version used to test the MINHOTAURE 1 model was written in Fortran 77 and set up on an HP 9000 series 300 computer.

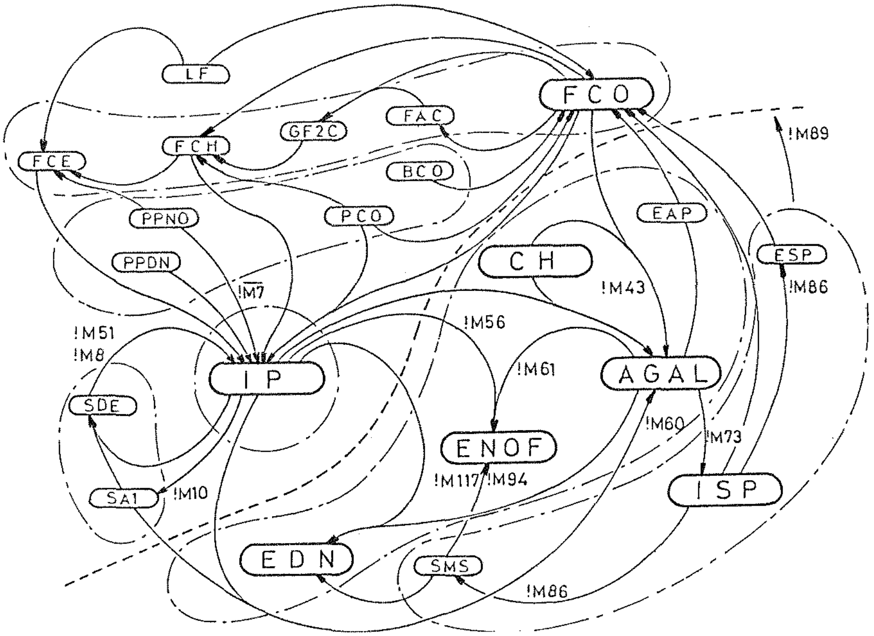

**FIGURE 1. The MINHOTAURE model**

Modules in figure 1
LF : location of the floor on which the fire originated
FCO : fire in room of origin
FAC : fire in opposite room
FG2C : large fire in 2 rooms
FCH : fire in corridor on original floor
FCE : fire in stairwell
BCO : condition of window
PCO : condition of door in original room
PPNO : condition of landing door in original room
PPDN : condition of landing door on top floor of rooms
CH : behaviour of first person alerted
AGAL : general alarm and alert
EAP : extinguishing of a small fire by staff
IP : practicability/impractibility of escape routes
SA1 : availability and functioning of alarm system
SDE : availability and functioning of smoke control system
ENOF : evacuation of floor on which fire originated
EDN : evacuation of top floor of rooms
ISP : intervention of fire brigade
SMS : rescuing of people
ESP : extinguishing of fire

After forming the batch input file, which is representative of the network, and defining the intial state of the system, the user must give the following before launching simulation :

- the maximum duration of a scenario,
- the number of scenarios to be simulated based on the initial condition.

He must also indicate the type of results he wishes to obtain at the end of simulation. These results concerne entities of one of the following types :

- the probability of places being marked at the end of the scenarios,
- the probability of reaching certain states at the end of the scenarios,
- the number of passages through given states during the scenarios.

The user must define the places or states he is interested in before launching simulation since only the corresponding data are stored during each scenario and not the whole of the path, and then processed at the end of simulation by conventional statistical methods which give the average of the quantity being considered and the standard deviation. Simulation of a large number of scenarios, of a suitable length with regards to the time delays of the longest scenarios, ensures that all possible configurations are explored, both intermediate and final, of the downgraded system which constitutes the development and extinguishing of the fire and its repercussions on the hotel's clientele.

To determine, using MINHOTAURE, the "experimental" probability that a fire which broke out in a room in a given hotel, will result in multiple victims, we must look at the markings of five different places at the end of the scenario. These places are called "presence of dead guests in ...":

- the horizontal passageway on the floor on which the fire originated,
- the rooms on the floor on which the fire originated,
- the upper part of stairscases,
- the horizontal passageway on the top floor of the building,
- the rooms on the top floor of the building.

If one or two of theses five places are marked at the end of a scenario, then the fire safety system has failed. This can occur during evacuation or be the result of attempting to save occupants trapped in a fatal situation too late. Since a given scenario can result in the marking of two of theses places, the probability of reaching 18 final states defined by the various combination of marked or empty places, must be calculated, in order to define the number of fatal fires contained in the group of scenarios generated automatically, independently of the precise location of the victims.

## EXAMPLES OF RESULTS

These concern the initial states which define variants of the same project, for which the protection equipment varies :

- case 1 : the hotel has an automatic fire detection system in the corridors ; a mechanical smoke control system for the corridor is slaved to the detection system as well as the general alarm ; the doors of the rooms have good fire resistance ;
- case 2 : the hotel does not have an automatic fire detection system ; smoke can be evacuated from the corridors mechanically but only manually ; the fire resistance of the rooms is mediocre ;
- case 3 : the hotel has the same weak points as in case 2, and there is no possibility of mechanical smoke control in the corridors.

For each of these cases, it is assumed that the corridor walls are covered either with thin, combustible, low density covering or with thick, non flame retardant combustible facings.

Given that the total number of transitions which the first version of the simulator can handle is 300, it is only possible to simulate fires which break out in the highest rooms of the hotel. Only guests on this floor are threatened, since MINHOTAURE does not describe the descending propagation of fire and smoke, which only occurs in buildings with wooden floors. The network therefore only includes two "failure" places for simulated cases.

For each of the six examples considered, a group of 5000 scenarios was simulated, with the maximum duration of each scenario limited to one hour. The size of the groups of scenarios gives a sensitivity threshold of $2.10^{-4}$. Table 1 gives the "exprerimental" probability of the following occuring within one hour :

- two events which the regulations wish to prevent - the presence of multiple victims in rooms or their presence in the corridors of the top floor of the hotel,
- an ultimate event inclued in the regulations - the rescue by firemen of guests who were not able to leave the floor where the fire is ; here, it is only considered for people in danger in the smoke-filled corridor ;
- an event normally expected when there is a correct fire safety system - successful evacuation.

**TABLE 1. Experimental probability of certain events occurring**

| Event considered at the end of the scenarios | Reference n° of simulated case | Combustible finishing of corridor walls | |
|---|---|---|---|
| | | Thin covering | Thick facing |
| Presence of multiple victims in the rooms on the floor concerned | 1 | $< 2.10^{-4}$ | $18.74.10^{-2}$ |
| | 2 | $< 2.10^{-4}$ | $28.22.10^{-2}$ |
| | 3 | $< 2.10^{-4}$ | $24.98.10^{-2}$ |
| Presence of multiple victims in the corridor on the floor concerned | 1 | $< 2.10^{-4}$ | $< 2.10^{-4}$ |
| | 2 | $< 2.10^{-4}$ | $2.10^{-4}$ |
| | 3 | $6.10^{-4}$ | $2.10^{-4}$ |
| Rescue of guests incapacitated in the corridor of the floor | 1 | $< 2.10^{-4}$ | $< 2.10^{-4}$ |
| | 2 | $8.10^{-4}$ | $4.10^{-4}$ |
| | 3 | $2.0.10^{-3}$ | $2.2.10^{-3}$ |
| Successful evacuation of some guests from the floor concerned | 1 | $22.40.10^{-2}$ | $22.8.10^{-2}$ |
| | 2 | $15.12.10^{-2}$ | $15.60.10^{-2}$ |
| | 3 | $14.52.10^{-2}$ | $15.16.10^{-2}$ |

The table does not mention the percentage of fires at the end of which guests who remained in their rooms were safe and sound, since this is not relevant to the risk analysis.

These examples show that the presence of combustible facings in the corridors is an excessively aggravating factor with regards to the presence of multiple victims in rooms. On the other hand, this parameter has little influence on the risk of finding victims in the corridor. The risk seems here to be extremely low and depends on the safety equipment in the hotel. Rescue by firemen of guests incapacitated in the corridor during their attempt to flee is also a rare event. It does not occur if the hotel is equipped with an automatic fire detection system. This type of system encourages early evacuation of the floor on which the fire occurs and, consequently, successful evacuation i.e. in the cases considered, the guests reach an enclosed staircase sheltered from fire and smoke.

## CONCLUSION

These few examples illustrate the feasibility and the advantage of using a probabilistic approach to the safety of persons in the event of a hotel fire. The approach presented is based on a simulation technique. It describes possible outcomes if a fire breaks out in a guest room. On the other hand, it does not give the probability of a fire breaking out in the room, which is what initiates simulation : this probability is deduced from statistics relating to hotel fires. The product of the two probabilities considered represents the risk that a given hotel will be the seat of a deadly room fire causing multiple victims.

The use of an approach such as MOCASSIN (1) is indispensable for calculating this risk. It is possible to envisage extending this approach to various types of establishments open to the public. However, it means writing special modules for each major location which may be at the origin of a fire. Similarly, the design of premises accessible to the public and their escape routes, which varies according to the type of establishment, is a paramater to be considered when writing modules and making the associated time delay choices. This means building up a library of modules with associated time delays presenting options according to the size (category) and configuration of the establishment. The network, corresponding to the case described by a MOCASSIN user, could then be built and automatically temporized according to the modules contained in the library. Pursuing this project therefore requires computer developments as well as the writing of modules or sub-networks.

(1) MOCASSIN : Monte-Carlo / Safety of Systems/ Incendie = Fire