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Contribution to the Development of a Systemic Approach for Building Fire Safety Characterisation

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Abstract

Fire safety in buildings is a society issue. Fire safety engineering aims at adapting the preventive measures in order to obtain a security level considered as acceptable. SCHEMA-SI, a CSTB developed numerical tool, quantifies the fire safety level of a public building. This article presents the current state of a systemic method that aims helping CSTB fire safety researchers to conceptualise all issues of a public building submitted to fire while mathematically modelling it. The objective is to extend the numerical tool SCHEMA-SI to building types with complicated configurations. To reach this objective, a global method including SCHEMA-SI is proposed. This method is derived from the systemic approach and brings on one hand a clear and limited system definition and on the other hand a broad, wise and overall scope of analysis. This established method creates links between systemic approach and SCHEMA-SI's mathematical model.

Key words: occupant safety, risk evaluation, systemic approach, building fire safety

Introduction and context

Designing efficient building configuration to ensure the occupant safety in the case of fire building is a challenging task. In France, fire safety design is traditionally reliant on prescriptive rules in building codes. These prescriptive building regulations are specified to the situation for occupant safety in the case of fire. Thus, they have a relatively easy implementation and the occupant safety is already embodied in the prescribed values. However, these prescriptive regulations have major disadvantages: they are complex and may be difficult to apply to some particular configurations. As a consequence of these drawbacks, alternative so-called performance-based building engineering have been developed in several countries during the last two decades. Performance-based approach defines an objective, but do not define how it should be accomplished [1].

Currently, computer tools such as two-zone multi-volume fire model (for example CFAST Consolidated Fire And Smoke Transport [2]) and/or 3D fire model (FDS – Fire Dynamic simulator [3]) are used to design fire safety measures that fulfil performance-based building advises. Therefore, the fire expansion and smoke movements are currently numerically predicted when the architect specifies the building geometrical parameters and the fire safety engineer assesses a potential heating release rate (HRR) of fire. In the same way the time available for escape is calculated and compared with the assumed evacuation time. However, this method used to satisfy the regulation actually has nothing to do with the current requirement. Performance-based approach recommends an objective and not a particular design method for occupant safety [4]. Thus, predicting fire spatiotemporal behaviour is not sufficient to assess fire safety. Analysing disaster clearly shows that the building configuration, the security system as well as the behaviour and response time for people escaping from fire are important factors to take into account [5]. Hence, the development of available methods of fire safety assessment is required. The objective of such new methods is to reveal whether certain design strategies are sufficiently safe for a various range of undesired event sequences.

A new holistic approach to evaluate the fire safety level in a hotel is under development at the CSTB (Centre Scientifique et Technique du Bâtiment). This method integrates and improves a new numerical tool so-called SCHEMA-SI (Stochastic Computation and Hybrid Event Modelling Approach – Sécurité Incendie) which was partially developed at the CSTB in the framework of the PNISI program (French National Project for Fire Safety) in 2007. SCHEMA-SI belongs to dynamic hybrid system tool [6], which means that discrete events and continuous phenomenon are connected at each instant. Example of continuous phenomenon could be fire spatiotemporal evolution whereas example of discrete events could be the opening of smoke ejection system trap doors. Using a hybrid model is required as the spatiotemporal evolution of smoke and fire, the building, the security system and the human behaviour are permanently interacting ones others. Additionally SCHEMA-SI considers random (or stochastic) process [7], [8] to mitigate certain uncertainties as well as to better describe the variability of potential situations. The formalism of SCHEMA-SI is based on stochastic and hybrid Petri nets [9].

Goals, objectives and method

SCHEMA-SI was previously applied to a simple configuration: case of a fire in a hotel considering fire and smoke spreading only in a room and a corridor. The purpose of this study is to extend this numerical tool to different building types with more complicated configurations. To reach this objective, a global method including the numerical tool is developed. This method derived from the systemic approach brings [10], [11], [12]:

- a clear and limited system definition,
- a broad, wise and overall scope of analysis.

The method presented in this paper helps to model the system with SCHEMA-SI and therefore to evaluate the level of building fire safety. The fundamental concept of this method consists, initially, on a systemic description (global model) of any public building in the case of fire. In the case of this study, a public building is a set composed by the building itself characterised by its activities, the fire security system as well as the occupants and rescue crew. The global model aims been exhaustive even if this goal will probably never been achieved. The reader should keep in mind that a systemic method translates the intellectual progression of a team at one specific instant and thus is never completely finished. Indeed while studying various configurations new elements may appear and the user should then make the global model evolve. The current global model is explained on next paragraph.

Secondly, a specific model is derived from data collected for a particular configuration and is optimised upon teamwork (groups consisting of representatives from the authorities, the fire safety expert, the architect and the contractor). The specific model is included in the global model. It corresponds to a particular and unique configuration. Teamwork is especially required at this stage of the project because important assumptions about the model and its achievement have to be defined. Finally, the specific model is translated into a mathematical model [9], [13], computed and simulations are performed to evaluate the fire safety level of that particular public building. This established method creates links between systemic approach and SCHEMA-SI's mathematical model. In addition, this systemic method is convenient to expose a particular configuration and thus makes it easier to comment results while performing feedback. As a consequence, the method improves efficient and effective communication. Fire safety analysis is used to evaluate the risk to which the occupants of a building may be subjected if a fire breaks out. Therefore, a *scenario* is defined and the systemic approach enlightens and enriches the description. Hence, the scenario is characterised by:

- the scenery namely the landscape where the action takes place. For example, describing the geometrical building parameters as well as the security system configuration is important
- the action, namely both energy release rate and the combustible characteristics
- the actors and their roles. Some actors (living or not) will enter the scene and "play a role". Theses roles are not easily anticipated since the response of people and fire safety system to fire depends on their awareness as well as on the environmental conditions. Although, it is now relatively simple to predict the fire growth and smoke transport, the response of the actor to fire requires more analysis. This investigation is an important step to elaborate the model and the simulation.

Fire behaviour in a room

Fire starts by a single burning object. The first flame surrounding it is usually not dangerous itself but may propagate fire either by extension of the single burning object size or by igniting others objects. Assuming combustion continues and fire grows: the temperature near the object increases. As a consequence:

- inner gas start moving because of the pressure gradient between cooler and hotter gas
- the more the flame temperature increase the more it radiates all around.

Hot gas and radiation may reach neighbour objects and possibly set fire to them. Inflammation requires sufficient energy to ignite flammable gas. However combustion only keeps going if the energy provided to the combustible solid material is sufficient to ensure a continuous release of flammable gas flow. The phenomenon of transforming a combustible solid material into a flammable gas is pyrolysis.

Fire grows and all the combustible objects available in the room may burn either one after the others or simultaneously. The latter case corresponds to a particularly dangerous phenomenon so-called flashover. In the same time, gas moves inside the room accelerates and gas flows establish at the openings: a fresh air flow enter the room bringing oxygen whereas vicious gas escape from the local evacuating combustion products.

System definition

A system is a set of interacting or interdependent entities, real or abstract, forming an integrated whole. However, beyond this definition, concepts on systems can be divided into fundamental characteristics of a system and scales of analysis [14].

Fundamental characteristics are the followings:

- the finality : namely either the goals or the functions of the system
- the structure : the elements of a system (fixed or mobile)
- the interactions : the dynamic relationships materialised by flows.

The system considered in this investigation is a public building in case of fire. It is a multiple finalities system as some elements are pro fire safety (fire alarm for example) whereas some others such as the gas inside a building, has no real safety finality. Complex systems are often multiple finalities one. The structures and the interactions are fully developed in the section 'Global Model Building' of this paper.

Scales of analysis are the different spatial and temporal scales considered to observe a system. Three different scales arise as follows:

- the geometrical scale corresponds to the size of the elements. Our system is human-sized
- the duration period is the time interval in which the system is observed. Observation period starts with ignition and ends with fire extinguishment either because of combustion reaction naturally ends or because of a deliberate extinction
- the phenomenon scale corresponds to the fastest event considered, typically one second in our system.

Global model building

General description

The model is inspired by a meta-model proposed by J. De Rosnay [15]. It uses a graphic representation involving structural characteristics (reservoirs, components, and communication networks) and functional characteristics (flows, valves, delays, and feedback loops). As defined by De Rosnay, a reservoir is a capacity in which energy, information and/or matter are stored. Networks (pipes, wires, cables...) are represented by oriented arcs between reservoirs. Flows circulate between the reservoirs through networks. Valves can control flows. Depending on valve position, it can stop, slow down or accelerate the flow in the arc (inlet flow and outlet flow from reservoirs). This formalism is applied in our investigation to describe the system building in the case of fire. It complies with the scales defined above but in addition smaller aspect than the reference scale may be studied by performing local and temporal zooms. Indeed the model offers an overall vision of the system and also fully describes each element. An element is fully studied by zooming and can be considered as a puzzle piece. A picture composed by all the puzzle pieces is the global model. A picture composed only with some of the pieces is a specific model. In a first time, the most overall model of the system will be exposed. Zooms are developed but will not be presented in this article. For a better understanding of the graphic representation used for the model, a legend is presented hereafter in table 1.

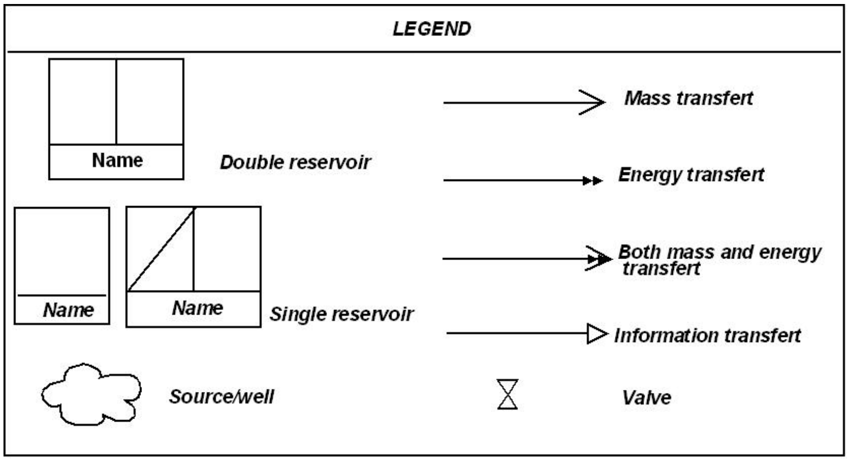

Table 1 : Legend of the systemic model used

The following flows are detailed in this article:

- gas and energy,
- information.

Model of the gas and energy fluxes

Gas and liquid flows circulate in the system networks. In this model, only gas flows are represented as combustion and smoke transport are dealing with compressible fluid mechanics. Concerning energy, only heat transfers are considered. Three different mechanisms are modelled: *(i)* heat transfers between volumes (rooms of the building) by gas flow (enthalpy), *(ii)* heat transfers by convection and radiation between volumes and/or wall and solid surfaces and *(iii)* heat transfer inside solids (conduction).

The scheme presented hereafter (on figure 1) describes the systemic representation proposed for both gas and energy flows in a room building subjected to fire.

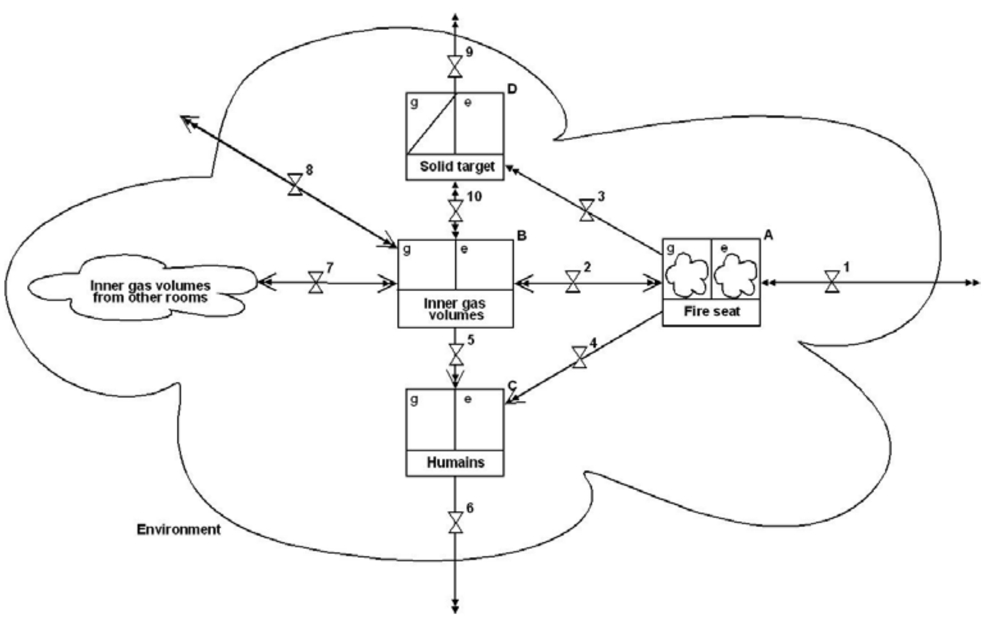

Figure 1 : Systemic model for gas and energy in one room where the fire stands

The overall system is encircled by an infinite source and/or well of gas and energy so-called environment. The environment symbolise the world outside both the public building and the fire brigade. Indeed firemen are considered as part of the system. The system itself is made of four reservoirs which exchange gas and energy. Additionally reservoirs may exchange with the environment or with inner gas volumes from other rooms. One of the reservoirs (solid target) does not accumulate gas. Examples of solid targets could be walls, door leafs or any component that could be thermally aggressed (detector, electrical leads, fire extinguisher for examples). Another reservoir is considered as a source of both gas and energy: fire seat. Fire seat is composed by the solid combustible and its surrounding flame. This model is nearly total meaning that several significations per valve, per communication network or per flux exist. Theses significations can be understood by consulting the table available with this model (on table 2). The table presented is not exhaustive because it would be too long for an article. The valve degree of liberty stands for the potential valve position variation (opening or closing). These variations are illustrated with the changing context.

Upstream reservoir	*Downstream reservoir*	*Flux*	*Signification and example*	*Communication network*	*Valve degree of liberty*
Environment	Fire seat	Energy	Fire ignition	Gas: convection Electro-magnetic waves: radiation	Valve 1 opens when a spark heats the solid combustible and closes in case of extinction
Fire seat	Environment	Energy	Fire extinction	Water, mist or extinguisher: heat transfer by liquid flow (enthalpy)	Valve 1 opens in case of extinction
Fire seat	Inner gas volumes	Mass	Products of combustion (smoke) and of pyrolysis (gaseous combustible)	The space available inside the room for the gas to spread	Valve 2 is fully opened when requirements for the combustion reaction (or pyrolysis) are obtained
Fire seat	Inner gas volumes	Energy	Heat release due to exothermic combustion reaction or to vaporisation	Gas flow: enthalpy Gas: convection Electro-magnetic waves: radiation	Valve 2 is fully opened when requirements for the combustion (or pyrolysis) reaction are obtained
Inner gas volumes	Fire seat	Mass	Fresh air (combustive) supply	The space available between reservoirs	Valve 2 closes with oxygen depletion. It could be deliberate (extinction) or not (chemical reagent shortage, seclusion …)
Inner gas volumes	Fire seat	Energy	Reverse heating	Gas: convection Electro-magnetic waves: radiation	-
Inner gas volumes	Human	Energy	Heating from hotter gas to human body	Gas flow: enthalpy Gas: convection Electro-magnetic waves: radiation	Valve 5 closes if the person dies, goes out of the room or wears PPE
Inner gas volumes or environment	Environment or Inner gas volumes	Mass	Air renewal and smoke extraction system	Embrasure, ventilation, leak, smoke extraction system trap doors	Valve 8 closes when a door leaf or a shutter closes and opens when the ventilation or extraction system starts. However, valve 7 is never fully close as leaks are considered
Inner gas volumes or environment	Environment or Inner gas volumes	Energy	Air renewal, smoke extraction system, radiations	Gas flow: enthalpy Gas: convection Electro-magnetic waves: radiation	Valve 8 closes when a door leaf or a shutter closes and opens when the ventilation or extraction system starts. However, valve 7 is never fully close as leaks are considered

Table 2: Details of the systemic model for gas and energy flows

Model of information exchanges

The information is carried by diverse supports such as electric flow, luminous flux, sound flux, speech, human behaviour, and human sense perception. Information may be divided into two categories:

- information exchanged between reservoirs via information flows supported by networks. A reservoir stores information. Information can be directly transmitted without any modification from one reservoir to another one or can be processed in a reservoir (the message emitted is different than that received). In that particular case, the reservoir is a cognitive entity (symbolised by a cloud). This kind of information is modelled using the same graphic representation then in figure 1. The corresponding scheme is figure 2. Table 3 presents a full description of the valves role and position variations.
- information responsible of a valve position variation. This kind of information is emitted by a reservoir and received by a valve. It ensures the system dynamism and completes feedback loops. It will be presented in an (NxM) feedback matrix available hereafter in table 4. A feedback matrix is composed of N lines and of M rows: N is the number of reservoirs and M the number of valves. At each component i,j (line, row) of the matrix the value 0 or 1 is given. 0 means the i^{st} reservoir do not act the j^{st} valves and 1 means it can. Such a representation was previously used by Godet [16] and Dassens [17] to represent the links between hazard processes.

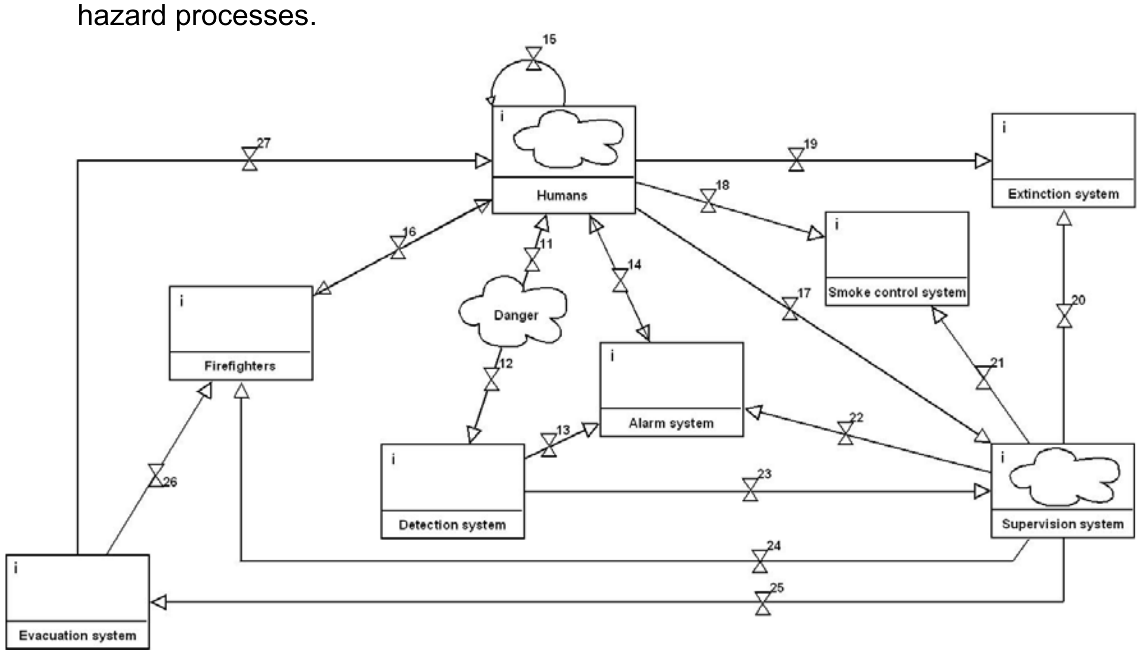

Figure 2 : Systemic model for information in the whole system

All the reservoirs accounted for in this model the fire safety security system response whereas figure 1 rather represents the undesired, unexpected and unforeseen part of the story. This difference could be related to the multiple finalities: the second model clearly has a pro-security finality whereas the first one deals with fire hazard. It is possible to retrace the story starting by the detection and ending by intervention and extinction. Additionally, all information reservoirs and some communication networks may be included into the solid target gas and energy reservoir as the security system organs may be thermally aggressed. Two major reservoirs arise: humans and supervisory system. They both are cognitive entities and are almost connected to all other reservoirs. The supervisory system is a machine that centralise information and automatically transmits order to others security organs. The “humans” reservoir represents all the people that may be inside the building during the duration period. This reservoir should be duplicated as many as the number of persons located inside the building. Once the fire-fighters enter the building, they are then represented by the "humans" reservoir too. This modelling choice broadens they scope of action while in the place.

Valve number	*Signification and example*	*Network type*	*Valve degree of liberty*
11	Human detection	Human sense of perception (sense of smell, sight thermoception, nociception, etc.)	Valve 11 opens when organoleptic thresholds are reached. It closes if the person dies
12	Automatic detection	Depend on the detector type + electric flows	Valve 12 opens when detection thresholds are reached. It closes if the detector is destroyed or weakened
13, 20; 23, 21, 22	Electric transfer of information	Electric flow	These valves closes in case of weakening (cable interruption, short-circuit for examples)
14	Alarm awareness	Acoustic waves and visual sign (light)	Valve 14 opens of the alarm is audible or visible. It closes in case of death or weakening (either of the human or of the machine)
17, 18, 19	Human set safety system in motion	Human muscle + mechanic or electric contactor	These valves close in case of death or weakening (either of the human or of the machine)
15,16	Inter human communication (speech, non verbal communication)	Acoustic waves, sight, behaviour, cognition and situation analysis, …+ telecoms	Valves 16 and 28 closes if people does not speak the same language, does not hear or see each other (too much nose, too much smoke), are badly injured or dead etc. Additionally, valve 16 closes in case of weakening of the telecommunication.
24	Automatic alert	Telecoms	Valve 24 closes in case of weakening of the telecommunication.
26, 27	Evacuation procedure	Evacuation maps, in case of emergency procedures, emergency exits, emergency lightening etc.	Valves close if people are not able to see (too much smoke), to read (not the same language or alphabet) and to understand the information (panic, injuries…).

Table 3: Details of the systemic model for information

The feedback loops appear by consulting the following matrix:

		Valves																											
		1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***SUM***
Reservoirs	***Inner gas volumes***	0	0	0	0	0	0	0	0	0	0	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	**1**	**1**	**10**
	Solid target	0	0	**1**	0	0	0	**1**	**1**	**1**	**1**	0	**1**	**1**	**1**	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	0	0	**17**
	Fire seat	**1**	**1**	**1**	**1**	0	0	**1**	**1**	**1**	0	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	0	**1**	**1**	**17**
	Humans	**1**	0	0	**1**	**1**	**1**	**1**	**1**	**1**	0	**1**	0	0	**1**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	**1**	0	**1**	**1**	**17**
	Firefighters	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	0	0	0	0	**1**	0	**1**	**1**	**14**
	Alarm system	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	0	0	0	0	0	0	0	0	0	**1**	**1**	**5**
	Smoke control system	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**
	Extinction system	**1**	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**
	Supervision system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
	Evacuation system	0	0	0	0	0	0	**1**	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**	**4**
	Detection system	0	0	0	0	0	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
	SUM	**3**	**1**	**2**	**3**	**2**	**2**	**6**	**7**	**5**	**1**	**4**	**3**	**1**	**5**	**5**	**5**	**5**	**5**	**5**	**1**	**1**	**1**	**1**	**3**	**1**	**6**	**6**	

Table 4: Details of the systemic model for information

A particular attention has to be focused on the sum row and line of the matrix. A high score in the sum row means the corresponding reservoir is a polymorphic actor in the system. More precisely, this actor has a broad scope of action (may move a lot of valves). A high score in the sum line means the corresponding valve is an important system dynamic control key: the valve can be solicited by a lot of different actors. Thanks to this matrix, system critical points may be determined. These points are strength or weaknesses of the system, depending whether the effect of the valve movement is positive or negative on fire safety (positive or negative feedback loops, desired or undesired flux establishment, etc.)

Note that the four reservoirs involved in gas and energy flows are important actors of the system. Fire-fighters are also an important system dynamic initiator. The security system organs rather have one specific role implicating they move only some specific valves. Concerning valves, it clearly appears that important one are those related to evacuation (valves 26, 27), to door leafs opening and closing as well as to smoke control and ventilation systems (valves 7, 8). In addition, some valves can be noticed as critical points: the alarm awareness (valve 14), extinction (valves 8, 9) and human behaviour (human actions and inter-human communication) (valves 15, 16, 17, 18 and 19). These valves are related to human reliability. They are weak points because they may be closed in case of human weakening or death.

Specific model building

Specific models where already built in the CSTB for two configurations: *(i)* a one corridor and two bedrooms motel configuration and *(ii)* a one corridor and two flats rest-home configuration. They are described in [18].

Conclusion

This investigation is devoted to the development of a systemic approach for the description of an establishment submitted to fire. The resulting model enables to describe the system and to understand how it works. Understanding flow establishment and dynamic behaviour helps to mathematically model the system. Additionally, studying the holistic model allows assessing the system strengths and weaknesses. Critical points identification permit to focus team awareness on the most relevant issues involves in fire safety. Particular attention should be accorded to the description of human behaviour, smoke control, alarm, extinction and evacuation. Currently a temporal description that fully describes the valves movement chains needs to be performed. As a consequence, further researches will focus on a schedule creation.

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