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FORENSIC INVESTIGATION OF A CIVIL BUILDING EXPLOSION BY CFD MODELLING

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Forensic investigation of fires and explosions **is a formal process** of determining origin, cause and development of a fire or explosion.

NFPA 921 "*Guide for Fire and Explosion Investigation*"
First step: analysis of fire and explosion scenario and collected evidences - pre and post-explosion (fire) description of the accident zones.

Second step: development of a geometrical model of the area and the definition of a set of scenarios (flammable cloud size, location, concentration of fuel-air mixture, ignition location, determination of the effects of these scenarios).

Third step: verification of hypotheses on the origin and cause, to evaluate different explosion scenarios with the aid of three-dimensional **simulation models** of Computational Fluid Dynamics (**CFD**) type.

Final step: comparison of the obtained results with the actual data coming from the collected scenario evidences in order to select the most likeable scenario among the simulated ones.

THE EVENT

One night, at about 2.25 am, a call to a local Fire Brigade, required intervention due to an **explosion and** the **subsequent fire** occurred **at a restaurant premise** in the city that had caused its partial destruction.

Serious damage to load-bearing and separation walls of the premise. **Fire then developed and involved principally the ground floor** (dining room, kitchen) **and the mezzanine** (further dining room and toilet).
The explosive event involved other adjacent business and residential units.

The public Prosecutor's Office gave to the Investigative Fire Prevention Unit (NIA), **the task to inquiry in order to ascertain**:

- "**If the event was due to an arson**";
- "**If** it had been **caused by gas explosion or by** the presence of **other flammable substances**";
- "**How** fire and explosion **developed** ";
- "**Any other circumstance** helpful in order to reconstruct the dynamics of the event."

SITE INSPECTIONS

Description of the original state of places

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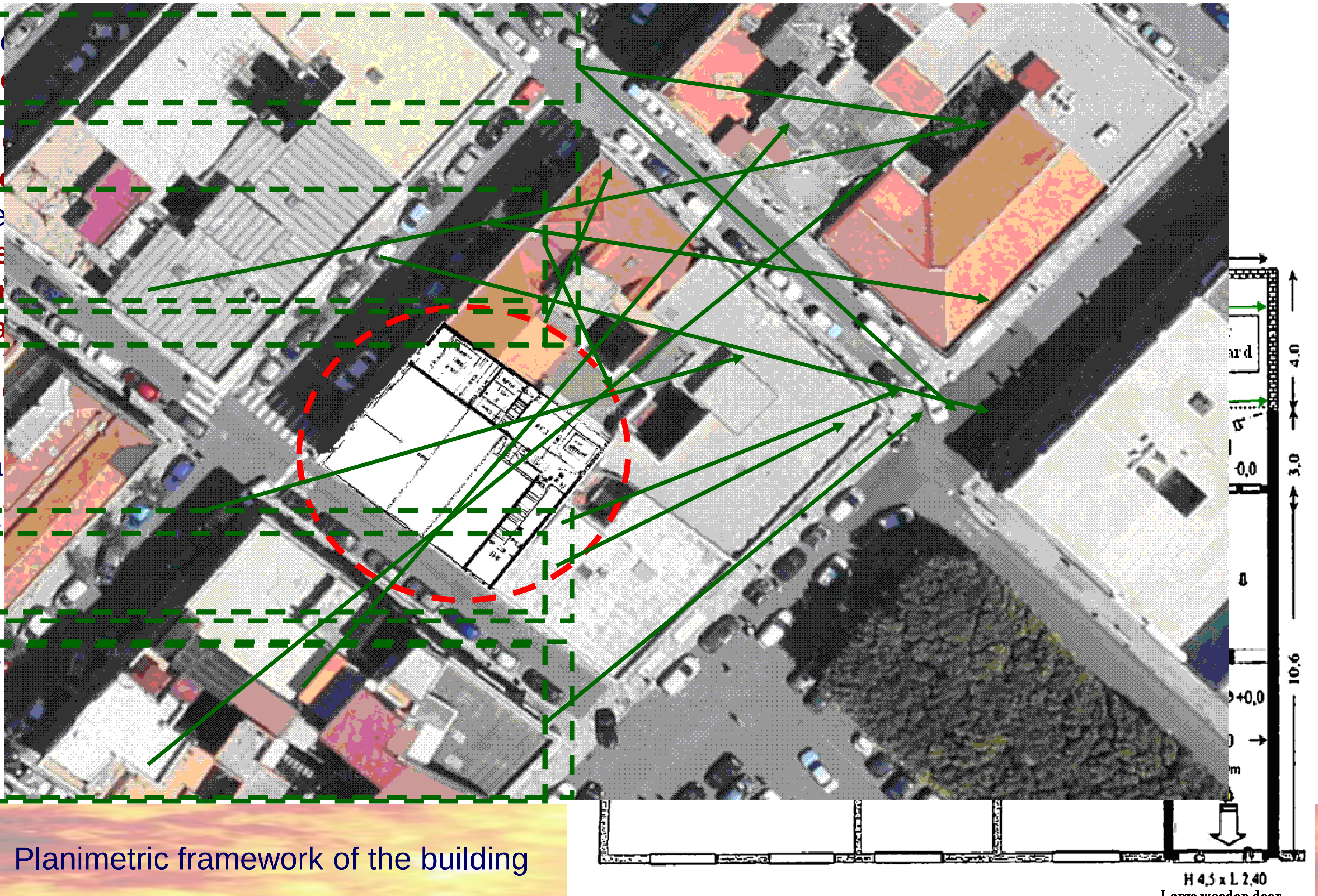
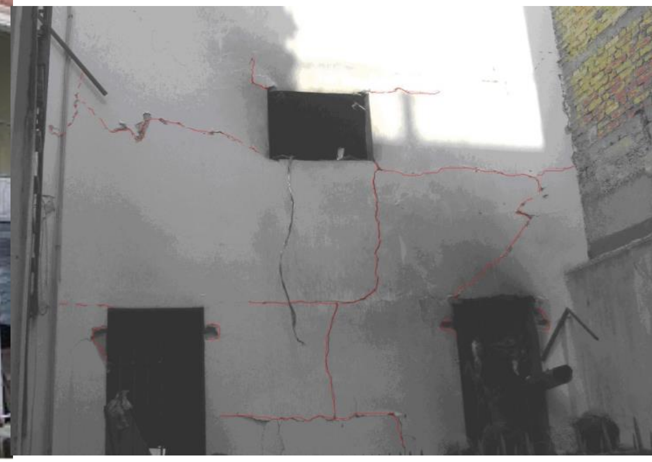
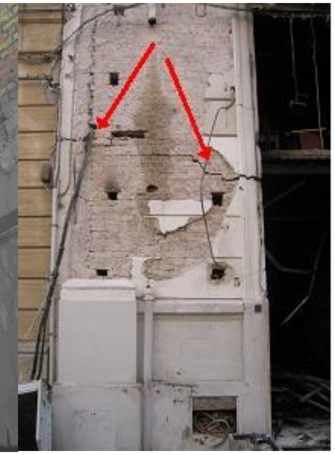


Planimetric framework of the building

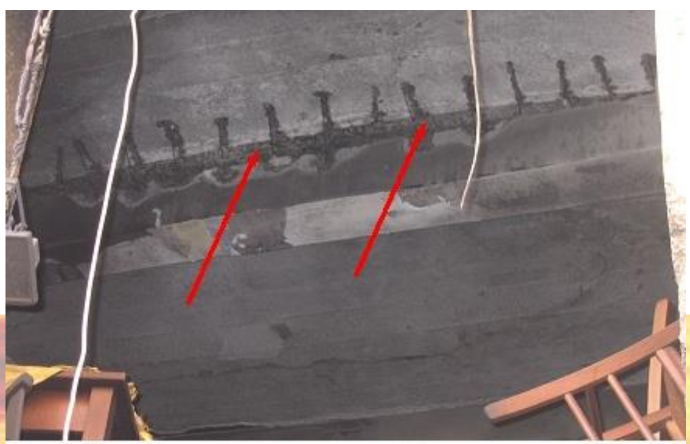
EXPLOSION DAMAGE

Metal rolling shutter of the access door of the commercial premise thrown against the opposite building and found on the opposite sidewalk, and fixtures always torn by the explosion.





Masonry structures damaged. The outer wall of the building corresponding to the access was visibly damaged to form a convexity towards the outside characterized by various surface fractures of various sizes.



The separation floor with the apartment above was buckled, causing the detachment from the beams

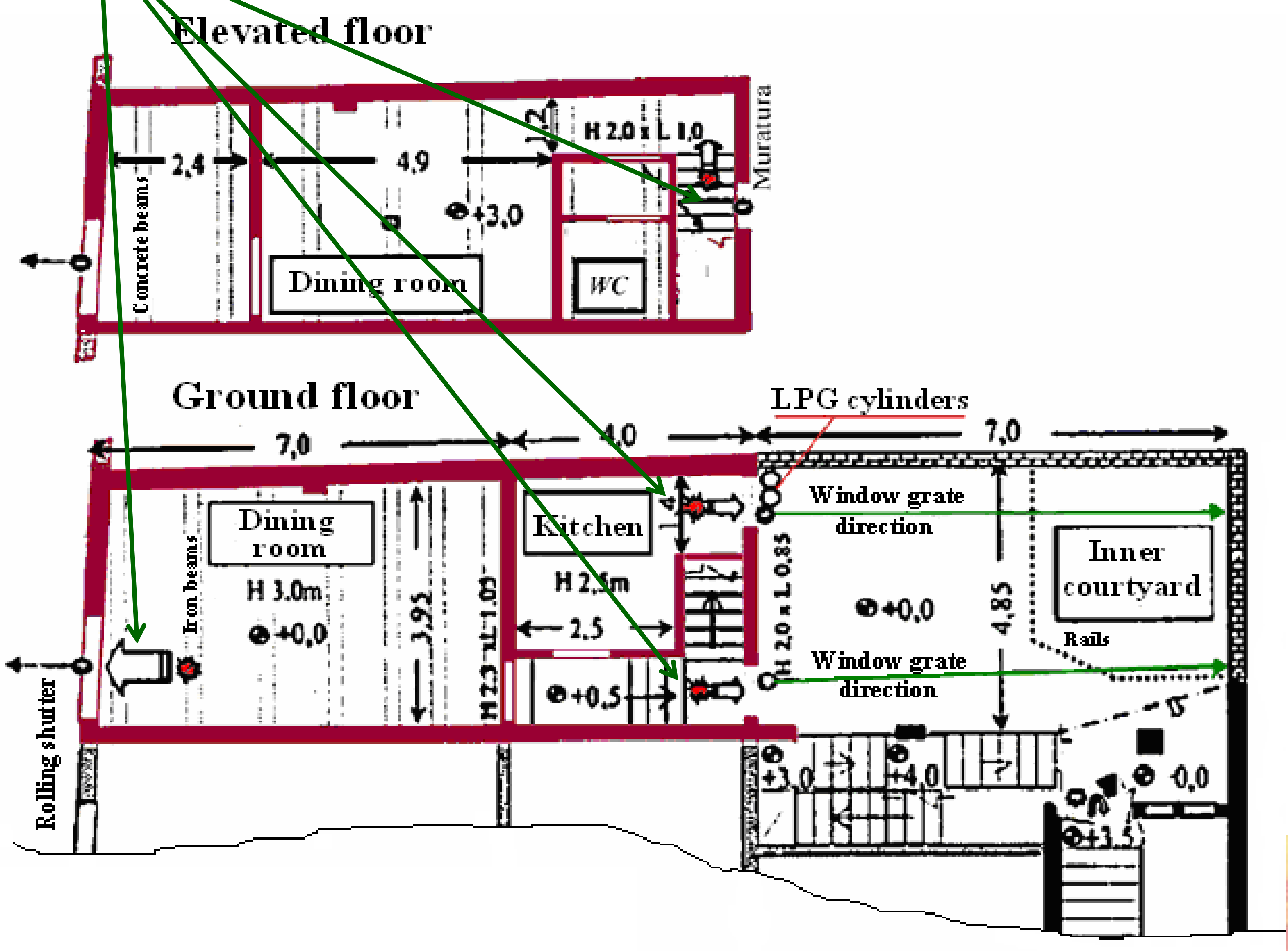
EXPLOSION DAMAGE

Loss of constraint of the iron beams that supported the floor of the loft area.
Metal frames in suspension, presumably as part of a false ceiling destroyed by the joint action explosion-fire.

The windows of the loft area were completely shattered and the protective metal balustrade was also ripped off as the rolling shutter.

The inner courtyard of the block, accessible from the street on the corner of the main entrance of the commercial exercise, was protected by a large wooden door partially torn off by pressure wave due to the explosion.

The **vectors in figure show the direction of propagation of the flame front**. Based on the observed damage, the explosion could be classified as **low-order damage**.



ANALYSIS OF THE ACCIDENT CAUSES

After examining the scene, the collected information and witness statements, the **first question** concerns the **definition of the cause that originated the event**.

Once assessed that **the event occurred can be classified as a combustion explosion**, **two alternatives** have been **taken into consideration depending on the type of fuel**, that may have generated it, and subjected to further examination:

- **Scenario 1 - Fugitive emission of flammable gases - LPG losses (ACCIDENT)**
- **Scenario 2 - Vapours of flammable liquid (ARSON).**

Possible sources of ignition were related to:

•**Compressor** of the refrigerator (hereafter "refrigerator")

•**Motor** of the metal rolling shutter (hereafter "rolling shutter").

•**Ignition at the same time of closing of the rolling shutter by the restaurant owner!!!**

Computational Fluid Dynamics (CFD) is an extremely powerful tool that allows a **detailed study of fluid flow** in complex geometries and is normally applied to compressible or incompressible flows, laminar or turbulent, chemically reactive or not.

The CFD code used in this study is the FLACS v10.2 by GexCon. The code solves the Reynolds-Averaged Navier-Stokes (RANS) equations for mass, enthalpy, momentum and species.

The main results obtained by the simulations of the case study **were quantitative information about static and dynamic overpressure fields and temperature fields** as consequence of the explosion.

These results allow to have **numerical confirmation of the investigative hypotheses**, obtained **according to the formal procedure of NFPA 921**, and investigate aspects such the **position of the source of ignition**, the **position and size of the cloud** of flammable vapours as well as the **quantities at stake.**

Computational domain

On the basis of what has been described in previous sections, **it was built the geometric model** of the site where the event occurred **using the pre-processor CASD. In order not to lose information** on the pressure generated by the semi-confined explosion inside the restaurant, **the representation is not limited just to the premise but the also to entire block to which it belonged**.

For the boundary conditions, all the openings, doors and windows were represented by pressure relief panel structure. For all of them the weight (kg/m2) and the rupture overpressure (barg) were assumed according to Harris (1983).

All the **furniture** in the restaurant, the **courtyard** and the **stairs** were **represented in detail**, in order **to take into account the effect of the turbulence induced** by these objects, **which influences the speed of the flame front** and the **trend of the pressure** during the explosive phenomenon.

Panel	Material element	Overpressure rupture Barg	Specific weight of the element kg/m	Position	Panel	Material element	Overpressure rupture Barg	Specific weight of the element kg/m2	Position
1	Load-bearing wall	[illegible]	[illegible]	Courtyard	[illegible]	Partition wall (dressing and dining room)	[illegible]	50	Mezzanine
2	Load-bearing wall	[illegible]	[illegible]	Courtyard	14	WC door	0,01500	10	Mezzanine
3	Load-bearing wall	0,35000	900	Courtyard	15	Dressing door	0,01500	10	Mezzanine
4	Load-bearing wall	0,35000	900	Courtyard	16	Large window on the entrance	0,02000	20	Main street
5	Load-bearing wall	0,35000	900	Courtyard	17	Rolling shutter	0,03000	40	Main street
6	Load-bearing wall	0,35000	900	Courtyard	18	Partition wall (WC and dining room)	0,03000	50	Mezzanine
7	Load-bearing wall	0,35000	900	Courtyard	19	Partition wall (WC and dining room)	0,03000	50	Mezzanine
8	Load-bearing wall	0,35000	900	Courtyard	20	Partition wall in the dining room	0,03000	50	Mezzanine
9	Load-bearing wall	0,35000	900	Main street	21	Stairwell window (high)	0,02500	20	Courtyard
10	Load-bearing wall (Courtyard access)	0,35000	900	Main street	22	Kitchen window	0,02500	20	Courtyard
11	Large wooden door	0,02500	40	Corner street	23	Stairwell window (low)	0,02500	20	Courtyard
12	Partition wall (dressing and dining room)	0,03000	50	Mezzanine					

Preliminary simulations

Panel	Material element	Overpressure rupture Barg	Specific weight of the element kg/m^2	Position	Panel	Material element	Overpressure rupture Barg	Specific weight of the element kg/m2	Position
1	Load-bearing wall	0,35000	900	Courtyard	13	Partition wall (dressing and dining room)	0,03000	50	Mezzanine
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The **minimum criterion of compatibility between the simulated scenarios and objective evidence** of the investigation is as follows:

- **panel n° 11** corresponding to the entrance door to the courtyard from the corner street **has to be torn down**;
- **panels from n° 1 to n° 10**, corresponding to the load-bearing masonry, **must not collapse**.

Preliminary simulations

For the **LPG fuel**, **only 4 scenarios can be considered plausible** according to the criteria set out above. The **calculated amount of fuel** (between 5,2 kg and 7,66 kg) **does not agree** well **with the absence of detectable losses**.

Scenario	Distribution (above ground)	Concentration	Fuel/air mixture composition	Initial fuel kg	Source of ignition	ER
1	h = 3m	LFL	0.58% propane, 1.35% butane, 20.54% O2, 77.52% N2	4.4328	Refrigerator	0.57
2	h = 3m			4.4328	Rolling Shutter	0.57
3	h = 1m	Intermediate LFL - Stoichiometric	0.81 % propane, 1.89% butane, 20.39% O_2, 76.92% N_2	1.4483	Refrigerator	0.8
4	h = 1.5m			2.2590	Refrigerator	0.8
5	h = 2m			4.1739	Refrigerator	0.8
6	h = 2.5m			5.1646	Refrigerator	0.8
7	h = 3m			6.1733	Refrigerator	0.8
8	h = 3m			6.1733	R. S. Motor	0.8
9	h = 1m	Stoichiometric	1.00 % propane, 2.34% butane, 20.25% O_2, 76.40% N_2	1.7983	Refrigerator	1
10	h = 1.5m			2.8049	Refrigerator	1
11	h = 2m			5.1824	Refrigerator	1
12	h = 2.5m			6.4125	Refrigerator	1
13	h = 3m			7.6650	Refrigerator	1
14	h = 3m			7.6650	Rolling Shutter	1

Preliminary simulations

For Petrol fuel, **only 2 scenarios can be considered plausible**. These scenarios correspond to two different sources of ignition:

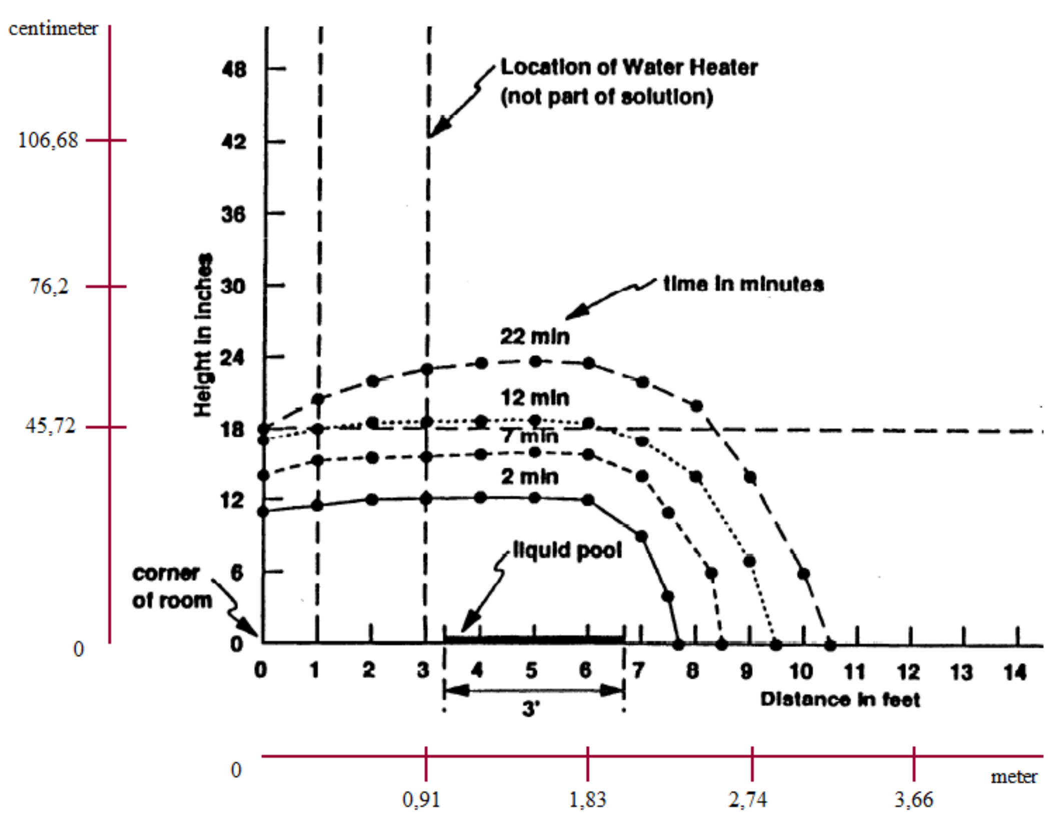
- Scenario with **trigger by the refrigerator** of a stoichiometric petrol/air mixture (about **5,4 kg of gasoline**) and a fill of local 2 m in height;
- Scenario with **trigger by the rolling shutter** of a stoichiometric petrol/air mixture (~ **8 kg of gasoline**) and a fill of the local 3 m in height.

15	h = 3m	LFL	0.03 % heptane, 0.62% octane, 20.81% O_2, 78.53% N_2		Refrigerator	0.39
16	h = 3m				Rolling Shutter	0.39
17	h = 1m	Intermediate LFL - Stoichiometric	0.06 % heptane, 1.11% octane, 20.71% O_2, 78.13% N_2	1.3198	Refrigerator	0.7
18	h = 1.5m			2.0585	Refrigerator	0.7
19	h = 2m			3.8034	Refrigerator	0.7
20	h = 2.5m			4.7062	Refrigerator	0.7
21	h = 3m			5.6254	Refrigerator	0.7
22	h = 4.5m			8.9166	Refrigerator	0.7
23	h = 3m			5.6254	Rolling Shutter	0.7
24	h = 4.5m			8.9166	Rolling Shutter	0.7
25	h = 1m	Stoichiometric	0.08 % heptane, 1.58% octane, 20.60% O_2, 77.74% N_2	1.8760	Refrigerator	1
26	h = 1.5m			2.9261	Refrigerator	1
27	h = 2m			5.4064	Refrigerator	1
28	h = 2.5m			6.6897	Refrigerator	1
29	h = 3m			7.9963	Refrigerator	1
30	h = 4.5m			12.6750	Refrigerator	1
31	h = 3m			7.9963	Rolling Shutter	1
32	h = 4.5m			12.6750	Rolling Shutter	1

Plausible scenarios

In the preliminary simulations, we hypothesized the presence of a flammable cloud, at fuel concentrations variable with the height, in the entire volume of the restaurant.

The act an arsonist could tend to randomly shed the fuel. It may happen, **using a flammable liquid such as gasoline,** a **part of the structure could be saturated** with vapours **while another**, in close proximity, **could remain almost completely devoid**.

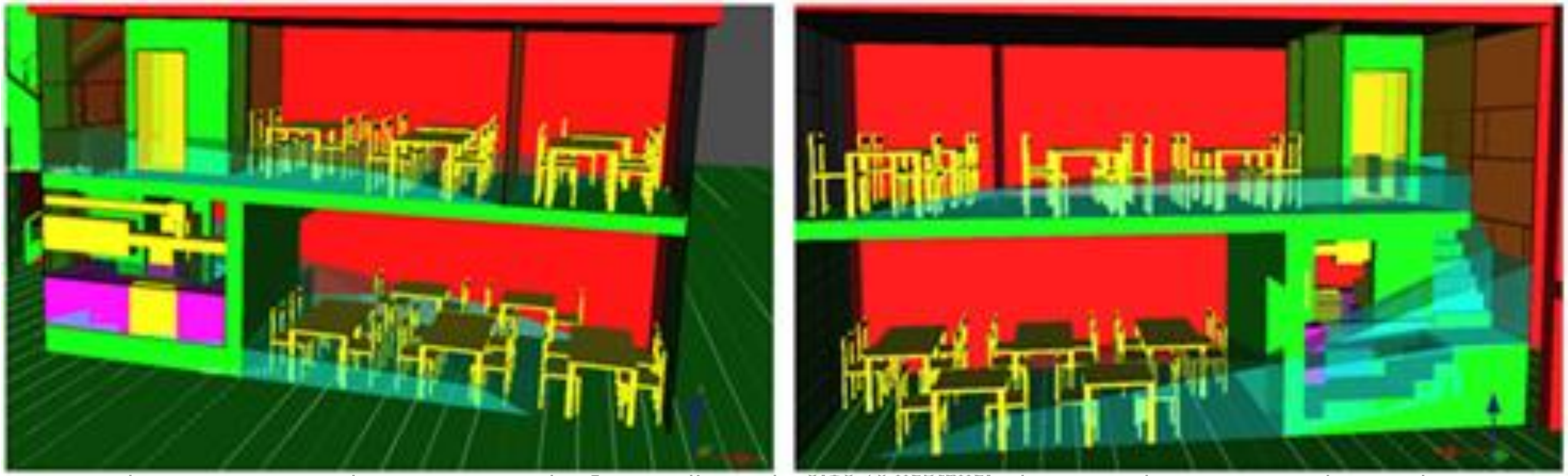


On the basis of literature data (ADL, 1992) for a spill on the ground in a room without ventilation (quiescent air), we assumed 75 cm as the height reached by gasoline vapour.

Refrigerator has been considered the only source of ignition, (rolling shutter, 3 m of height too high).

Plausible scenarios

Once set the size and location of the cloud of fuel-air mixture, **the concentration of the fuel was varied in order to find the range** of concentrations **that can lead to an explosion** with results according to the above criteria.



Vapour cloud of gasoline that would result from an act of shedding by an arsonist based on findings

Maximum Fuel Concentration	heptane 5 % octane 95 %	Intermediate Stoichiometric-UFL	[illegible] heptane; 1.95% octane; 20.52% O_2; 77.43% N_2	4.46	Refrigerator	1.242

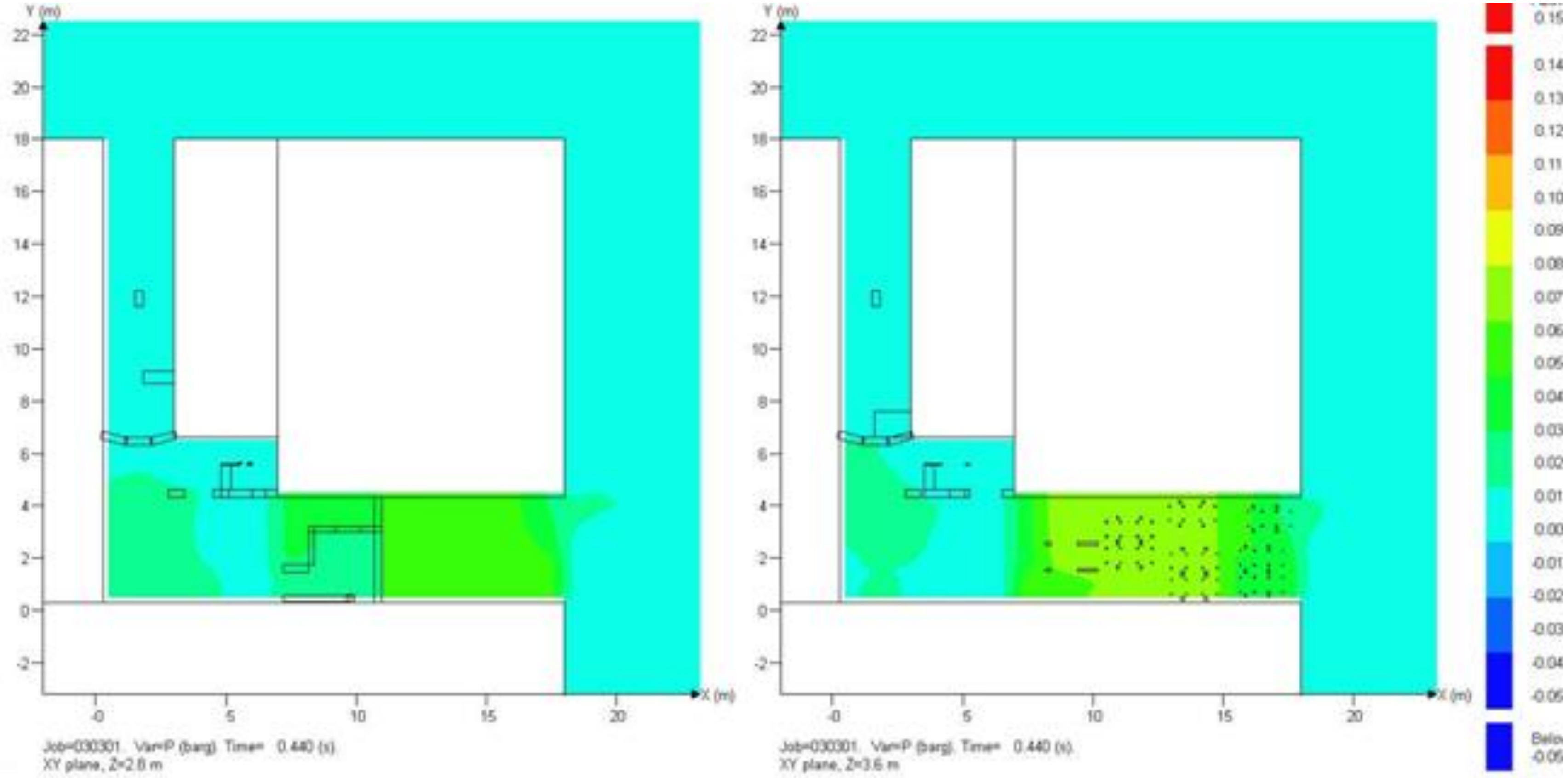
RESULTS

In this case study, the **simulation methods have been used starting from data and evidence collected** in the field **and from the layout of the building** in order to reproduce the "event scene", the more realistic as possible, by reconstructing the fluid dynamic processes, explaining and describing “a posteriori” the development of pressure, temperature and configuration of the fuel and, of course, the ignition source. In this sense, **it has been possible to follow a post-dictive approach** for the identification of the most credible scenarios.

The **screening activity** on the scenarios, **has allowed us to confirm what has already been suggested as a result of investigations** and to reach further conclusions:

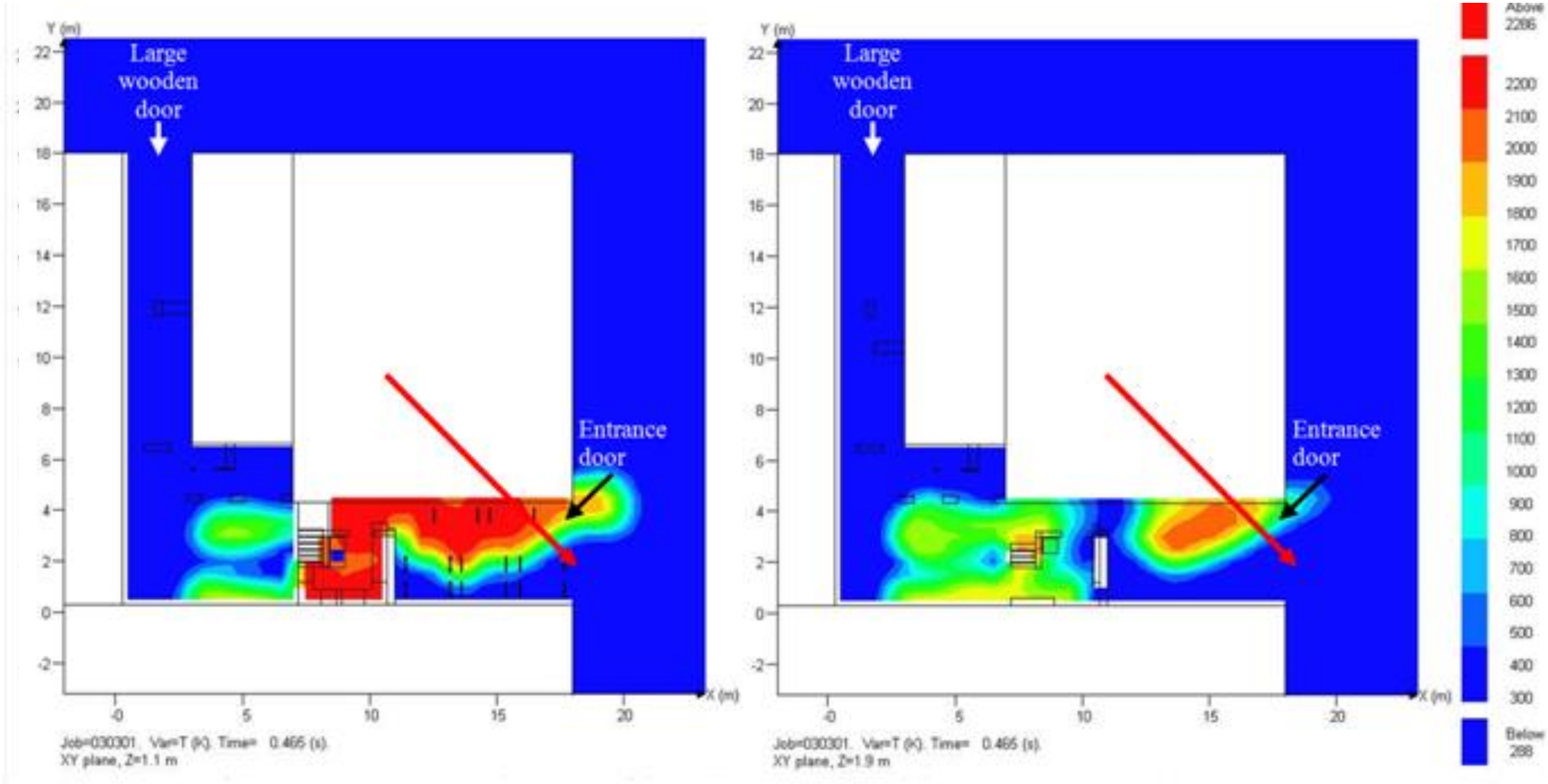
- **Unfounded hypothesis that the explosion may be ascribed to a loss/release of LPG** inside the premise. The presence of this type of fuel, in calculated quantities to cause the observed damage, can not be justified by the presence in the kitchen of leaks, ruptures, disconnections, or by the opening of the knobs of the gas stove found in the closed position.

- **The most credible ignition source among those contemplated is identified in the refrigerator placed in the kitchen.**



Comparison between the maps of pressure under (2.8 m) and over (3.6 m) the mezzanine floor, 0.440 s after the ignition of 5 L of fuel

Assuming a filling of vapours, articulated following the findings of paper soaked in gasoline and rolled up similar to rudimentary fuses, the **sensitivity analysis performed leads to the further following conclusions**:

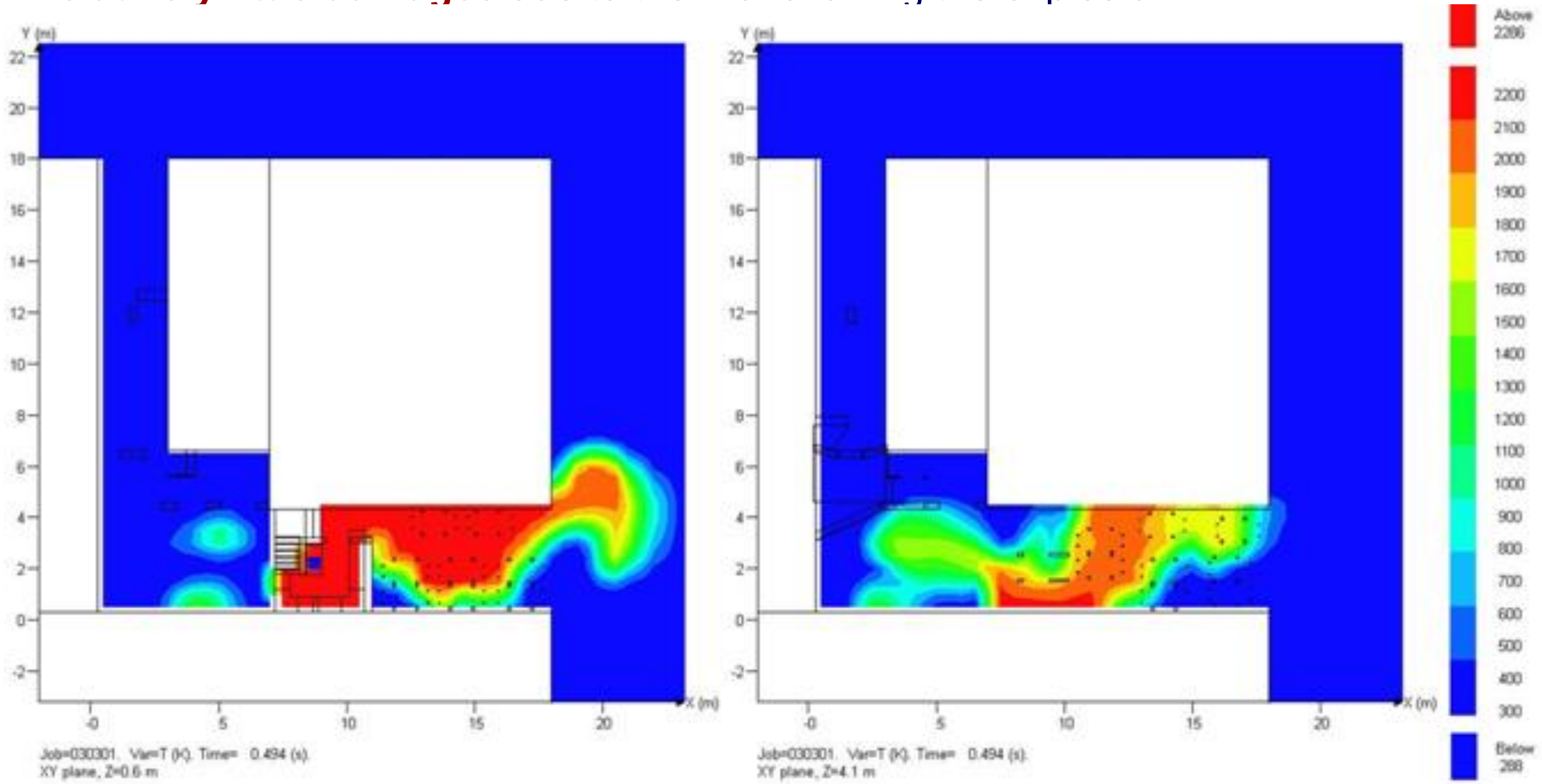


Position of the restaurant manager at the moment of the explosion, as presumed during investigations, and pressure temperature at at 1.1 m and 1.9 m of height from the ground, 0.465 is after the ignition of 5 L of fuel

Position of the restaurant manager at the moment of the explosion, as presumed during investigations, and pressure field at 1.1 m and 1.9 m of height from the ground, 0.465 s after the ignition of 5 L of fuel

RESULTS

- Finally, **the comparison of the temperature maps** on the ground floor and the mezzanine floor, **confirms why the furniture of the dining room on the ground floor was almost completely destroyed**, **while the upstairs had suffered relatively little damages** due to the fire following the explosion.



Maps of temperature at 0.6 m of height on the ground floor (left) and at 0.45 m of height on the mezzanine floor (right), 0.494 s after the ignition

Results of the INSPECTION

Scenario 1 - Fugitive emission of flammable gases - LPG losses (accident)

During the inspection, there was found:
•**no evidence of accumulation of LPG**,
•**total absence of leaks, ruptures** and/or **disconnections** in LPG pipeline.

Scenario 2 - vapours of flammable liquid (arson)

Presence of flammable liquid (subsequent gas-chromatography analysis said gasoline) was **found in some twisted and soaked paper materials**, "Scottex" type in several areas of the premise. **This arrangement likely reminds a propagation fuse**.

Time interval between the distribution of the accelerant liquid and the trigger (rolling shutter or refrigerator activation) could have been **sufficient to produce a quantity of vapour within explosive range**, causing the explosion and fire.

Both scenarios are not consistent with **the summary statements provided by the owner**, at the time of the explosion, **he would have been in the courtyard** in the immediate vicinity of the cylinders.
He reported only burn injuries primarily on his face and on the right side of the his body.

CONCLUSIONS

In this work CFD modelling was applied for the forensic investigation of an explosion accident and subsequent fire in a restaurant.

It was demonstrated that the use of **CFD simulations,** even though **can not replace the investigation activity, can give a useful support to it.**

In particular, **following an exhaustive investigation** and having clearly **defined** the **scope and boundary conditions**, the **CFD model** proves to be a **valuable, non-intrusive technique**:

- **To make a comparison of a wide range of possible accident scenarios** and select the most credible;
- **To validate the assumptions selected and obtain detailed numerical results** in support of the statements constituting the forensic reconstruction of the event.

Finally, but not least, **such models can be a support to field investigation** when, for example, it is not possible to clearly determine from the evidence the ignition source or the point of origin

Thank you for attention

MINISTERO DELL'INTERNO

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