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Original article

Modelling and numerical simulation of pedestrian flow evacuation from a multi-storey historical building in the event of fire applying safety engineering tools

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ABSTRACT

Fire prevention in museums is a much more complex matter because the safeguarding of human life must be integrated both with the protection of the cultural heritage of buildings and the unrepeatability of the works of art exhibited. While most fires cannot be prevented, implementing complementary safety measures can help both to mitigate the negative impacts and limit costs. This is an issue that researchers have little investigated over time and thus very few studies are available in the literature. The paper shows the results of fire simulation and visitors' evacuation processes from one-exit multi-storey historical building, which is used prevalently as a museum, equipped additionally with a non-invasive supplementary countermeasure based on an automatic people entry flow control system in the hall of the building. For achieving the purpose of our research, an extension of the analysis tools generally applied in the field of engineering was made. Computational fluid dynamics (CFD) modelling showed that for all fire scenarios investigated the gradual spread of combustion gases and smoke is influenced by fire size, building geometry, and chimney effect along the ceiling and the stairwell. The very high temperatures that could endanger the building structure and lining occurred only in the fire room. Evacuation simulations showed the effectiveness of the current fire safety plan and equipment to manage fire emergencies, and suggested including in security procedures staff alert and guidance for a quick evacuation of visitors. People entry flow micro-simulation proved that the implementation of a control system, which counted both the number of visitors and those leaving the museum in the same time and stopped temporarily the passages through the entrance, prevented the possibility of having an overcrowded museum for the safety of occupants in the event of fire.

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1. Introduction

Italy has a unique, artistic and cultural heritage in the world, with thousands of museums, churches, libraries, castles, villas, palaces, theatres, and archaeological sites [1].

Unfortunately, the historical buildings are, in general, more vulnerable to fire than other buildings more especially for the presence of the high amount of combustible materials. Specifications of the types of buildings, open to the public, which are under the Italian State protection for their artistic, historical, archaeological, and/or anthropological value (e.g., libraries, archives, museums, art exhibitions, galleries, and so on), as well as technical standards of fire prevention and general criteria to be followed in not-invasive interventions that are compatible with the artistic-historical constraints of the protected buildings are reported in [2–4].

With regard to museums, these structures should be made safer against fire with operations that have to be compatible also with the works of art contained in them. Unfortunately, their content has been, in some cases, considerably destroyed [1,5,6]. However, if it is our duty to take care of museums with their masterpieces so that new generations may appreciate them, the safety of human life is also a major concern; as a consequence, jointed safety measures for fire protection should be guaranteed. But this often comes in conflict with constraints concerning especially historical-artistic objections against meeting egress requirements such as, for instance, a higher number of emergency exits and/or to build

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outside stairs for people evacuation. Finding a good compromise is, therefore, a relevant question, and a major driving motivation for researchers to investigate the issue in greater depth. Fire protection should include not only minimum requirements (e.g., alarm and monitoring systems, extinguishers, emergency phones) and operations (e.g., personnel training, emergency response plans, maintenance schedules of safety measures); but also, complementary measures, rather than structural interventions, that do not involve the conservation and aesthetics of museums. Additional measures could be based, for example, on people entry flow control systems. Counting both the number of entering visitors and those that leave the museum in the same time, as well as stopping the passages through entrances temporarily when the number of occupants exceeds the threshold value fixed by the fire brigade, might be an appropriate solution. The evaluation of the effectiveness of pedestrian control systems at museum entrances, as a complementary safety measure in order to reduce the risk level of occupants in the event of a fire, has been little investigated over time, and appears to represent a gap in the literature. One of the main objectives of the present paper is to provide additional knowledge on this issue.

As far as the authors of this paper are aware few studies [7–18] have hitherto investigated fires and fire protection systems in historical buildings such as museums. Moreover, these studies are focused prevalently on certain specific aspects such as temperature and smoke propagation, people evacuation, or conventional fire protection systems.

People evacuation process from a building is a very complex phenomenon. Starting from the firebreak out and the subsequent perception of danger, it ends when all occupants reach a safe place. There are many factors that may affect the evacuation of occupants from a building. These might be summarized in three main categories: configuration of the building (e.g., size and number of exits, width and maximum length of the escape routes along the different components of the structure; such as doors, corridors, and staircases), behaviour of occupants (with and without staff guidance) during the evacuation procedure, and the environmental conditions along escape path.

The high temperatures and smoke, can expose people during evacuation to the danger of burning or suffocation. These effects, in turn, depend on numerous factors; for example, the floor where the fire starts, the heat release rate (HRR), the presence and types of inflammable materials, and the distance required to achieve the evacuation route.

People evacuation models based on the three-dimensional reproduction of buildings, with the associated analysis of environmental conditions generated by fire and corresponding human behaviour of people involved, have been developed in the literature [19–31]. However, a wider evaluation that simultaneously combines different factors which seem to have a role in influencing people safety in the event of fire (i.e. different locations of fire, one emergency exit, maximum occupancy rate due to the contemporaneous presence of visitors, and a pedestrian control system in the hall) does not appear to have been sufficiently investigated. Thus, the present paper focuses on all the aforementioned variables.

In the light of the above considerations, the paper investigates different fire scenarios in a multi-storey historical building used as a museum, which is novel and of great importance since the safeguarding of human life must be integrated both with the protection of the cultural heritage of buildings and the unrepeatability of the works of art exhibited. The novelty of the paper is also in combining three different approach: a CFD code, an evacuation model and a micro-simulation model for simulating pedestrian flow, in order to evaluate the effectiveness of the current fire safety plan and equipment to manage fire emergencies and to suggest procedures for a rapid evacuation of visitors.

2. Research aims

The present paper is set in the context of research on the evacuation process from museums in the event of fire, but extends the use of certain safety engineering tools for evaluating risks and for designing complementary not-invasive interventions at entrance-doors aimed at jointly increasing the safety level of occupants and preserving the original state of the buildings. An automatic people entry flow control system is designed in the hall of the museum without any architectural and/or structural modifications being introduced to the original building characteristics. This research aims to serve as a possible reference for museum management agencies, and to further our knowledge in the field of fire safety in museum buildings.

3. Methods

Among strategies for studying building fires and quantifying consequences, as well as for evaluating the effectiveness of safety measures, there are typically three ways: full-scale experiments, reduced-scale experiments, and computer simulations. Computer simulations have become an ever common practice for giving the following advantages:

- reasonable costs of calculation compared to real or reduced-scale tests;
- evaluating fire behaviour more efficiently since many detailed data are included;
- understanding better the relationships between the fire and evacuation conditions;
- evaluating quickly the benefits of complementary countermeasures.

These goals are expected to be achieved, in this paper, by numerical simulation tools.

In this respect, three 3D models were specifically developed. The first, based on computational fluid dynamics (CFD), was performed for simulating fires at different floors of the museum. Then an evacuation modelling was set up for evaluating the effects of the aforementioned environmental conditions on occupants' safety along the escape path. Subsequently, a micro-simulation model for simulating pedestrian flow entering the museum was developed, and the effectiveness of a pedestrian control system in the hall of the museum was evaluated.

3.1. Description of the historical building

The Historical building investigated is known as *Fruscione Palace*. It is in the old centre of Salerno City (South of Italy). Its construction began in the 12th century and it is based on the ruins of a Roman thermal complex of Imperial age of the second century B.C.

The *Fruscione Palace* presents a stratified and decorated structure, as shown by the two main perspective views reported in Fig. 1. Fig. 2 shows exterior and interior views with some paintings, several antiquities, a sculpture, and a wooden false ceiling.

The building has been subjected to numerous interventions over time, even sometimes invasive, and changes of use. The recent restoration (2009–2013) has allowed the use of this building as museum with temporary art shows and/or cultural events. The building consists of five levels (ground floor, 1st floor, 2nd floor, 3rd floor, and attic) connected by a staircase and an elevator. In addition, in the building basement (an area located at 3 m below ground level) the archaeological remains are contained. That room is closed to visitors and visible only from a viewpoint on the ground floor (Fig. 2c). Fig. 3 shows two sections of the building.

a) Adelberga Alley

b) Barbuti Alley

Fig. 1. Perspective views of *Fruscione Palace* from: a: Adelberga Alley; b: Barbuti Alley.

Each level has a total floor area of about 300 m^2, subdivided into rooms and exhibition areas of different sizes, and is about 4.5 m in height (only the attic level has a sloping roof with a maximum height of 2.1 m).

The whole building is not equipped with a HVAC (heating, ventilating and air conditioning system). However, it is equipped with a fire detection system (smoke detectors and fire alarms), fire hoses, and portable fire extinguishers. Moreover, it has only one escape route (i.e. through the 1.2 m wide staircase) toward the exit portal on the ground floor with a width of 2.5 m (Fig. 1a). There are also two secondary exits, which only allow people to access on two opening terraces on the first floor and at the attic level, respectively, and are not connected to the ground level. In order to consider the worst situation for people safety, the two secondary exits were not considered in the analysis of the evacuation process. The internal divisions at each floor, as well as the positions of fire alarms, fire hoses and extinguishers, and smoke detectors, are shown in Fig. 4.

3.1.1. *Fire scenarios investigated*

Fire scenarios representative of typical fires for the building and occupancy were assumed according to [15], by taking into account both the inflammable materials and potential ignition sources present in the building, in conjunction with the location of fire extinguishers and hoses as well as the distance from the egress route. Four different realistic fire scenarios, that potentially can endanger occupants and areas of historical significance, were investigated, all of which involving a fire of the wooden false ceiling: (scenario I) in a technical room on the attic level (Fig. 4a); (scenario II) in a room on the 2nd floor, far from evacuation staircase, water system and extinguishers (Fig. 4b); (scenario III) in a side room on the 1st floor, far from both staircase and fire equipment (Fig. 4c); (scenario IV) in a room on the ground floor, far from the exit door and the closest shop/info point, where the staff would be likely to immediately detect and extinguish a fire, and from fire equipment (Fig. 4d). Possible ignition source could be faulty installations: a short-circuit in the electrical panel of the elevator (scenario I) or in the ceiling lamp (scenarios II–IV).

3.1.2. *Building maximum occupancy rate*

According to the fire protection project, which was approved by the local fire brigade, the maximum occupancy rate of *Fruscione Palace* is assumed to be equal to the contemporary maximum presence of 75 people. Moreover, the distribution of occupants by floor is as follows: ground floor (11), 1st floor (20), 2nd floor (22), 3rd floor (22), attic (0).

3.2. *Modelling*

3.2.1. *CFD modelling*

CFD models are nowadays useful tools for simulating a fire, quantifying temperature, smoke, and toxic gas concentrations, and showing the effects on people's safety. In the present study, the code ANSYS CFX was used [32]. It has been widely adopted and validated for many applied aspects of fire safety. Some applications of this numerical simulation tool can be found also in [33,34], with reference in particular to reduced-scale tunnel fire. In this respect, a sensitivity study was carried out, evaluating the effect of mesh approach and resolution, as well as of solving numerical scheme and of wall heat transfer and radiation modelling, on the solution stability and on the results accuracy. Simulation results showed that the experimental fire-induced temperature profiles and airflow were predicted with fair agreement.

The CFX Code uses the finite volume technique and permits the solution of the fundamental equations of conservation (momentum, heat, and mass transfer), in conjunction with sub-models accounting for turbulence, combustion, and radiation. In this work, turbulence was modelled by the buoyancy-modified RNG k-ε model. Combustion was modelled as a volumetric heat source. A mass source was also assumed for considering the generation of smoke (soot) and toxic gases (CO, CO_2). The multiphase system made of soot particles (smoke) in the gas phase was modelled by the Eulerian approach. Radiation was accounted for by the Discrete Transfer radiation model, also using correlations for absorption coefficients for combustion gases and smoke [35]. The first-order upwind advection scheme for the space discretization and the backward Eulerian transient scheme for the time discretization of convective and pressure terms were used. Convergence criteria were residuals lower than 10^{-4}.

3.2.2. *Evacuation modelling*

An evacuation model was set up and the code STEPS was used [36]. STEPS has been recently applied, in conjunction with the CFD, also to the case of tunnel fires [37,38]. STEPS employs an agent-based approach which predicts the movement of discrete

a) b) c) d)

Fig. 2. a: the main facade of *Fruscione Palace*; b: interior view of an exposition room; c: archaeological remains in the building basement; d: interior view of the so-called ‘noble floor’ decorated with painted frescoes dating from the XIX century and terracotta paving.

individuals (virtual people) through three-dimensional complex space towards the exits. Planes are divided into Cartesian meshes to solve the free-space movement algorithm and the inter-agent collision problem. The mesh size is chosen in general to represent the area occupied by a single person. Each person is modelled by basic attributes: free walking speed; awareness of the environment; patience; group relationships; pre-movement time in the case of evacuation. Randomness is built into the solution procedure of people decisions and movement, and an ensemble average of several simulations should be used [39].

The evacuation model was validated by means of a comparison with experimental data of one of the evacuation drills at the Altamira School, in Camargo, Spain [40]. During the drills, eleven video cameras were used to record the preparation and the holding time for each classroom, as well as the exit usage and the evacuation time. A sensitivity analysis of numerical parameters (time step and grid size), here not reported for sake of brevity, was carried out with respect to the evacuation process of the drill E3, involving 235 pupils and 12 teachers from the main building of the school. The pre-evacuation times observed during the trial E3 for each classroom and the distributions of the average walking speed derived for both children and adults from all the drills were used as the input data of the model. A good prediction of test data was obtained: the evacuation time was slightly overestimated by the model, within acceptable tolerance levels (an average difference of 10 s was predicted).

3.2.3. *Entering people flow modelling*

Different simulation models have been developed over time for predicting the pedestrian flow characteristics under normal conditions and for evaluating the corresponding service level for various pedestrian facilities. These models are derived, in general, from road traffic micro-simulation models that are prevalently used as a method for studying transport-planning, traffic-engineering situations, and pedestrian-vehicle conflicts. According to the objective of the present paper, a current micro-simulation model was used to simulate the process of pedestrians arriving at the *Fruscione Palace*. This was made in order to evaluate the level of service upstream of a possible automatic control system that counts the number of people entering and stops the visitors at the entrance-door when the building maximum occupancy rate fixed by fire brigade is to be exceeded (i.e. 75 people). In this respect the software AIMSUN with the associated pedestrian micro-simulation module Legion was used [41]. Some applications of AIMSUN can be found in [42–44]. Legion is a multi-agent simulator in which each simulated pedestrian makes his own choices about his route and his next step, reacting to the environment and following other pedestrians. It permits defining: pedestrian behaviour and speed models, the origin and destination (OD) points, the uni- or bi-directional pedestrian flow, the pedestrian lane formation, etc.

The calibration of the micro-simulation model was conducted by comparing pedestrian flow values obtained by simulation to those measured on entering the building, on different days and time of day before an exhibition. Calibration was conducted until the corresponding differences were within predefined statistical tolerance levels. In this respect, the GEH statistic was used for validating the calibration process:

$$GEH = \sqrt{\frac{2(M-C)^2}{M+C}} \tag{1}$$

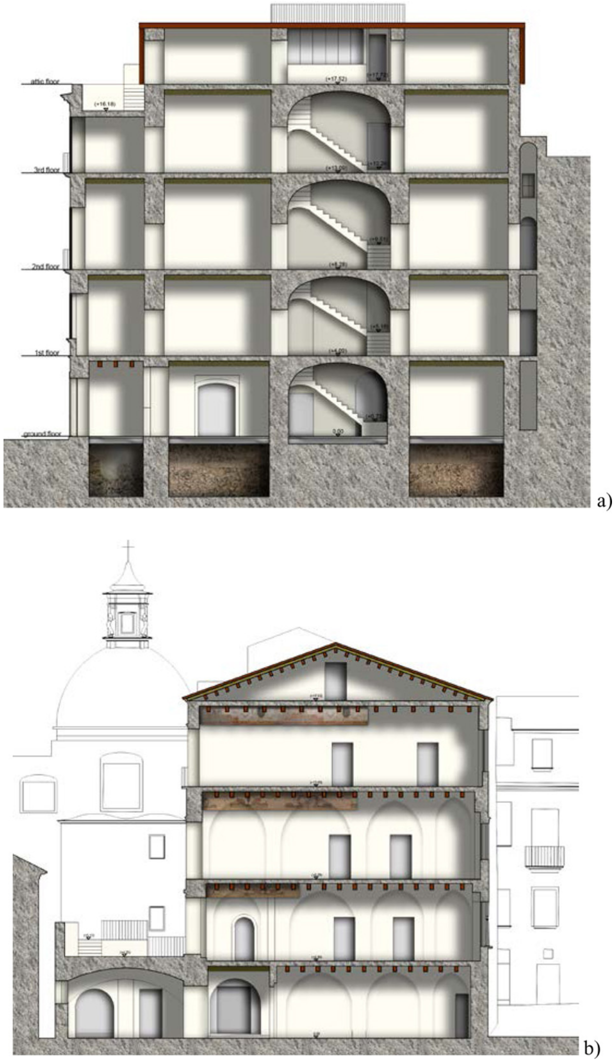

Fig. 3. Building sections: a: longitudinal section; b: cross section.

where M = simulated pedestrian flow volumes; C = pedestrian flow volumes measured entering the building. In all the cases considered the recommended GEH value less than 5 was observed, thus demonstrating that a good level of conformity was obtained.

4. Fire simulations

4.1. CFD simulation settings

A 3D model (Fig. 5) of the building was created, and an unstructured non-uniform mesh based on tetrahedral cells was used. The mesh was refined near the burning surface for each fire scenario, according to the recommended CFD standard for the grid resolution to adequately resolve plume dynamics [45].

It is recommended to set the ratio of the fire characteristic length scale to the grid size between 4 and 16. On the whole, surface cell size was set in the range of 0.05–0.5 m, with an automatic grid adaptation technique used to gradually coarsen the mesh length scale for each successive element away from the fire region (0.05 m), up to a maximum body spacing of 1 m. A total number of about 650,000 cells was obtained.

According to the literature [46–48], a slow t^2-growth curve (1055 kW reached in 10 min) was considered, which is typical of fires involving thick, solid wooden fuels. In addition, yields of soot and toxic gases (CO_2 and CO) generated by the fire, as well as smoke optical properties, were assumed based on literature data [46,49], as summarized in Table 1.

The front door of the building was assumed as the only opening to the outside. It was also considered that all the internal doors of exhibition rooms and corridors were open. Moreover, adiabatic walls were considered, i.e. no heat flux was allowed. Furthermore, given the assumption of fire locations far from fire equipment, it was supposed that escaping people do not use available extinguishers. This conservative approach was chosen in view of assessing tenability and safety conditions. The initial ambient temperature was assumed 20 °C.

4.2. Results of fire scenarios

The overall spread of hot gases during the fire along the floors of the building for the assessed fire scenarios is shown in Fig. 6, in terms of gas temperature.

Fig. 6 shows that the hot gases generated by the fire gradually moved from the fire room and slowly spread towards the other rooms of the floor and then down to the flooring. This is influenced by the internal division on each floor as well as by floor height. However, in scenarios II-III-IV the main propagation path was towards the stairwell, and hence primarily ascending due to the chimney effect (Fig. 6b, c, and d, respectively). In scenario I on the attic level (Fig. 6a), the spread of combustion products went downwards toward the exit door already in the first few minutes. The highest temperatures (about 2000 °C, i.e. of the order of the adiabatic flame temperature of wood) were predicted only in the fire room below the ceiling. Only in fire scenario I, very high temperatures resulted in most of the fire room, due to the lower and sloping ceiling and to the small size of the room. In scenarios II and III, the assumed location of fire room induced higher temperatures after 10 min both in the fire room (up to about 1800 °C and 1600 °C for scenario III and II, respectively) and in the adjacent spaces, up to about 800 °C. On the contrary in scenario IV, the assumption of fire start in a larger room connected to other spaces resulted in a faster dispersion of combustion gases and hence larger gas cooling, with gas temperature up to 800 °C after 10 min. With regards to fire detection, it was assumed that this occurred when at the detector head the optical density per meter reached the value of $0.14\,m^{-1}$ [46], i.e. the smoke concentration exceeded 0.052 ppm for the fire type.

The widespread presence of ceiling smoke detectors in all the rooms allowed a quick detection of the fire in each scenario, at about 2 min after fire break out ($t = 135$, 110, 110 and 120 s in the event of fire scenario I, II, III and IV, respectively). In order to evaluate the safety level for building occupants, the environmental conditions were considered in detail at the conservative 2 m eye level, and compared to tenability limits [19], reported in Table 2.

With regards to species concentrations, predicted values always resulted within the safety limits, thus not posing an immediately dangerous threat to life or health of occupants. On the contrary hazardous conditions due to heat and visibility occurred in fire rooms after about 3 min, and later (after 5 min) in nearby spaces, gradually spreading over the floor and then towards the stairwell.

According to the evacuation simulations reported in the paragraph 5, thanks to the widespread presence of smoke detectors ensuring a quick fire detection and alarm in the event of a fire, the egress process from *Fruscione Palace* would be completed within 4–7 minutes after fire break out. Results up to $t = 7$ min were therefore here mainly focused and reported. Predicted contours at 2 m height are reported in terms of temperature and visibility in Figs. 7–8, with legend colour ranges limited to safe values, and red areas showing building spaces where untenable conditions were obtained ($T > 60$ °C and visibility < 10 m,

Fig. 4. Building levels and fire scenarios: a: attic (scenario I); b: 2nd floor (scenario II); c: 1st floor (scenario III); d: ground floor (scenario IV).

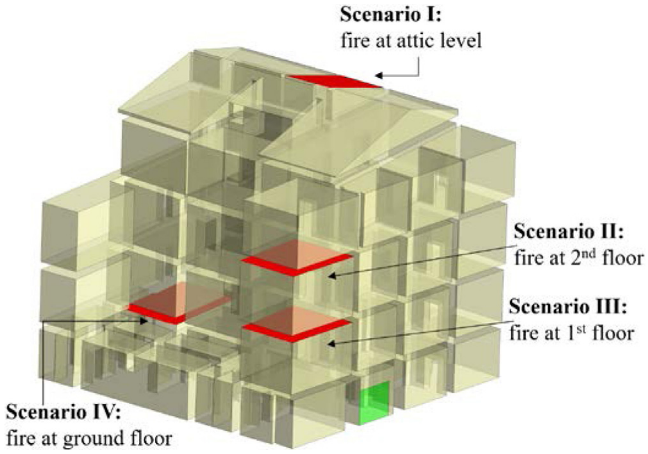

Fig. 5. The CFD computational domain with the location of burning surfaces for each of the fire scenario (I, II, III, IV) and the building front door at street level.

respectively). Predictions in terms of hazard due to radiant heat flux, not reported here, were similar but slightly delayed compared to temperature contours. For exposure to hot gases (Fig. 7), hazardous conditions occurred after 5 min only for people who had not escaped from either the fire room or the adjacent exposition room and spaces or, in fire scenario I, on the landing of the staircase on the 3rd floor. At 7 min, only for scenario I in some rooms on the 3rd floor the temperatures are lower than 60 °C. For the other scenarios, untenable conditions occurred over a large part of the fire floor as well as along the stairwell toward the upper floor, due to the chimney effect. People eventually still going down the stairs from either the fire floor or the upper one could be exposed to untenable temperatures. Moreover, in the scenario IV on the ground floor, late evacuees could find hazardous conditions along the escape route towards the building exit door. Impairment due to smoke could occur only for late evacuees from fire rooms and the closest spaces, as shown in Fig. 8 for every fire scenario.

In summary, CFD results showed that for all fire scenarios the highest temperatures that could endanger the building structure and lining occurred only in the fire room.

With reference to people safety the presence of active fire detectors triggering evacuation within few minutes could ensure the end of the egress process for almost all building occupants before hazardous conditions occur. Only people who hesitate or delay their escape could be briefly exposed to untenable conditions, still quite tolerable for a short period.

A more detailed evaluation of the evacuation process and people safety was performed by the combined use of CFD and evacuation modelling by STEPS code, as reported in the paragraph 5. Indeed, STEPS imports and uses the output of CFX to assess both the time required for the occupants to evacuate in safe conditions (required safety egress time [RSET]) and the time available to exit in safety (available safe escape time [ASET]).

Table 1
Wood fire parameters.

Parameter	Value
ΔH_{ch} (kJ/g)	12.4
ΔH_{con} (kJ/g)	7.8
ΔH_{rad} (kJ/g)	4.6
CO_2 yield (g/g)	1.27
CO yield (g/g)	0.004
Smoke yield (g/g)	0.015
D_m (m^2/g)	0.037

Table 2
Acceptable safety criteria in case of fire.

Parameter	Criterion
Temperature	< 60 °C for 30 min
Radiation heat flux	< 2.5 kW/m^2 for 5 min
CO_2	< 40,000 ppm for 30 min
CO	< 1200 ppm for 30 min
O_2	> 14%
Visibility	> 10 m

5. Evacuation simulations

5.1. Simulation settings

The building occupancy rate at the beginning of the fire emergency was considered in accordance with the safety plan. People were assumed to be all unrelated able-bodied adults, and to use only the staircase to escape.

The building front door on the ground level was considered the only system exit used for evacuation.

The RSET time is composed of four components [46,50]: (t_1) time from ignition to detection; (t_2) time from detection to the provision of a general evacuation warning to occupants (e.g. by a sound alarm system); (t_3) pre-movement time (the time required for occupants to become aware of the emergency and carry out a range of activities before beginning to move towards the exits); (t_4) travel time (the walking time required to reach a safe place).

In this work, the alarm time $t_1 + t_2$ was calculated by CFD simulations at smoke detector locations, assuming the sound alarm system to be activated just at the predicted detection times.

For the pre-movement time three hypotheses were considered, in accordance with the literature [13,51,52]:

- all occupants moving immediately as the fire alarms starts, i.e. $t_3 = 0$ [51];
- a uniform distribution in the range 5–10 s [13];
- a normal distribution with: $\mu = 120$ s, $\sigma = 40$ s, range = 60–200 s [52].

The maximum unimpeded horizontal walking speed was assumed for each person according to a normal distribution

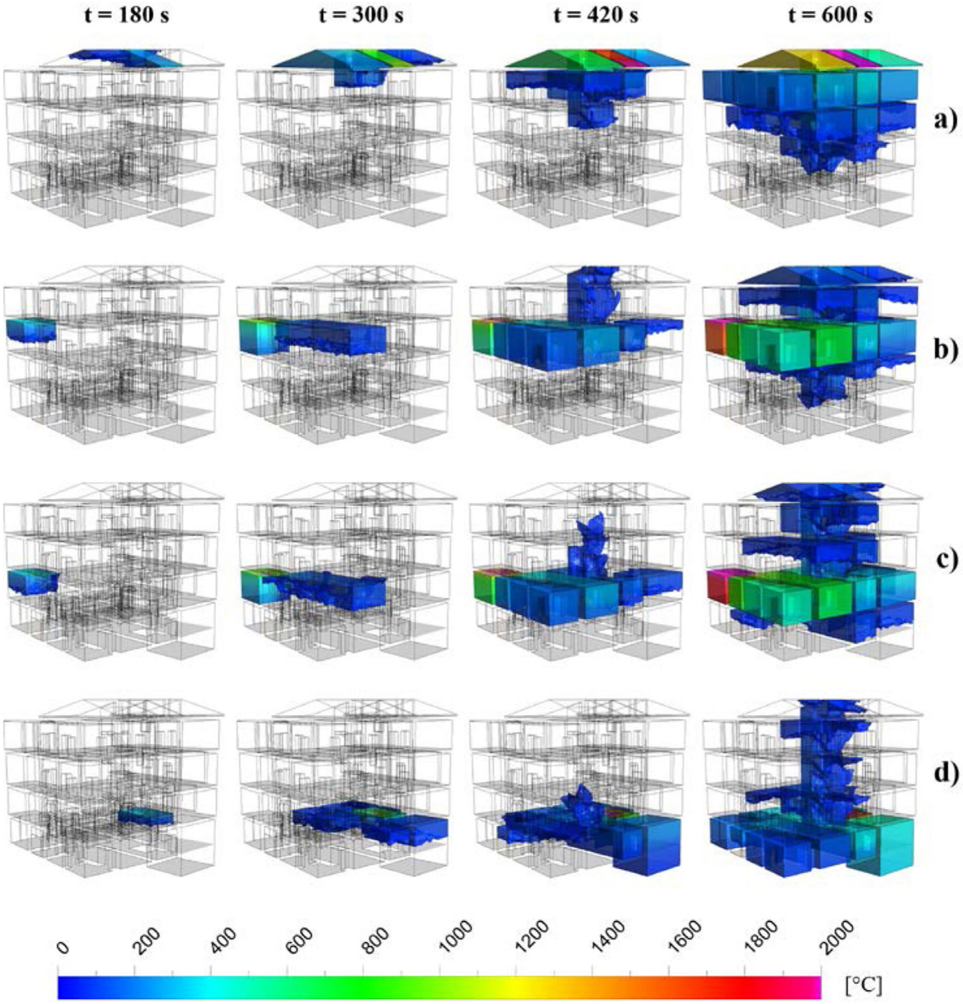

Fig. 6. Time evolution of gas temperature, t = 3, 5, 7 and 10 min: a: fire scenario I on the attic level; b: fire scenario II on the 2nd floor; c: fire scenario III on the 1st floor; d: fire scenario IV on the ground floor.

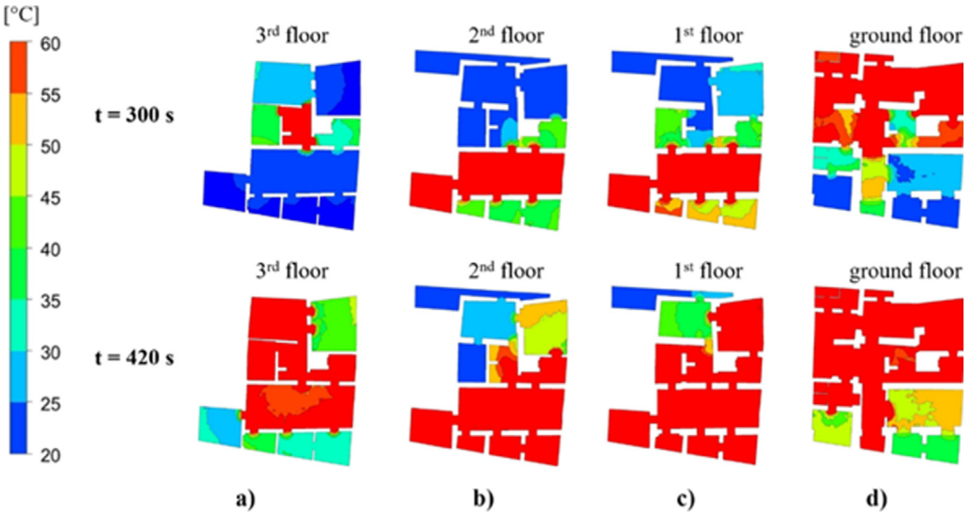

Fig. 7. Temperature contours at eye level, on floors with untenable conditions (in red) for people, t = 5 and 7 min: a: fire scenario I on the attic level; b: fire scenario II on the 2nd floor; c: fire scenario III on the 1st floor; d: fire scenario IV on the ground floor.

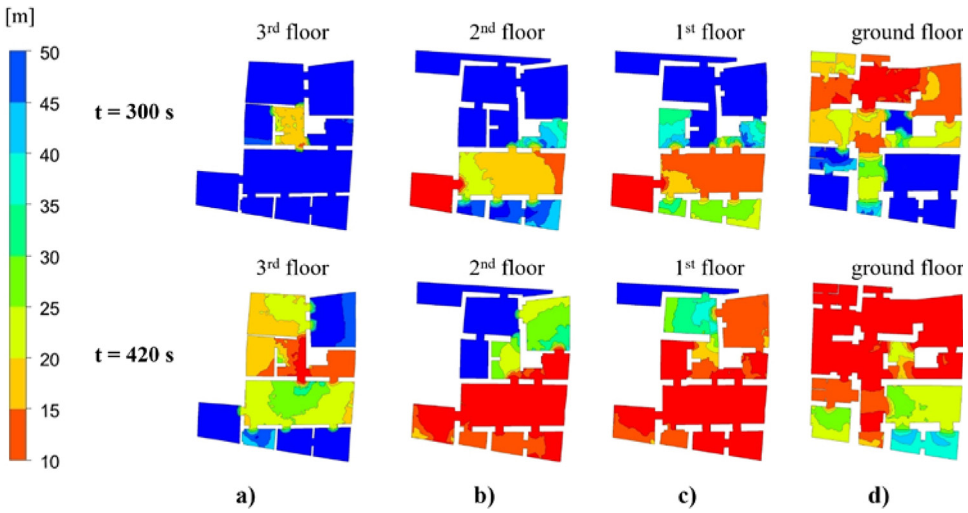

Fig. 8. Visibility distance contours at eye level, with untenable conditions (in red) for people, t = 5 and 7 min: a: fire scenario I on the attic level; b: fire scenario II on the 2nd floor; c: fire scenario III on the 1st floor; d: fire scenario IV.

for able-bodied adults [53] with: $\mu = 1.25$ m/s, $\sigma = 0.32$ m/s, range = 0.82–1.77 m/s.

The actual vertical speed on stairs was considered in STEPS [36] according to the travel speed for stairs in NFPA 130, i.e. about 0.24 m/s referring to the change in elevation. In addition, as in the presence of smoke the walking speed can be reduced because of both smoke obscurity and irritation, CFD smoke data at eye level were imported into STEPS in order to evaluate the actual occupants' walking speed according to the built-in Jin & Yamada relationships [54], in the assumption of irritant smoke. In total twelve evacuation scenarios were analysed.

Table 3 shows the settings for the alarm time, the pre-movement time and the maximum unimpeded walking speed.

Evacuation simulations were performed using grid size of 0.5 m and time step of 0.1 s. For each scenario 30 runs were carried out, to obtain satisfactory accuracy of the evacuation results (with a significance level of 0.05).

Moreover, convergence criteria on the total evacuation time [55] were satisfied, i.e. for 10 consecutive runs the percentage error was:

- lower than 0.5% for the mean;
- lower than 5% for the standard deviation.

5.2. *Evacuation results*

Results were evaluated in terms of total evacuation time and average walking speed, as affected by smoke as well as by staircase, corridors, internal doors and people obstruction along the evacuation path. In Fig. 9, the cumulative distribution function of the evacuation time is reported for each evacuation scenario and for the three hypotheses of the pre-movement times (a, b, c), respectively.

Moreover, in Table 4, the estimation of mean, standard deviation, minimum and maximum values of the evacuation time of all 75 occupants is also reported for each evacuation scenario.

In all fire scenarios, the predicted evacuation times for the two hypotheses with pre-movement time up 10 s (Fig. 9a and b) were similar to each other, and the total evacuation time was about 3.5–4 min. When the pre-movement time increases (Fig. 9c) a longer egress process was predicted and the maximum total evacuation time was about 6–6.5 min. Beside the pre-movement time, another factor inducing differences in the evacuation time was the detection/alarm time. Specifically, at a fixed pre-movement time, the effect of the alarm time clearly appears by comparing the curve profiles reported in each Fig. 9a–c, which were shifted at higher times as the alarm time increases. In order to focus people

Table 3
Alarm time, pre-movement time, maximum unimpeded walking speed in each scenario.

Evacuation scenario	I-a	I-b	I-c	II-a	II-b	II-c	III-a	III-b	III-c	IV-a	IV-b	IV-c
Fire scenario	Attic level			2nd floor			1st floor			Ground floor		
Alarm time [s]	135			110			110			120		
Evacuation hypothesis	a	b	c	a	b	c	a	b	c	a	b	c
Pre-movement time [s]	0	5–10	$\mu = 120$ $\sigma = 40$ 60–200	0	5–10	$\mu = 120$ $\sigma = 40$ 60–200	0	5–10	$\mu = 120$ $\sigma = 40$ 60–200	0	5–10	$\mu = 120$ $\sigma = 40$ 60–200
Maximum unimpeded walking speed [m/s]	$\mu = 1.25$			$\sigma = 0.32$				Range = 0.82–1.77				

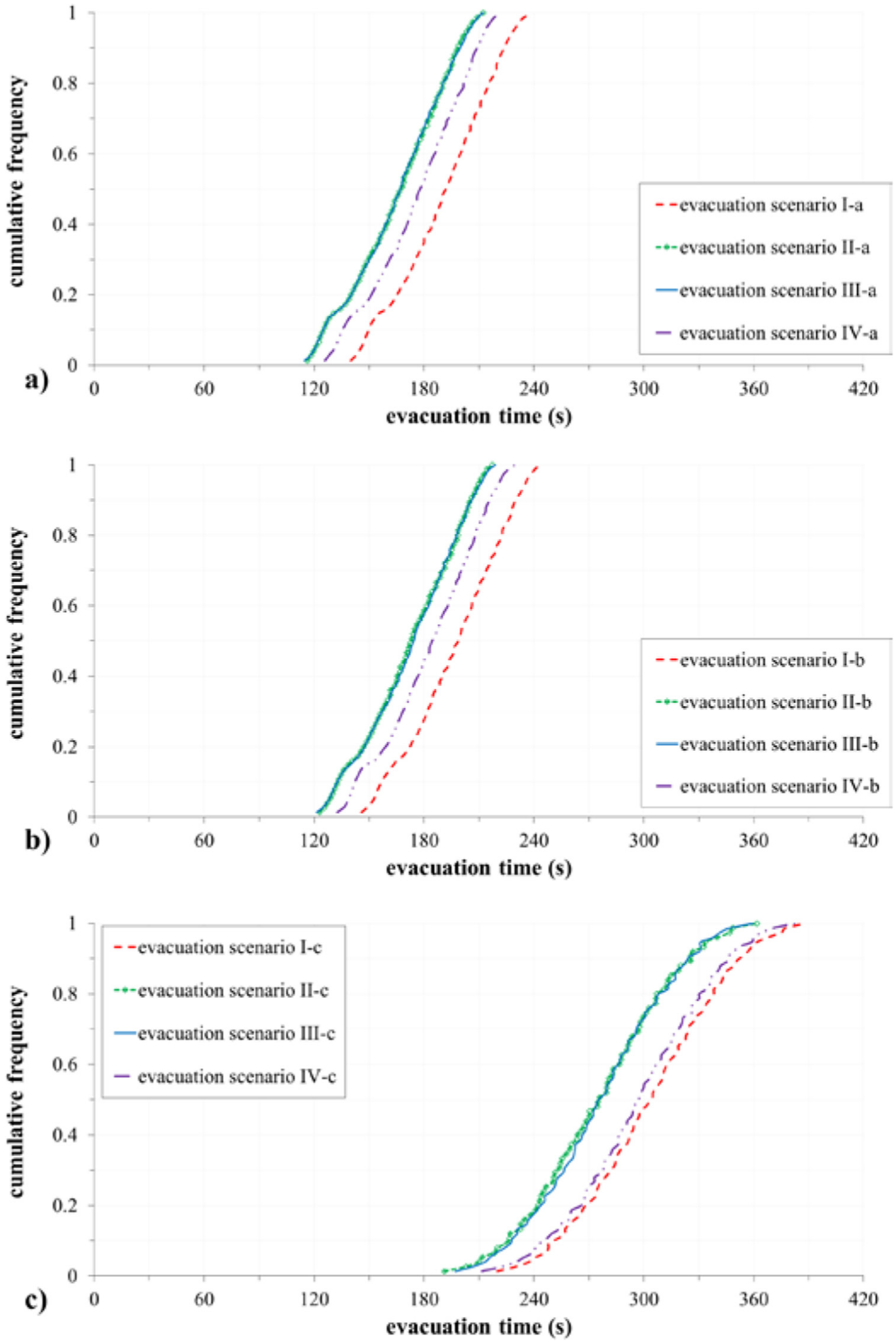

Fig. 9. Function of cumulative distribution of the evacuation time of all people in case of evacuation hypothesis: a: null pre-movement time; b: pre-movement time in the range 5–10 s; c: pre-movement time with mean = 120 s.

Table 4
People evacuation time (s) for all the evacuation scenarios.

Evacuation scenario	I-a	I-b	I-c	II-a	II-b	II-c	III-a	III-b	III-c	IV-a	IV-b	IV-c
Fire scenario	Attic level			2nd floor			1st floor			Ground floor		
Alarm time (s)	135			110			110			120		
Evacuation hypothesis	a	b	c	a	b	c	a	b	c	a	b	c
μ	191	197	304	166	173	276	166	173	277	176	183	298
σ	26	26	38	26	26	37	26	26	36	26	26	37
min	140	146	220	116	123	191	115	121	197	126	133	212
max	239	243	388	212	217	362	212	219	360	222	230	382

Table 5
Average evacuation times (min) per floor for the three evacuation hypotheses.

	Evacuation hypothesis		
	a	b	c
Ground floor	2.2	2.3	4.2
1st floor	2.6	2.8	4.6
2nd floor	3.0	3.1	4.9
3rd floor	3.4	3.5	5.2

evacuation from each building floor, further statistical treatment analyses of mean data of all the occupants present on a specific floor at the beginning of the egress process were performed. As expected, besides the alarm and pre-movement times, evacuation times were mainly influenced by the length of the evacuation path, i.e. essentially by the floor from which the evacuation started. On average, the mean evacuation time increased by about 20–25 s floor by floor for each scenario. The predicted average RSETs per floor are reported in Table 5.

With regard to people's average walking speed, occupants always escaped before the visibility at eye level decreased significantly, therefore the effect of smoke on the actual walking speed was almost negligible, and no significant differences between the scenarios were observed. However, for each scenario differences in occupants average walking speed were only due to the floor from which the evacuation started (and hence due to the diverse length of the escape path along the stairs where the speed was reduced). Moreover, the limited number of occupants escaping from each floor, as allowed by the safety plan of *Fruscione Palace*, ensured that almost staggered evacuation occurred without people hindering each other along the staircase.

5.2.1. *Safety evaluation*

Data at breathing height from CFX simulations were elaborated and imported into STEPS also in terms of temperature, radiant heat flux, and toxic concentrations, in order to calculate the fractional effective doses (FED) absorbed by each person moving towards the building exit door during the evacuation simulation. According to the incapacitation models for exposure to heat and toxics [46], safe conditions occur as long as FED < 1, hence, the ASET time can be evaluated as the time at which FED = 1, and untenable conditions for

Fig. 10. Proposal of re-organization of the existing hall of the museum with turnstiles (two for entering, and two for exiting), and waiting area: a, b: photorealistic renders; c, d: micro-simulation snapshots.

evacuees occur when FED > 1. Results showed that for all the evacuation scenarios the egress process ended before dangerous effects for almost all the occupants. Specifically, hazardous conditions due to toxic concentrations were never achieved. With regards to heat exposure, the pain tenability limit could be exceeded only for four occupants at most, and only in case of evacuation scenarios II-c, III-c and IV-c (i.e. longer pre-movement time). A single person could be at risk in case of evacuation scenario I-c. Evacuation simulations confirmed the effectiveness of the current fire safety plan and equipment to manage fire emergencies. The widespread presence of smoke detectors in all the rooms is able to ensure a quick detection of fire and a prompt sound alarm system, so to have a safe fast evacuation for all the occupants also in the case of further hesitation and delayed walking. A further higher level of safety could be guaranteed by combined activation of sound alarm systems and staff alert and guidance by pushing visitors for a quick evacuation.

6. Micro-simulation of entering pedestrian flow

In order to prevent the building maximum occupancy rate from being exceeded, we thought of providing the hall of *Fruscione Palace* with an automatic control system that counts people entering, as well as people exiting, and stops temporarily the passages through the entrance-door. We investigated the solution based on turnstiles, each allowing only one person at a time to pass through. Their presence on pedestrian entry flow, expressed in terms of queue length (number of people waiting in line for entering) and delay time (due to turnstile), were evaluated by applying the associated AIMSUN-Legion model. Initially one turnstile for entering and two for exiting were considered. Three hypotheses for visitors entry flow in 15 min were investigated: “a” increasing up to 75 people with 0 exiting; “b” increasing up to 100 people with 25 people who leave the building contemporaneously; “c” as the hypothesis “b” but no one leaving the building. Results showed that the queue length and delay time increased in a non-linear way with the increasing pedestrian arrival flow, up to 27 people and 160 s, respectively. Since these values were not acceptable, we introduced a second entrance turnstile, obtaining for the hypothesis “b” a significant reduction of the maximum queue length and delay time (down to 4 people and 13.6 s, respectively). This is compatible with the geometric characteristics of the hall. If no one exits from the building (hypothesis “c”), a waiting area should to be organized to host the remaining 25 people that cannot be entered temporarily. In this respect, we designed the re-organization of the existing hall (Fig. 10).

For preventing the possibility of having a crowded hall so that the remaining people are kept out, the Museum Management Agency might also plan when the other visitor groups may arrive at the museum.

7. Conclusions

This paper investigates people safety in historical buildings in the event of a fire. The *Fruscione Palace*, generally used as a museum, was examined. The effects of the position of fire on different floors both on the environmental conditions and on people safety along the escape route were evaluated by CFD and evacuation modelling. Moreover, the effectiveness of providing the building hall with an automatic entry flow control system was also assessed by modelling the arriving pedestrian flow. On the basis of this study, the conclusions which follow may be drawn.

CFD results showed that for all fire scenarios the gradual spread of combustion gases and smoke will be influenced by fire size and location, building geometry (height and internal division of floor), buoyancy and chimney effect along the ceiling and the stairwell. The highest temperatures that might endanger the building structure and lining could occur only in the fire room.

With reference to people safety, the combined use of CFD and evacuation modelling showed that the widespread presence of fire detectors can ensure a quick detection and fire alarm for every fire scenario, triggering a safe evacuation for all the occupants also in the case of delayed escape. On the whole, evacuation simulations confirmed the effectiveness of the current fire safety plan and equipment to manage fire emergencies, and suggested including during security procedures staff alert and guidance for a quick evacuation of visitors.

Regarding the installation of an automatic entry flow control system, the presence of two turnstiles could allow acceptable people queue and delay time. A waiting area was also designed to eventually host the remaining people that cannot be entered at the same time, preventing the number of occupants from exceeding the building maximum occupancy rate fixed by the fire brigade.

In general, a comparison is very difficult with other studies of the literature for the multitude of variables, different modelling, complex human behaviour, different safety measures and control systems, and so on. The authors are confident that by carrying out an appropriate analysis and implementing suitable assumptions, they have calibrated and applied the models quite accurately, so that this work provides a contribution to the state-of-the-art by showing the effects of combined variables both on the consequences of fire and on people evacuation process, as well as on people waiting to enter the historical buildings. However, there are still some points of interest that are worth investigating. Future research should be focused on the evacuation process of people with different types of disabilities, as well as of established people groups. Finally, the behavioural uncertainty that can affect the escape process should be better taken into account.

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