EVACUATION ANALYSIS OF A LARGE EXPERIMENTAL CAVERN OF THE CERN ACCELERATOR COMPLEX

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ABSTRACT

This contribution describes the evacuation analysis of a large underground facility of CERN, the European Organization for Nuclear Research. The facility is located at approximately 100 m below ground and is part of the CERN largest particle accelerator complex: the Large Hadron Collider (LHC). The experimental area is composed by a main cavern connected through corridors and passages to service caverns. Those are served by lifts foreseen in the evacuation procedure to reach the surface buildings. Given the complexity of the cavern from an evacuation standpoint, the use of agent-based modelling is employed. The evacuation model Pathfinder has been selected, and its capability to automatically integrate FDS toxicity data along the occupants' paths and to calculate their Fractional Effective Dose (FED) has been used. The cavern also includes a particle detector, unique in its layout, for which the evacuation procedure foresees self-rescue masks to be collected at specific locations before moving towards the exit. Behavioural scenarios are carefully defined based on literature and evacuation drills. Repeated evacuation simulations are run with Pathfinder adopting pseudo-random sampling from distributions to vary the model inputs and evaluate behavioural uncertainty. Depending on their initial position in the cavern, the occupants - likely to be involved in maintenance activities - would need to evacuate using scaffolding, ascending and descending stepladders and stairs. The case study shows the importance of using advance modelling techniques to evaluate the consequences to life safety during fire evacuation in complex underground facilities.

INTRODUCTION

CERN, the European Organization for Nuclear Research, operates the largest particle accelerator complex in the world, including the Large Hadron Collider (LHC). The LHC complex comprises underground facilities and surface buildings, often with unique equipment, which periodically needs maintenance activities performed by specialized workers.

The object of the present study is a large underground cavern that includes a particle detector, accessible to workers often through narrow passages, as well as mechanical items and other combustible materials (pumps, cryogenic installations, cable trays, etc.). In the context of a fire risk assessment, a detailed evacuation analysis is needed in order to make sure that tenable conditions are guaranteed during the overall evacuation process. The evacuation analysis appears particularly challenging (Ronchi et al, 2016) for the following reasons:

- First of all, the means of egress of the facility are not standard, falling outside of prescriptive fire regulations. The equipment adjacent to the means of egress is often cumbersome, possibly obstructing the line-of-sight to the exits and including electrically-powered items.

The floor of the mezzanines is a metallic-based grid, where smoke could potentially flow, and the width of some passages (especially those in the detector) is locally low (see Figure 1). The elements of the evacuation path are similar to scaffoldings. The occupants located in the most remote positions have to change direction many times during the evacuation. Therefore, way-finding issues may occur for people unfamiliar with the premises;

- Secondly, the detector is a unique environment, with narrow passages, where one may need to move by crawling, climbing over elements or using vertical ladders. The evacuation procedure from this part of the cavern foresees the use of self-rescue masks[1], to be worn before starting the evacuation towards the lifts;
- The number of occupants inside the cavern varies depending on the type of the activity performed inside as well as the status of the facility (shut down or operation). There is a well-defined threshold limiting the maximum allowed occupants for safety reasons, but for the purpose of a risk assessment, this value does not correspond to the real usage of the facility.

The aim of this study is showing the need of using agent-based evacuation modelling when large complex underground facilities have to be assessed.

Figure 1 Detail of the escape routes with grid floor on the right and the detector on the left (see stairs and narrow passages)

DESCRIPTION OF THE FACILITY

The cavern is located ≈100 m below ground. The volume of the cavern is ≈45000 m^3 (50m x 30m x 30m) and is connected with a surface building through two large vertical shafts. Those are used for material handling and to ensure natural recirculation of air. A mechanical ventilation system is also present and guarantees an inlet of air at the bottom of the cavern. In case of fire, the occupants would need to abandon the main cavern by moving towards the sides and evacuate using one of the two lifts leading to surface buildings. There are in total seven exits from the cavern, and they lead to places of relative safety, which are compartmentalized with respect to the cavern (see Figure 2 and Figure 4 later on in the text for a better understanding of the geometry):

- the two exits on the left-hand side lead to a corridor connected to a lift (Lift 1);
- the five exits on the right-hand side are located at three different levels. They lead to corridors, eventually leading to a lift (Lift 2), which is accessible from two different floors (the lowest and the intermediate one). This lift also serves another cavern, of smaller size with respect to the main cavern of interest.

The lifts are located in pressurized shafts and each of them can be used by 30 occupants in case of a fire. From the standpoint of fire prevention and protection systems, the facility is equipped with a fire detection system that triggers an evacuation alarm to the overall underground complex and alerts the CERN Fire and Rescue Service for intervention. There are alarm push buttons and fire

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[1] The self-rescue mask is a Personal Protective Equipment (PPE) for protection against lethal hazards used in CERN underground areas. The mask contains potassium dioxide (KO_2) that, reacting with H_20 and CO_2 contained in the inhaled air, generates oxygen and absorbs CO_2. Users must mandatorily be trained and qualified to use them.

extinguishers; moreover, some electrical items are equipped with automatic fire suppression systems.
The facility can be accessed only when it is in shut down mode by occupants who passed an online training. The training includes information on the layout of the facility, its main hazards and risks, the location of the emergency exits, the emergency procedure, the use of Personal Protective Equipment (PPE). PPEs such as dosimeter, safety helmet and shoes are always mandatory to access the site.

DESCRIPTION OF THE MODEL

Evacuation model and features used

The selected evacuation model is Pathfinder 2020 (Thunderhead Engineering, 2020). The workflow for its use included:

- Importing the geometry from FDS;
- Integration of FDS PL3D data (CO, CO2, O2 concentration) to calculate the FED (Fractional Effective Dose) along the evacuation paths;
- "Monte Carlo" mode to randomize occupants' position, pre-evacuation time and walking speed and investigate the variability in evacuation model results. The number of Monte Carlo simulations is set as 50.

Geometry

The overall underground and surface area in which the evacuation takes place was modelled in Pathfinder, except for the detector that was only modeled as a geometrical obstruction (see Figure 2). The occupants of the detector are assumed located at selected floors and start evacuating at a time compatible with the time needed to exit the detector (red occupants in Figure 2). In fact, the internal layout of the detector is so complex that the modelling effort to create the navigation mesh would be high, time consuming and probably not sufficiently accurate, resulting in no significant added value to the overall evacuation model.

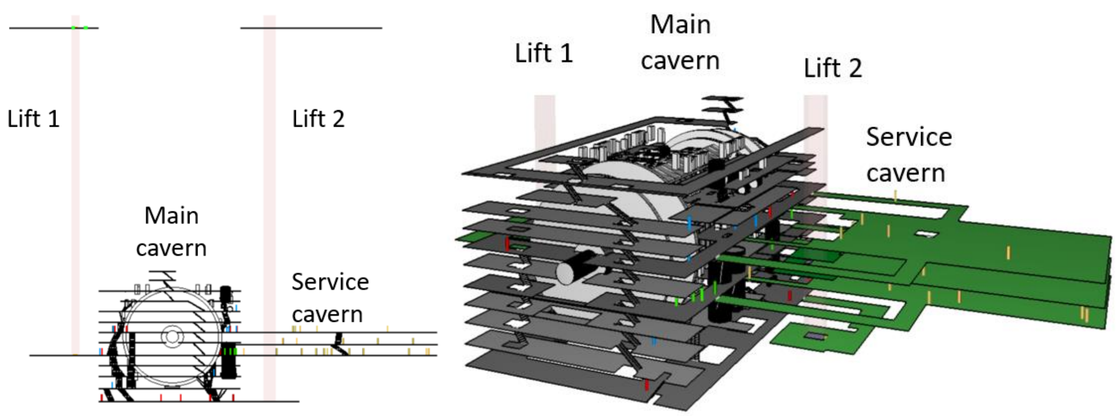

Figure 2 Overview of the Pathfinder model

Model input

Number of occupants and position

CERN facilities are equipped with an access system that tracks the instantaneous number of occupants in experimental areas. A distribution of the occupants based on real data in the last two years was extracted and used to define the initial number of occupants for evacuation simulations. The 90th percentile of this distribution (28 people) for the facility of interest (main cavern) is retained

as a representative value. Out of the total number of occupants, half was assumed to be in the detector and the other half randomly distributed in the floors and mezzanines. The same logic based on real data was used to define the initial number of occupants (22 people) of the adjacent service cavern, served by the same lift.
The facility is also part of the CERN visit circuits. Therefore, a group of visitors (12 people) led by a safety-trained guide is modelled and located at the fourth floor (green occupants in Figure 2).
This estimate is sufficiently conservative and realistic for the purpose of the study.

Pre-Evacuation Time Distribution

The selected pre-evacuation time distribution was based on the work recently published by Galea et al. (2019) for the so-called High Performance Form Works (HPFW) whereas the distribution recommended in the BSI PD 7974-6 for Cat. A (M1 B3 A1), awake and familiar, is assigned to the guided group of visitors (see Figure 3). The distribution of the occupants of the detector is based on the HPFW's one but the mean value is increased by 60 seconds to take into account of the time spent to exit the detector. The delay of 60 seconds should be intended as an assumed travel time. This value comes from a set of hand calculations based on an announced evacuation exercise, during which few occupants (familiar with the facility) were monitored while evacuating using the longest paths in terms of time.
In order to couple the evacuation simulations with the fire simulations, the pre-evacuation time distribution inputted in the Pathfinder model was finally obtained by shifting the aforementioned distributions of the ignition time (200 seconds) used in FDS and the detection time, estimated as 60 seconds.

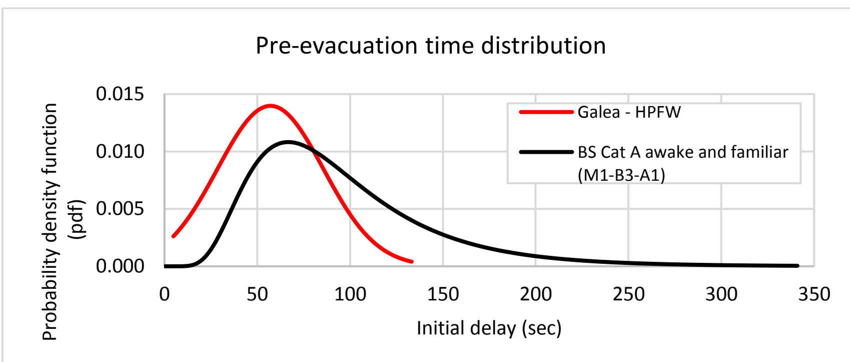

Figure 3 Pre-evacuation time distribution of the occupants of the main cavern

Walking Speed

The assumed unimpeded horizontal walking speed was a normal distribution with mean 1.35 m/s and standard deviation 0.25 m/s, based on Fridolf et al. (2019), with minimum and maximum values of respectively 0.85 and 1.85 m/s.
The speed was reduced when occupants move in descending and ascending stairs using a *k* factor of 0.7 and 0.5 respectively. An additional reduction due to long ascending evacuation was not considered appropriate in this context. The occupants' speed was not decreased due to the presence of smoke since the fire simulations carried out for the same domain showed that the smoke goes towards the ventilation shaft (see later on Figure 5), without overlapping with the evacuation paths at a time compatible with the evacuation (10-15 min).

Exit Choice

The occupants are assumed to know all the exits and move towards the nearest one. The following scenarios are considered (see Figure 4):

- All emergency exits are available (Scenario 0);

- The five emergency exits on the Lift 2 side are not available (Scenario 1 – the evacuation is through Lift 1);
- The two emergency exits on the Lift 1 side are not available (Scenario 2 – evacuation is through Lift 2).

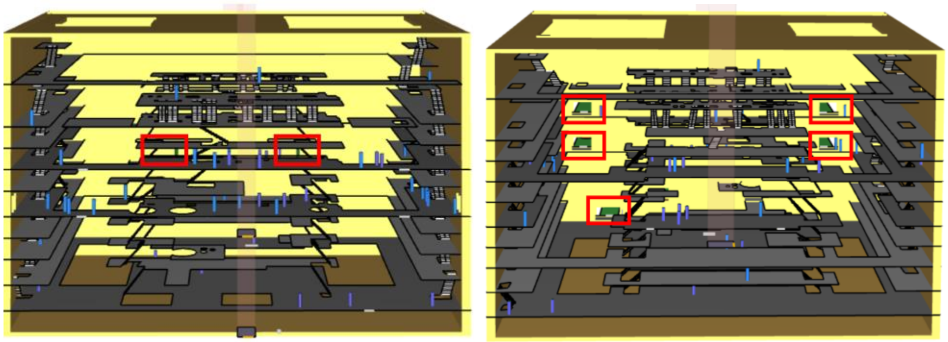

Figure 4 View on the Lift 1 side (left) and Lift 2 side (right) of the cavern; the emergency exits are marked in red

Treatment of fire and smoke

Pathfinder has the capability of calculating the FED by integration of the PL3D data coming from fire simulations obtained with the Fire Dynamics Simulator (FDS) (McGrattan et al, 2020). The FED expression is based on the SPFE Handbook (2016) and accounts for the toxic effect of carbon monoxide, hyperventilation due to carbon dioxide and hypoxia due to low oxygen concentration. In addition to the FED, the tenability conditions are checked by looking at the slices of visibility and temperature as well as the soot density (see Figure 5).

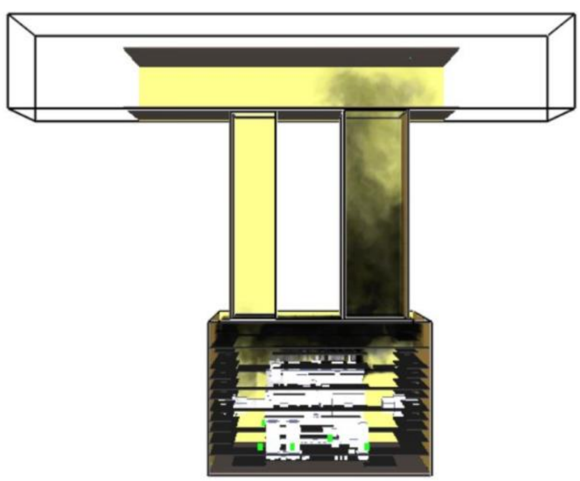

Figure 5 Soot density from an FDS simulation at 15 min from fire ignition

EVACUATION ANALYSIS

The evacuation simulation results show the evacuation process up to the surface building that, in case all exits are available, is 520 s, as shown in Figure 6 on the left. This highlights that, despite the large dimension of the cavern and the relatively long distance to be cover towards the exit (see Figure 6 on the right) the evacuation is rather quick, also considering that the first 200 seconds are added to the evacuation simulations in order to have the same time scale of the fire simulations. For the Scenarios 1 and 2 (only Lift 1 and Lift 2 are respectively available), the evacuation completion times are slightly different i.e. the average of the overall averages is 514 s and 561 s respectively. However, there are no consequences in terms of evacuation safety. In fact, the FED is very low (order of magnitude is 10^{-4}) for all Scenarios, so no incapacitation is expected.

It is noticed that, among the three cases, the Scenario 1 has the lowest completion times: in this case, the evacuation process is optimized because the Lift 2 is used only by the occupants of the service cavern, while the occupants of the main cavern evacuate through the Lift 1. On the contrary, the Scenario 2 shows the highest completion times, because all occupants have to use the Lift 2 to evacuate. Finally, the Scenario 0 is in the middle between the previous two cases: the completion times are higher compared to the Scenario 1 (more occupants use the Lift 2 and in total more elevator rides are needed) but better compared to the Scenario 2 (occupants are distributed between Lift 1 and 2 resulting in a less crowded Lift 2).
The Monte Carlo mode shows no significant variation among the different cases as well. No significant crowding in proximity of the exits are observed, in accordance with the low occupant density in the facility.

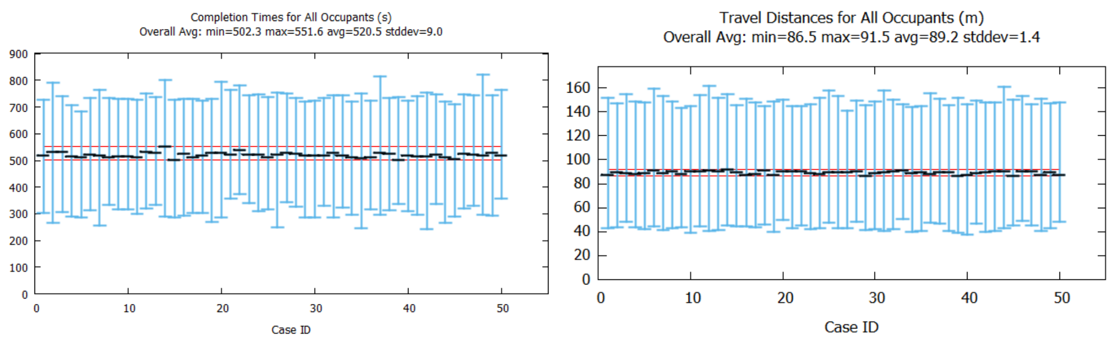

Figure 6 Completion times and travel distances for all occupants in case of availability of all exits (Scenario 0)

RESCUEABILITY ANALYSIS

This analysis had the objective of assessing the FED for occupants unable to evacuate by themselves due to physical or psychological incapacitation, conservatively neglecting that some of them will be wearing a self-rescue mask. This is based on the assumption of the existence of (likely a very low number) injured evacuees. If the person is exposed to high concentration of toxic gases for a long time this could determine incapacitation. To do so, further evacuation simulations are run by randomly distributing a hundred occupants with a “victim behavior” in the facility i.e. with a fictitious and very long pre-evacuation time, preventing them from moving towards the exits (see Figure 7). These simulations are not used to calculate the travel time, but rather to estimate the FED by automatically integrating FDS PL3D data from five different fire simulations (CERN, 2020).

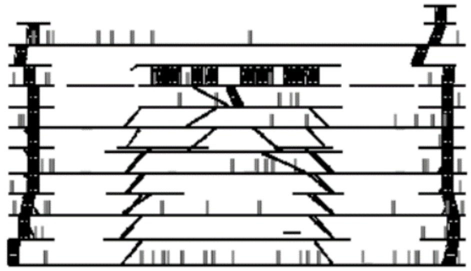

Figure 7 Occupants' position for the rescueability analysis

The results are expressed in terms of FED calculated for all victims after one hour from the fire ignition time (Figure 8), conservatively representative of the intervention time of rescuers. The key highlights are the following:

- some fire scenarios expose a large number of victims to high value of FED (e.g. >0.3);

- some victims, specifically the ones located at the highest floors of the cavern, are exposed to high value of FED regardless of the fire simulation.

Specific measures can be investigated to mitigate the risk associated to the identified situations e.g. local suppression system to reduce the HRR of the most penalizing fire scenarios, mandatory self-rescue masks for occupants going to the top of the cavern (areas with intrinsic higher risk with respect to other parts of the cavern due to smoke stratification), etc.

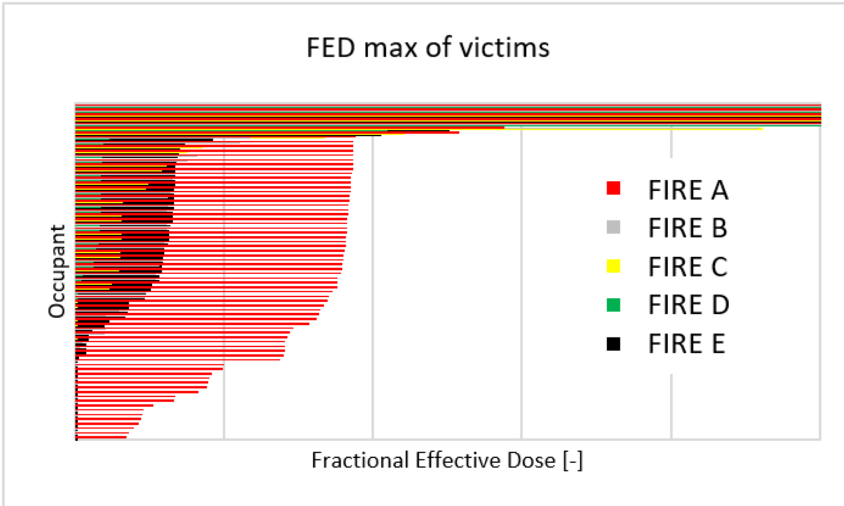

Figure 8 FED after one hour from the fire ignition time

DISCUSSION

A life safety study using evacuation simulations is performed with Pathfinder. The study shows the benefits of using agent-based evacuation modelling for complex facilities, characterized by the presence of several floors, among which occupants can move using ascending and descending stairs, multiple exits and behavioral uncertainties e.g. occupants which may show different level of alertness and reaction to an emergency.

The paper highlights the variety of results that an advance modelling can provide. In fact, the approach used foresees a direct coupling of the evacuation simulations with the FDS fire simulations, in order to calculate the cumulated FED along the evacuation paths for all occupants and check the impact of fire scenarios on evacuation e.g. visibility and temperature. The Monte Carlo model is used to treat the uncertainty linked to the position of the occupants in the facility as well as their pre-evacuation time and walking speed associated. A rescueability analysis is also carried out by checking the maximum FED of victims i.e. occupants who are not able to evacuate and have to wait for the arrival of the rescuers.

From the geometrical standpoint, the analysis is carried out using a relatively simple evacuation model, obtained by importing the geometry from the FDS model and extracting the navigation mesh from the main floors. Modelling the evacuation from the detector with Pathfinder is avoided given that the time spent in building an accurate navigation mesh would not be worth the effort: it would represent an additional source of uncertainties rather than being beneficial for the quality of the results.

This evacuation analysis allows to provide cost-effective safety recommendations, acting only on the most penalizing scenarios and providing specific indications for areas of the facility where the tenability conditions and FED requirements are not satisfied. It would have not been possible to achieve the same level of detail if a less advanced modelling approach had been followed.

From the computational standpoint, it is worth to mention that, when importing data from FDS, the evacuation simulations were run in a 4 core-machine (256 GB RAM) to avoid possible run-time errors due to the size of the FDS simulation (each simulation is about 200 GB).

LIMITATIONS OF THE STUDY

Several aspects presented in this study can be treated with a higher level of detail. Among others, it is noted that:

- To improve the representativeness of the results, it would be advisable in the future to use distributions of pre-evacuation time based on evacuation drills performed in similar facilities. This would allow to capture the specificity of the activities carried out at the moment of the evacuation and select input data in line with the safety culture of the Organization;
- The evacuation inside the detector is not explicitly modelled with Pathfinder, considering that the narrow passages would not allow a good representation of the navigation mesh. Moreover, the detector is modelled in FDS as a series of solid obstructions that in reality are partially open (grids);
- The number of Monte Carlo simulations is set *a priori* as 50. Additional considerations should be done to check whether they are sufficient for characterizing their convergence (Ronchi et al, 2013).
- The default floor priority of the lift model is not changed.

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