PROCEEDINGS, Fire and Evacuation Modeling Technical Conference (FEMTC) 2014
Gaithersburg, Maryland, September 8-10, 2014

FIRE AND CROWD EVACUATION MODELLING IN A LOW CEILING SPORT ARENA

Georges J Guigay, Davið S Snorrasson

Verkís Consulting Engineers
Ofanleiti 2
103 Reykjavík, Iceland
e-mail: gjg@verkis.is

ABSTRACT

In October 2014, Iceland will host the European TeamGym championships. The competition will be held in the Athletics and Exhibition Hall of the Laugardalshöll sports arena in Reykjavík.
Verkís Consulting Engineers undertook a project concerning the safe evacuation of the public from the competition arena in case of fire. This is a major concern for the organizers and the local fire authority as the arena is primarily intended for athletics training or local competition without stands.
For this competition, the Icelandic Gymnastics Federation wanted to install temporary stands with a seating capacity exceeding 4200 spectators. This configuration requires a completely new fire assessment of the building in terms of evacuation. The challenging factor is that the ceiling is rather low and people standing on the highest rows might thus be quickly submitted to smoke, requiring prompt and efficient evacuation. In addition, the probability of panic is high in such densely crowded stands. It is therefore essential to anticipate the causes and consequences of panic movements, and take adequate measures such as the design of alternative evacuation routes.
The smoke spread and time to critical conditions in the event of a 10 MW medium growth fire are simulated using Fire Dynamics Simulator (FDS6). The computational mesh was composed of 7.200.000 cells, and calculations are carried using 16 processors on a cluster computer.
The evacuation of occupants is simulated in 3 dimensions using the Pathfinder software, testing several occupation rates and evacuation routes. The combination of Pathfinder and FDS6 is shown to be very efficient to determine the maximum number of occupants and a new configuration of the stands, ensuring an acceptable safety for the spectators.

INTRODUCTION

The European TeamGym championships will be one of the biggest international sporting event to be held in Iceland. The competition will last 4 days and welcome 700 to 1000 participants from up to 20 countries; It will take place in the athletic and exhibition hall of Laugardalshöll (see Figure 1), Iceland's largest indoor multipurpose sports complex, in the heart of Reykjavík.

Figure 1: Views of the Laugardalshöll sport arena.

The athletic and exhibition hall was built in 2006, as an extension to the existing Laugardalshöll sport complex. Its intended usage is to host indoor athletics training and local competitions, as well as exhibitions, conventions or concerts. Except for 2 balconies, there are no areas to accommodate spectators, so it is necessary to install temporary stands for spectator events. The Icelandic Gymnastics Federation, host of the event, wishes to have a seating capacity exceeding 4000 spectators. This is completely different from the original configuration, and thus requires a complete new fire risk assessment, focusing mainly on the early stage of the fire, when safe public evacuation is of major concern.
The layout of the seating stands, originally designed by the architect and the stand supplier is shown on Figure 11 at the end of the report. The final design

resulting from Verkis' safety assessment is shown on Figure 12.
The athletic and exhibition hall is 5000 m^2 with a ceiling height between 8.35 and 11 m. The walls are made of concrete, and the curved roof is made of steel supported by a metallic truss structure. The structure beams are 1.7 m below the ceiling. In case of fire, the smoke is extracted by 7 mechanical vents placed on the roof. There are 18 different doors for evacuation, 10 opening directly to outside and providing fresh oxygen, and 8 to the central corridor on the west side of the hall.
The main challenging factor is that the ceiling is rather low and there are only 5 meters between the highest rows platform of the stands and the ceiling.
The combination of low ceiling and densely crowded stands enhances the feeling of danger, so panic must be carefully considered. It is therefore essential to anticipate the causes and consequences of movements, and take adequate measures such as the design of alternative evacuation routes.
For this fire safety assessment, fire and smoke calculations are carried out using Fire Dynamic Simulator version 6 (FDS6) [1] developed by NIST [2], and evacuation times are calculated using the Pathfinder [3] evacuation model from Thunderhead Engineering. FDS6 gives among other things the critical time, and Pathfinder gives the evacuation times of the stands and the complete building.

FIRE AND SMOKE SIMULATION USING FDS

The fire and smoke spread was simulated using Fire Dynamic Simulator (FDS). The goal of the simulation is to determine among other things the critical time, i.e. time before occupants are submitted to critical (untenable) conditions.
This project was also taken as an opportunity to compare the results and performances of FDS5 versus the newly released FDS6, and to test the computational power and capabilities of a cluster computer running the LINUX version of FDS6 in parallel, using the mpirun command.

Model description

Model geometry and computational domain

The model takes into account the athletics and exhibition hall and the storage area, with a fire situated in the middle of the competition floor. The doors to corridors are always closed, while some of the doors to outside open after 120 seconds. The total opening surface for air intake is 28 m^2. There are 7 blowers on the roof (see Figure 2), extracting a total amount of 50 m^3/s. The blowers are set to start after 120 sec. and are fully functioning after 150 sec. The computational domain is 100 x 75 x 15 (L x W x H). First, a mesh sensitivity analysis is carried, comparing results with 1 and 0.5 m resolution, in order to assess the influence of the mesh size on the results. A finer model is then built with a 25 cm mesh resolution, resulting in a total of 7.200.000 cells.

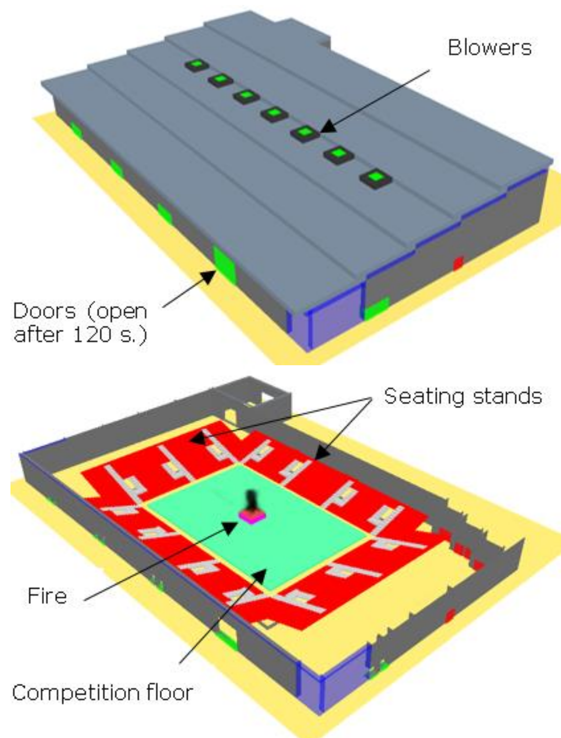

Figure 2: FDS model - 3D views of the arena

Design fire

The main fire threat in the sport arena is a big mattress fire on the competition floor. The British Standard [4] suggests a B2 risk profile (occupants who are awake and unfamiliar with the building), with a medium fire. The fire is modelled as a 10 MW medium fire, with a heat release rate Q calculated using the equation:
$Q = \alpha t^2$, α being the growth factor ($\alpha = 0.012$).

Criteria for critical conditions and critical times

The critical conditions that are considered to assess the safety of the occupants and the integrity of the building are [5]:

- Visibility through smoke. Smoke conditions are considered critical when the visibility drops below 10 meters for the general public (occupants, employees) and 5 meters for firefighters, at 2 meters above floors.
- Gas temperature in the upper layer higher than 400°C. Beams and columns might lose part of their resistance at this temperature, threatening the integrity of the building.

Because of the height of the stands, 2 critical times need to be considered:

- t_{crit_st}: Critical time on stand when smoke conditions become critical at 6.5 meters high, which is 2 meters above the highest seat rows. These rows must be clear of occupants before t_{crit_st} is reached.
- t_{crit_gr}: The time when smoke conditions become critical at 2 meters from the ground floor. All the occupants must have evacuated the building before t_{crit_gr} is reached.

Simulated scenarios

In order to test the robustness of the fire design, it is necessary to simulate the fire not only in normal conditions, when everything works as designed, but also in adverse conditions when something goes wrong, in this case when the smoke blowers fail to start.

Computational power

The preliminary calculations for mesh sensitivity and comparison between FDS5 and FDS6 were carried in serial mode on Windows, using a Lenovo Thinkcentre workstation with a processor type Intel(R) Core(TM) i7-2600 CPU – 3.40 HHz
The final calculation was carried in parallel mode (mpirun) under Linux using a cluster computer built of 2 lenovo Thinkcentre E32 workstations, each with 8 processors type Intel Xeon E3-1245V3 3,40-3,80GHz.

Results from FDS

Mesh sensitivity analysis and comparison between FDS5 and FDS6

As for every project involving Computational Fluid Dynamics (CFD) simulations, the choice of mesh resolution is difficult and of high importance. The user must make sensible choices to obtain the right balance between precision and computational cost, depending on the output and precision that really matters his particular project. In this case, the main difficulty is that this is a rather low building, and people standing on the highest rows will have their heads just about 3 meters below the ceiling. Therefore, the evolution of the hot layer height is the crucial factor in this project.
In order to investigate the influence of the mesh resolution, the evolution of the layer height was recorded at the same position, for runs with 100 and 50 cm resolution, in both normal and adverse conditions. This was done with both FDS5 and FDS6 in serial mode, to compare the computational performance and the sensitivity to mesh resolution of each FDS version. The results are shown on Table 1 and Figure 3.
The nomenclature for each FDS run in this article is such as: Conditions (N for normal / A for adverse) followed by the FDS version (FDS5 / FDS6) and the mesh resolution. For example A_FDS6_50 stands for a run in adverse conditions, using FDS6 with a mesh resolution of 50 cm.

Table 1: Results of mesh sensitivity and comparison between FDS5 and FDS6.

run	Layer height		t_{crit_st}
	Format. time (s)	Height (m)*	(s)
N_FDS5_100	480	5	690
N_FDS5_50	475	6.1	790
N_FDS6_100	465	4.2	630
N_FDS6_50	460	5.7	720

(*) Average value of the layer height between 600 and 900 sec.

Results show that the layer height stabilizes between 1.1 and 1.5 m higher when the mesh resolutions is doubled. This is a significant difference in this project, considering the small height difference between the ceiling and the stands. The time to critical conditions is 90 to 100 sec. longer with a finer mesh.
The results are significantly more conservative with FDS 6. The layer height stabilizes between 0.4 and 0.8 m lower than with FDS 5, and the critical time is about 1 min. shorter. The layer height forms about 15 seconds sooner with FDS 6.
Similar observations were made in adverse conditions. The results for all runs are summarized in Table 4 at the end of this article.

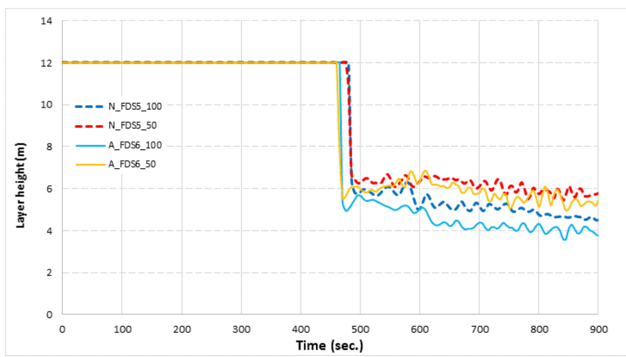

Figure 3: Time evolution of the layer height at the same position for different mesh resolution and FDS versions.

The computational cost (CPU time) is doubled when FDS6 (see Table 4). However, changes in FDS6 improve the robustness and accuracy of the simulations [1]. In this study, better accuracy gives more conservative results and is thus worse this increased computational cost.
The first outcome of this analysis is that the results are very sensitive to the mesh resolution. The second is that a better accuracy is obtained with FDS 6. 50 cm is still a rather coarse mesh relative to the ceiling height, so the final model is ran with FDS6 and a mesh resolution of 25 cm.

Final FDS model with FDS6

During the early stage of the fire, when the main concern is public evacuation, the most relevant parameter to assess the tenability is visibility through smoke. Figure 4 shows the smoke spread in the hall.

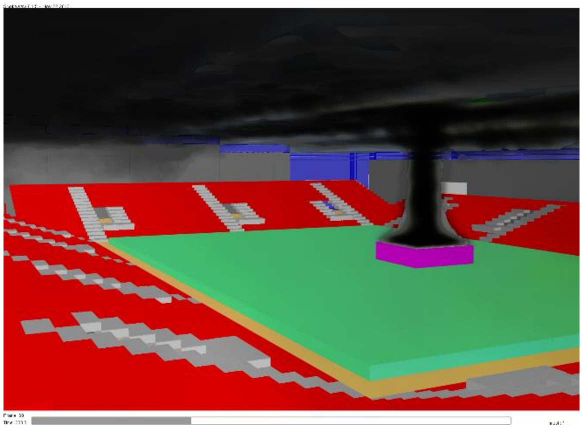

Figure 4: Smoke conditions after 300seconds from the viewpoint of an occupants seating on the top of the south stand.

Figure 5 and Figure 6 show visibility slices in normal (N_FDS6_25) and adverse (A_FDS6_25) conditions respectively. On both cases, the snapshot is taken at critical time, when areas where conditions are critical (visibility below 10 meters). These areas are shown by the yellow / orange pockets appearing above the South and North seating stands, at 6.5 meters high (2 meters above highest seating rows). These critical times are:

- t_{crit_st} [N_FDS6_25]: 670 seconds.
- t_{crit_st} [A_FDS6_25]: 520 seconds.

Results show that the critical time at the ground floor t_{crit_gr} is higher than 15 minutes.

The temperatures in the upper layer remain rather cold (significantly below 100°C) after 15 minutes even when the blowers are not functioning. At this time, the fire might start to decay naturally or as a result of firefighting actions. However, if temperatures still rise, the window panels below the roof will fail and vent the hot smoke out before the integrity of the structure is endangered. A closer analysis of the effect of temperatures would require a longer simulation involving important computational cost, and is not within the scope of this assessment study.

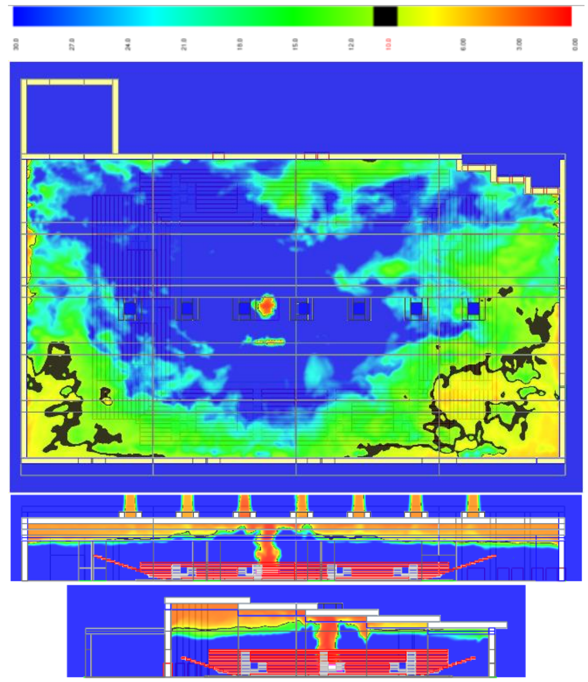

Figure 5: Visibility field (m) after 670 sec. (critical time) in normal conditions (N_FDS6_25). Top view at z = 6.5 m, East and South views in the fire plan.

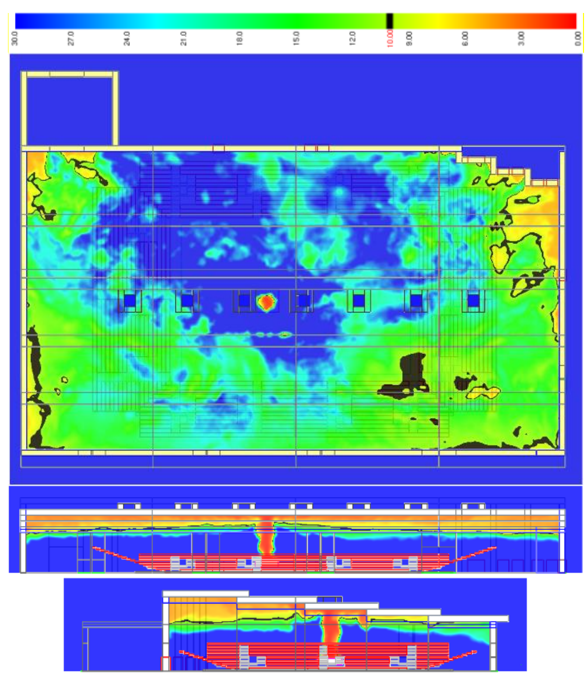

Figure 6: Visibility field (m) after 520 sec. (critical time) in adverse conditions (A_FDS6_25). Top view at z = 6.5 m, East and South views in the fire plan.

CROWD EVACUATION SIMULATION USING PATHFINDER

Model description

The geometry of the model used for the evacuation model is the same as the one used in FDS for the fire simulation, and described in the previous chapter.

Occupants and evacuation conditions

Occupants are considered safe once they have evacuated the athletics and exhibition hall. There are 18 different doors for evacuation, 8 to the central corridor and 10 directly to the outside. In total, there are 3966 occupants on the seating stands. Their distribution is detailed in Table 2 below. Note that the model only considers the public seating on the stands, and does not account for athletes, employees, security guards etc… who will stand on the competition area and on the hall floor.

Table 2: Distribution of occupants on the seating stands.

Stand	Nb of rows	Height of row	Nb of occup	Nb of occup (highest row)
South	18	4.5	1013	70
West	13	3.25	970	100
East	13	3.25	970	100
North	18	4.5	1013	70
Total			**3966**	

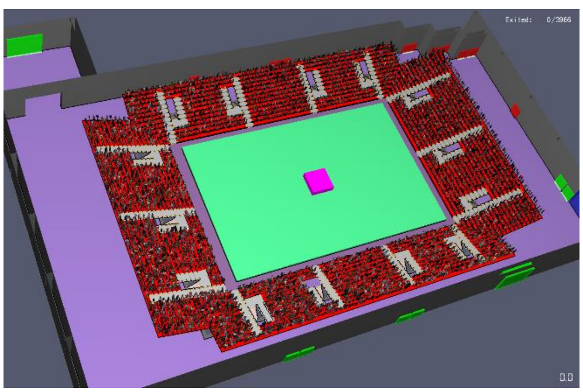

Figure 7: Initial distribution of occupants.

The total evacuation time t_{evac} is composed of:

- Pre-movement time, which is the sum of the detection time (t_{det}) and reaction time (t_{reac}).
- Movement time (t_{mov}), or time needed to travel to a safe place.

Consequently, the total evacuation time is:

$$t_{evac} = t_{det} + t_{reac} + t_{mov}$$

In the event of a 10 MW fire, it is assumed that occupants will detect and react quickly. Here, the pre-movement time is conservatively assumed to be 120 seconds.

Assumptions and limitations

Despite studies of human behavior in fire and the development of better numerical models, the evacuation simulations will never be 100% realistic, especially in such a complex case as a stadium stand evacuation. Assumption to the model and software limitations need to be clearly identified and understood in order to assess the validity of the results

Model assumptions:

- Occupants' characteristics: In the model, the default profile is used. This profile is set to be representative of a mixed general population.
- Evacuation through the competition floor directly to the exit routes is not possible, and occupants have to go via the stands stairs.
- Occupants can't step over the stairs to an adjacent row.

Software limitation:

- Stuck occupants: Sometimes occupants become "stuck", especially in narrow places, as in stands. This can lead to irrational behavior such as a group being blocked by one individual. In reality, occupants will look for an alternative route, such as jumping over the seats to another row.

These assumptions tend to slow the evacuation, consequently resulting in conservative results.

This Pathfinder evacuation model does not account for the effect of panic and its consequences.

Evacuation results

Stands evacuation

Figure 8 shows the time evolution of evacuation of the 2 highest rows (4.5 m from floor) which are at the top of the South and North stands. Occupants begin to move after 120 seconds and start to leave the floors. Between 120 and approximately 400 seconds, there is only a limited number of occupants who manage to leave the floor, as there is a lot of traffic in the stairways, creating bottlenecks in front of the stairs access. Once these bottlenecks disappear, the rows are evacuated very quickly. The evacuation of the highest rows is completed after 442 seconds. The complete evacuation of the hall (stands + ground floor) is achieved after 478 seconds, which is shorter than the critical time from FDS, also shown on Figure 8

3 D snapshots of the evacuation (see Figure 9 and Figure 10) confirm that bottlenecks appear in from of the stair access. The bottlenecks on the top row top rows take the longest to disappear, as their occupants are blocked and have to wait for traffic from lower rows to move towards the stairs before entering the stairways themselves. Their evacuation time corresponds to the total evacuation time for the entire

South or North stands, which was estimated to be 442 seconds.

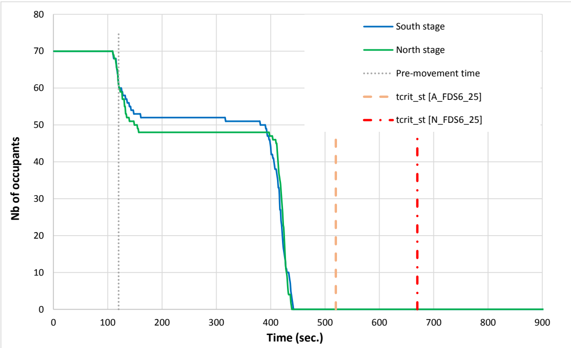

Figure 8: Time evolution of the evacuation of the highest seat rows (South and North stands).

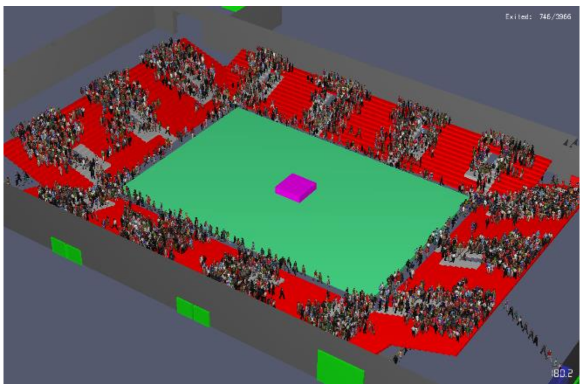

Figure 9: Stands evacuation after 180 sec.

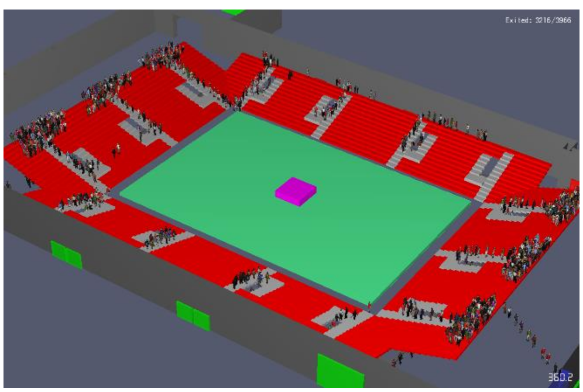

Figure 10: Stands evacuation after 360 sec.

Modification of stands further to the evacuation simulation

The Pathfinder model shows an orderly evacuation when everything goes well and occupants take the intended stairways. Results show that in this case, the evacuation time is satisfactory, which means that the stand layout is fine.

However, seeing the smoke layer forming below the ceiling and hearing evacuation orders can be very stressful for occupants especially in such densely crowded stands with stairs and narrow passages. An incident during the evacuation, for example someone falling in the stairs and hence slowing the evacuation, could easily lead to bottlenecks and panic. It is than likely that some occupants from the lower rows will go down to the competition floor. It is thus necessary to ensure that people will be able to evacuate safely from the competition floor to outside. In the original layout, there were only two narrow passages designed for the athletes to enter and leave the competition floor (See Figure 11), which was judged insufficient in the event of panic movements. The following modifications to the original layout have thus been requested by Verkís'engineers to create alternative exit routes and improve the evacuation:

- To replace the two athlete's passages by 3 exit paths of at least 1.35 m wide which could be used as attentive routes for evacuation. These new paths lead to areas where there are wide exit doors to outside or other fire compartments.
- To ensure at least a 1.40 m wide exit route between the stands and electronic advertising panels which will placed at some part around the competition floor. These panels are rather high and heavy and thus difficult to step over.
- To move the competition floor and seating stands a few meters to the south, in order to enlarge the area at the North end where the main entrance is. During an evacuation, most occupants have the tendency to go through the exit doors they are they are familiar with, i.e. the entrance door through which they came. Many occupants are thus expected to lead to the northern end of the hall where the main entrance is, so enlarging this area can only be beneficial to the evacuation process.

The final layout resulting from the risk assessment is shown on Figure 12 with the modifications mentioned above.

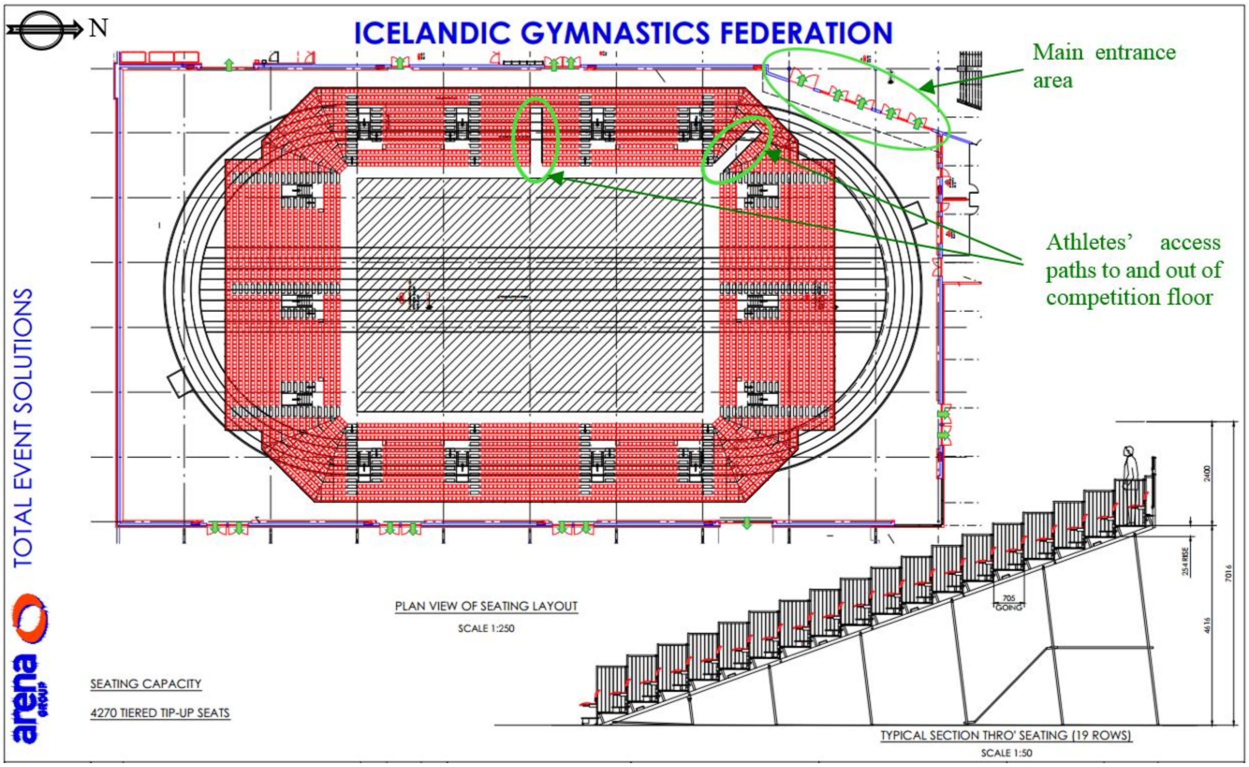

Figure 11: Competition floor and original layout of the stands, prior to the fire safety assessment.

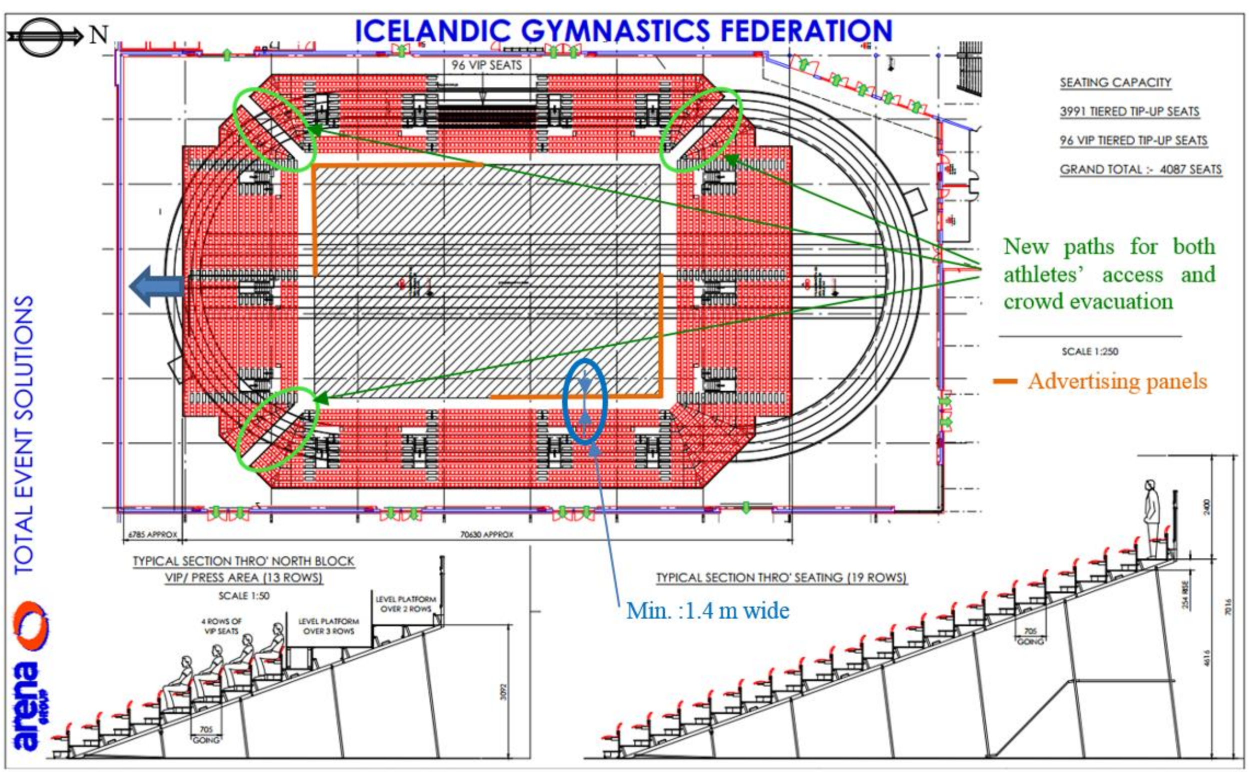

Figure 12: Competition floor and layout of the stands, modified as a results of the fire safety assessment.

SUMMARY OF RESULTS AND CONCLUSION

The safety of the public in the configuration required for European TeamGym championships was assessed by simulating the smoke conditions from a 10 MW fire using FDS6, and the stands evacuation using Pathfinder. Results summarized in Table 3 for 3966 occupants seating on the stands show that even in adverse conditions, i.e. when the blowers are not functioning, there is a safety margin ($t_{crit} - t_{evac}$) of 78 sec. This margin is 228 seconds when the blowers function correctly.

Table 3: Critical times and evacuation times.

Run	FDS	Pathfinder				Safety margin
	t_{crit}	t_{det}	t_{reac}	t_{mov}	t_{evac}	
N_FDS6_25	670	60	60	322	442	228
A_FDS6_25	520	60	60	322	442	78

An important improvement to the original layout was to create an exit route around the competition floor with 3 exit paths from the competition floor, at 3 corners of the stands. These alternative exit routes are essential in case of panic which could alter the original evacuation plan.

Simulation results showed that the safety of the public in case of a fire evacuation was ensured for a total of 3966 occupants on the stands. With the modifications mentioned above, we recommended that the total maximum number of people in the hall could be set to 4200 people. A report describing the fire assessment and suggested evacuation plan, shown in Figure 13 below, was submitted and accepted by the fire authorities.

This project was also used to test the performances of FDS6 vs. FDS5. The run times were significantly longer with FDS6, but results were more conservative and sensitive to the mesh size, and the higher computational cost required be FDS 6 was worth it.

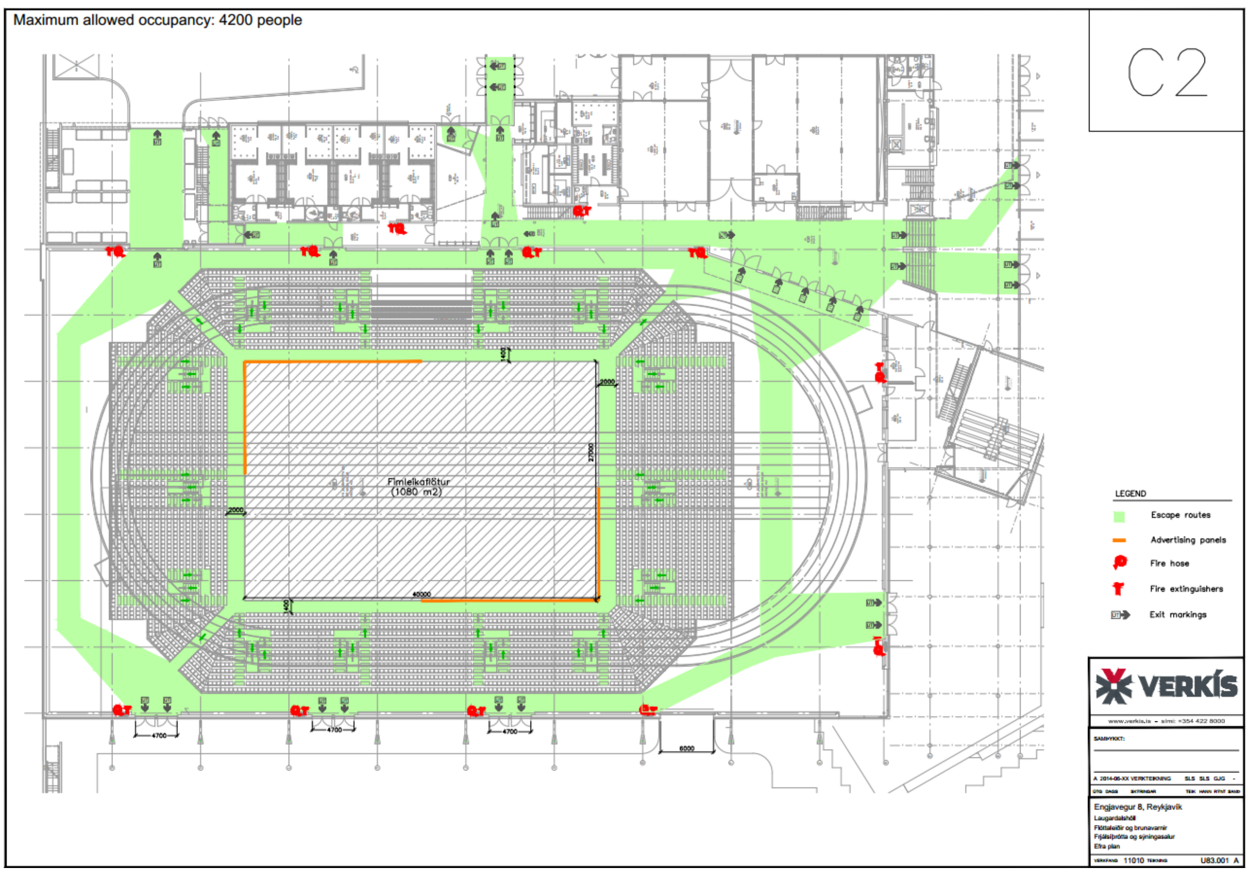

Figure 13: Evacuation plan resulting from the fire safety assessment, submitted and accepted by the fire authorities.

Table 4: Description and results summary of each FDS run.

Run	Model description					Results		
	Blowers	FDS vers.	Mode	Resol. (cm)	Cells	Layer Height* (m)	t_{crit_st} (s)	CPU (s)
N_FDS5_100	yes	FDS5	serial	100	112.500	5	690	1.715
N_FDS5_50	yes	FDS5	serial	50	900.000	6.1	790	27.504
N_FDS6_100	yes	FDS6	serial	100	112.500	4.2	630	4.032
N_FDS6_50	yes	FDS6	serial	50	900.000	5.7	720	60.192
A_FDS5_100	no	FDS5	serial	100	112.500	4.2	620	1.459
A_FDS5_50	no	FDS5	serial	50	900.000	5.3	680	29.160
A_FDS6_100	no	FDS6	serial	100	112.500	3	530	4.500
A_FDS6_50	no	FDS6	serial	50	900.000	4.3	550	63.396
N_FDS6_25	yes	FDS6	parallel	25	7.200.000	5.8	670	257.292
A_FDS6_25	no	FDS6	parallel	25	7.200.000	3.8	520	266.940

(*) Average value of the layer height between 600 and 900 sec.

REFERENCES

[1] Fire Dynamic Simulator (FDS) vers. 6. http://code.google.com/p/fds-smv/

[2] NIST – National Institute of Standard and Technology. www.nist.gov

[3] Pathfinder evacuation software 2014. http://code.google.com/p/fds-smv/

[4] British Standard BS 9999:2008. Code of practice for fire safety in the design, management and use of buildings.

[5] INSTA TS 950. Fire Safety Engineering – Comparative method to verify the fire safety design in buildings.