SOFT TARGET PROTECTION ANALYSIS USING PEDESTRIAN SIMULATION

Tomas Apeltauer, Jiri Apeltauer, Petra Okrinova

Brno University of Technology
Faculty of Civil Engineering
Veveri 331/95
CZ-60200 Brno, Czech Republic
e-mail: tomas.apeltauer@vut.cz

recognity s.r.o.
Smidkova 3089/5b
CZ-616 00 Brno, Czech Republic
e-mail: tomas.apeltauer@recognity.cz

ABSTRACT

The paper is focused on the risk analysis of the main railway junction in the Czech Republic using the microsimulation pedestrian model for the soft targets protection issues. We have analyzed the effects of specific scenarios that reproduce an attack by an attacker, such as the presence of an active shooter or the placement of an explosive device in an object. The results serve as quantitative risk analysis for the contracting authority for following specific measures. This analysis was performed with running a large number of simulations and their statistical evaluation in connection with Pathfinder and R statistical software.

PRESCRIPTIVE CODES AND PEDESTRIAN SIMULATIONS

Fire safety in the Czech Republic uses primarily a set of prescriptive codes [1], which have been gradually improved for decades. These codes are designed to enable the civil engineer to make a basic assessment of the fire safety of a building without specific technical requirements. Simply speaking, the assessment must be possible in a situation where the engineer has a project, a pencil, paper, and a calculator. Codes thus inevitably mean a significantly simplified view of the behavior of people in the building. You can see a comparison of the behavior of two identical groups of people in the same geometry in Fig. 1. While the upper simulation applies behavioral characteristics within the Pathfinder model [2], the lower simulation reproduces the behavior of people as seen by the prescriptive code.

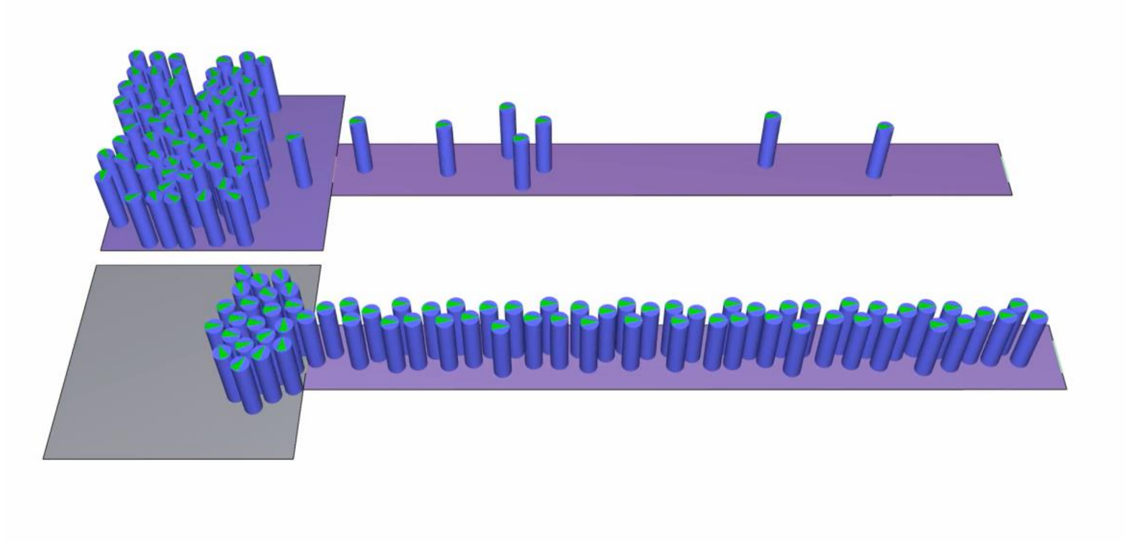

Figure 1: A comparison of the behavior of two identical groups of pedestrians in the same geometry and at the same time. The upper simulation applies characteristics of pedestrians as the distribution of the pre-movement time or speed, the lower simulation reproduces the behavior of pedestrians according to the prescriptive codes.

The codes do not consider different walking speeds of pedestrians depending on age or ability to move, they also assume exclusively immediate evacuation, i.e. zero response time to the alarm. Persons with a limited speed of movement or orientation are taken into account by the standard by increasing the width of the so-called escape lane, which is the required width of the evacuation route by the object. Each of the escape lanes can accommodate a limited number of people per unit of time. For the codes, the pedestrian movement is similar to the passengers at the airport on various moving walkways, but with uniform space gaps. This approach makes it possible to calculate the escape routes without any additional technical requirements, the simplistic view is compensated by very conservative values, such as the walking speeds. The results are then usually significantly on the safe side.

Football stadium as an ideal example for pedestrian simulations

So why do we need in the Czech Republic pedestrian simulations when we have simple and safe standards? The first important application is very complex objects, such as stadiums. For these types of buildings, the above-mentioned approach inevitably reaches its limits.
An example is the project of the UEFA 4 football stadium (the best class, suitable for Champions League final games) in Brno, which we evaluated in 2017. The basic model is in Fig. 2. We performed simulation tests for the full occupancy of 30,000 visitors and showed that in the event of its evacuation, the total evacuation time (Q95 percentile) is more than 27 minutes and approximately one-third of pedestrians are delayed for more than 5 minutes in the various types of jams during evacuation (Fig. 3). This factor is very important for the total evacuation time and risk analysis in general, but it is difficult to describe it with the classical approach using simple prescriptive codes.

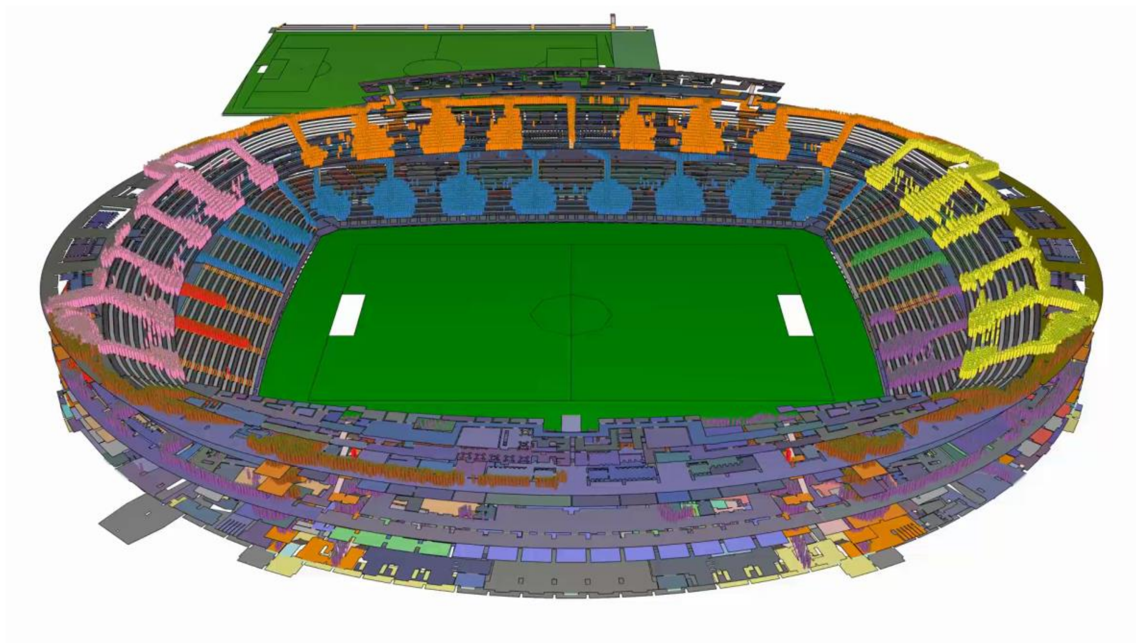

Figure 2: Evacuation simulation of the 30,000 visitors at the football stadium in Brno, Czech Republic.

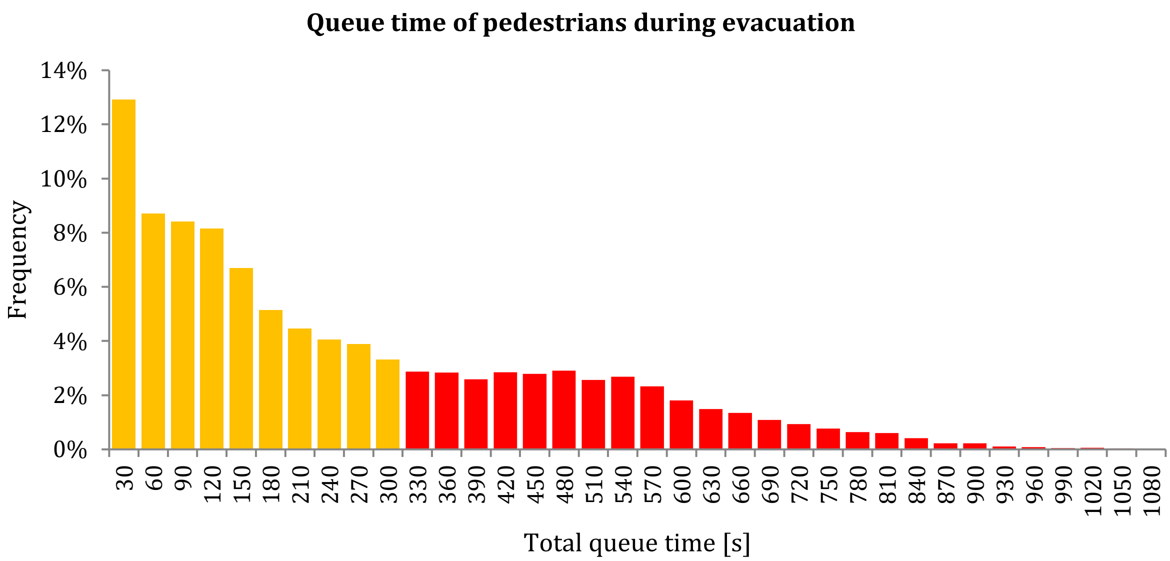

Figure 3: Distribution of the pedestrian queue time during evacuation. Approximately one-third of pedestrians was delayed 5 minutes or more during the evacuation (red region).

The trajectories show that the longest routes are around 650 meters, which would mean an evacuation time approximately 21,5 minutes when applying the above prescriptive velocities, which is only 80% of the simulated evacuation time (Fig 4). And this result would be no longer on the safe side.

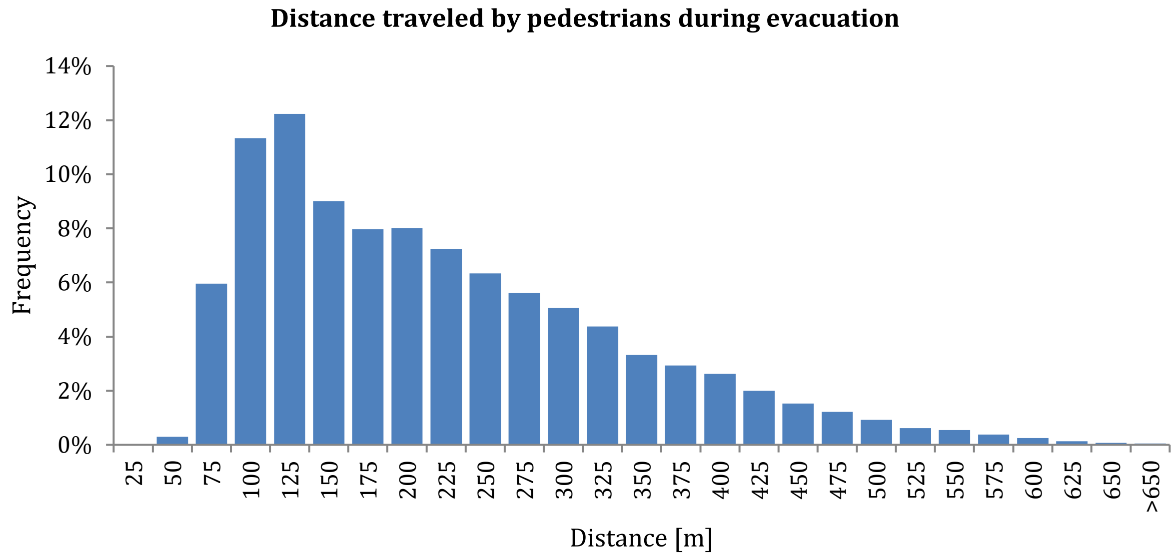

Figure 4: Distribution of the distance traveled by pedestrians during evacuation.

Soft targets and pedestrian simulations

The second application domain is objects or situations, which we refer to as so-called soft targets. The term is used by the security community to referring places with a high concentration of visitors and a low level of security against violent attacks. These objects do not necessarily have to be complex or complicated as in the first example, but the attack will cause a situation where the assessment of a classical evacuation through a prescriptive code is worthless.

The reason is simple: the fire safety assessment using prescriptive codes is designed for a case of fire. If such an object is in good condition and regularly inspected, in the case of a fire, all evacuation exits will be available, fire alarms will work, etc. In case of a terrorist attack, however, the attacker's very basic motivation is to change this situation. A typical example would be a van blocking one of the main exits, a smoke cartridge thrown into an escape route designed to be resistant for the fire, or disabling an electronic alarm. An example is the terror attack in Paris in November 2015. It was a clearly coordinated attack to Stade de France, when two attackers detonated their charges by the entrances to the football stadium. People were held inside the stadium and only evacuated in parts through the remaining exits.

For these reasons, it is necessary to perform a risk analysis, identify possible attack scenarios, and determine the impacts of these scenarios. In the case of scenario analysis, we usually choose a qualitative assessment. It does not make sense to search for example the exact probability of a knife attack, if it occurred in the object only exceptionally, or even not at all. On the other hand, the same qualitative analysis is unnecessarily simplistic for the impacts of these scenarios. Instead of a qualitative scale (low - medium - high), the security manager should request specific data on the number of affected persons, an extension of evacuation time, reduction of visibility due to smoke, etc. Simulation tools are extremely suitable for these answers. The result is then a *qualitative* analysis of the impacts of individual risks.

During the winter months of 2019/2020, we applied this procedure to the main railway station in Prague, where we tested the evacuation scenarios for the security managers in situations other than standard ones, especially when not all evacuation exits are available. These situations may include, for example, suspected explosive devices or shooter inside or outside of the object. These situations were tested for different occupancy and statistically processed. But the appropriate risk analysis as a necessary component for the soft target's protection was the first step for identifying these scenarios. Detailed results of risk analysis following simulations cannot be published in the full detail for the security reasons, but we will describe the general procedure in the following section.

Figure 5: Prague Main Railway Station, the new Terminal building © Wikimedia Commons

RISK ANALYSIS OF THE SOFT TARGETS

The goal of the risk management process is to find risks and work with them to minimize them. It consists of three phases:

- Risk identification. The result is a list of risks that we have found in our company or building.
- Risk assessment: Rankings from the most serious to the least serious.
- Risk regulation: Process to minimize or eliminate the risks.

Risk identification (R) has the following phases:

- Asset analysis (A).
- Threat analysis (T).
- Vulnerability analysis (V).
- Determination of the resulting risk.

The methods applied in the identification are quantitative (probability of occurrence and probability of loss of value), or qualitative (determination of vulnerability and degree of threat), or combined semi-quantitative.

The risk assessment can be summarized in a Tab. 1 that reflects a combined, semi-quantitative approach.

Table 1: The risk assessment of asset, threat, and vulnerability values.

Points	**Asset value (A)**	**Threat value (T)**	**Vulnerability value (V)**
0	None or not rated	Once every 10 years	None
1	Low	Once a year	Low
2	Not very significant	Once in half of year	Not very significant
3	Medium	Once a quarter	Medium
4	High	Monthly	High
5	Very high	Once a week	Very high

Then it is possible to quantify the risk by using the following relationship to assess and express risk

$$R = A \text{ x } H \text{ x } Z \tag{1}$$

If possible, we should also express how the risks can interact with each other. For this purpose, we can apply quantitative risk analysis with their correlation in Tab. 2. This method expresses the activity or passivity of each risk. *Activity* means that the selected risk has the potential to cause another risk, while *passivity* means that the selected risk has the potential to be caused by other risks. We then express the mutual connections, for example, with the following table.

Table 2: Quantitative risk analysis with their correlation.

	Index	1	2	3	4
Index	Risk	High temperature	Lightning	Fall of a tree	Icing
1	High temperature	X	1	0	0
2	**Lightning**	**1**	**X**	**1**	**0**
3	Fall of a tree	0	0	X	0
4	Icing	0	0	1	X

The character X means the fact that it cannot cause a risk by itself, 1 means the real possibility that the risk R_i can cause a risk R_j and 0 expresses a state where this possibility does not exist. For example, lightning (a bold table line) may cause a high temperature (fire) or a fall of a tree, but it will not cause an icing directly.

Activity is then defined as the coefficient of K_AR_i activity, which expresses the overall potential of the risk to cause additional risks. On the contrary, the coefficient of passivity K_PR_i, expresses the number of all risks that can cause a given risk. The following relations are used to calculate the given coefficients:

$$K_P R_i = \frac{\sum R_i}{x-1}$$

$$K_A R_i = \frac{\sum R_i}{x-1} \tag{2}$$

Where ΣR_i is the sum of the risks (for the activity coefficient it is the horizontal axis and for the passivity coefficient it is the vertical axis) and x is the total number of risks.

We can see that each risk R_i will be characterized by a pair of $K_A R_i$ and $K_P R_i$ values. These values can be plotted in a table or graph, which allows us to determine the most significant risks very easily. The following Tab. 3 and Fig. 6 are used as an example.

Table 3: Quantitative risk analysis with their correlation.

Risk	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$K_A R_i$	0,29	0,29	0,29	0,21	0,29	0,43	0,57	0,21	0,43	0,14	0,79	0,21	0,14	0,64	1,00
$K_P R_i$	0,43	0,43	0,57	0,43	0,43	0,57	0,50	0,07	0,21	0,29	0,21	0,07	0,36	0,50	0,86

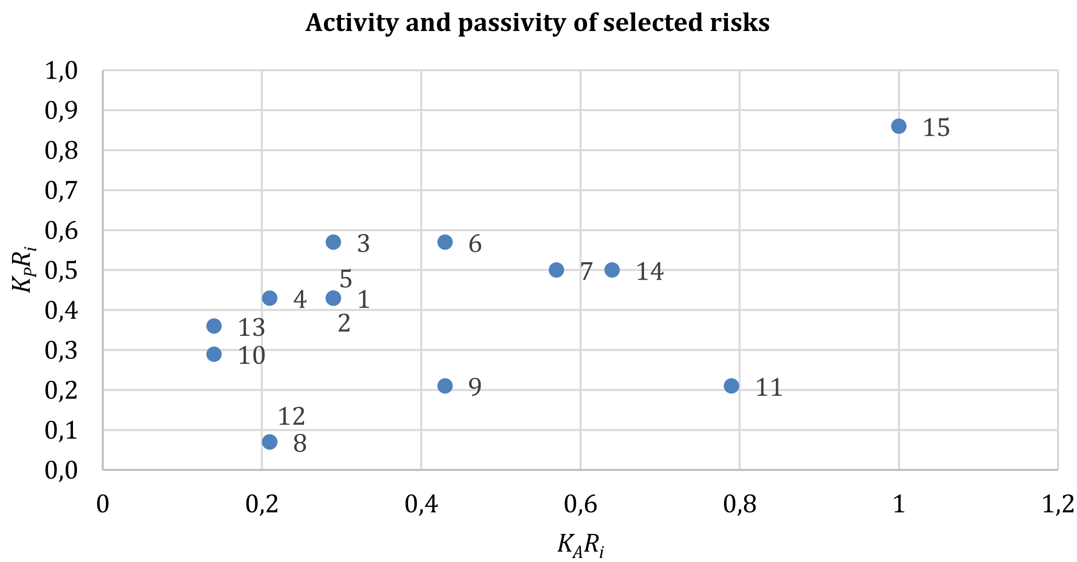

Figure 6: Activity and passivity of selected risks.

For better clarity, it is appropriate to divide the plot into segments. We define lines P_1 and P_2, which are divided into segments, assuming that in the first segment there will be 80 % of the most significant risks.

$$P_1 = K_{A\,max} - (K_{A\,max} - K_{A\min}) * 0.8$$

$$P_2 = K_{Pmax} - (K_{Pmax} - K_{Pmin}) * 0.8 \qquad (3)$$

where K_{Amax}, K_{Amin}, K_{Pmax}, and K_{Pmin} are the minimum and maximum values of the activity and passivity.

The resulting four segments express the degree of risk as follows in Fig. 7:

- Primary risks: the highest coefficient of activity AND passivity, segment 1.
- Secondary risks: high activity OR passivity coefficients, segments 2 and 3.
- Tertiary risks: low level of activity and passivity coefficients, segment 4.

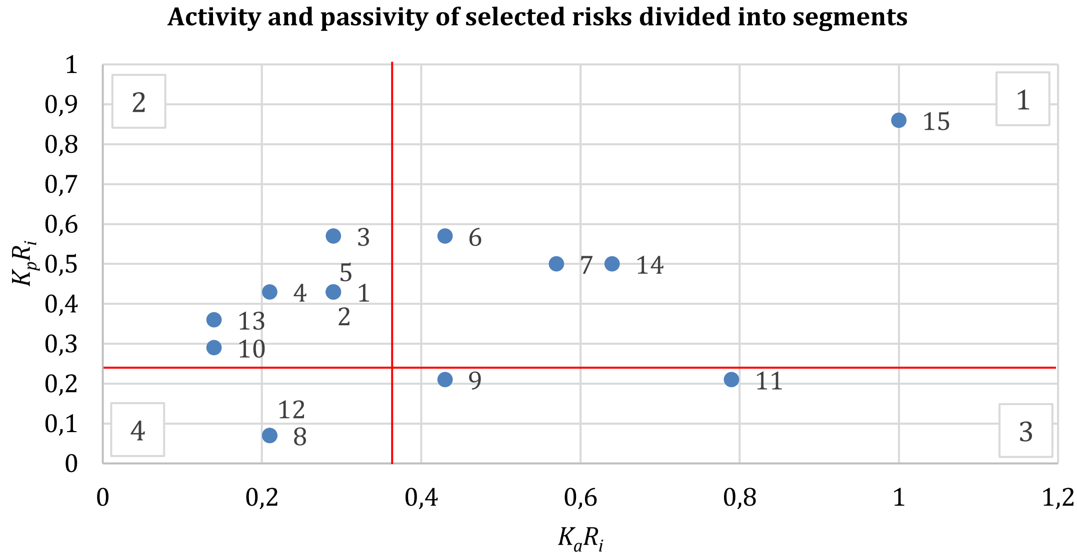

Figure 7: Activity and passivity of selected risks. Primary risks are in segment 1.

The described analytical procedure was also applied in the case of Prague main railway station. The results risk analysis was used for the identification of several specific scenarios. Examples include the following:

- Simple evacuation (all exits are available).
- An attack in the central part of the station (blocking of the central tunnel).
- An attack at the main exit, or the identification of an explosive device nearby.

These and other scenarios were then simulated using the Pathfinder tool to determine precise impacts, results were implemented to the guidelines of security managers.

PRAGUE MAIN RAILWAY STATION

The station hall has a rectangular floor plan with the main entrance from Vrchlického sady Street (bottom) and six side entrances. Below the check-in hall, there is a subway station of the line C. Evacuation from the subway takes place using escalators and stairs to the lobby of the check-in hall and then outside.

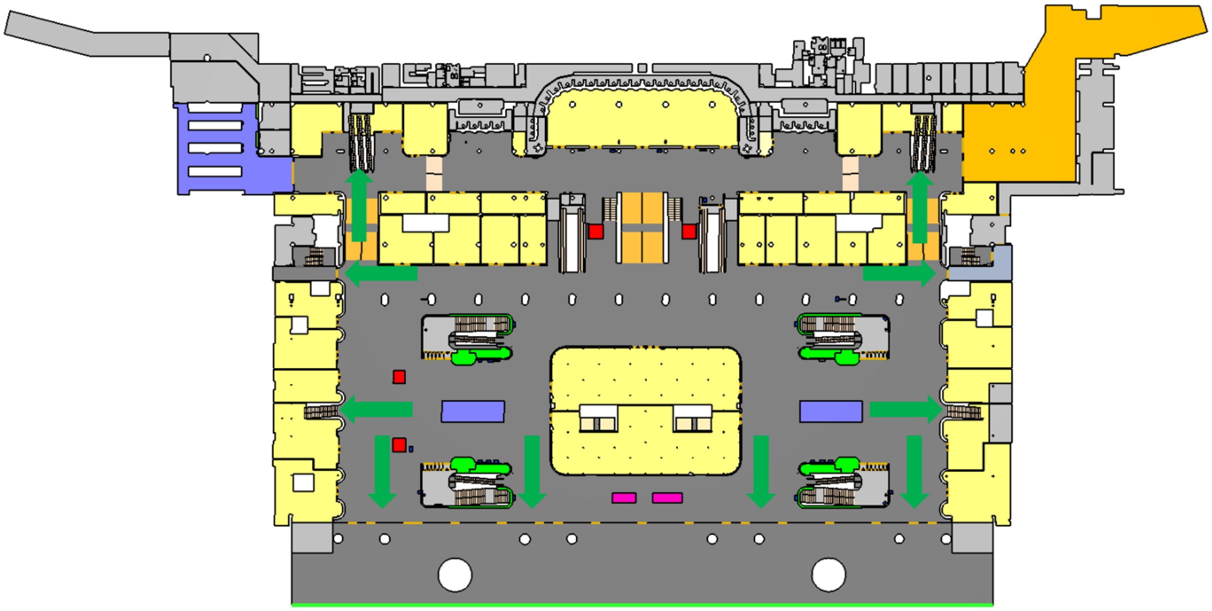

Figure 8: The floor plan of the Prague Main Railway Station with the evacuation routes.

Agents parametrization

Experimental data, especially the real evacuation trial and long-term empirical measurements, were not available. For this reason, we tried to derive the appropriate characteristics (especially the speed of movement and pre-movement time) for agents from the related studies [3, 4, 5].

The distribution of age classes of agents was determined as follows:

- Adults: 70%,
- Youths: 20%,
- Seniors: 10%.

The corresponding distribution of movement speeds is shown in the following Fig. 9.

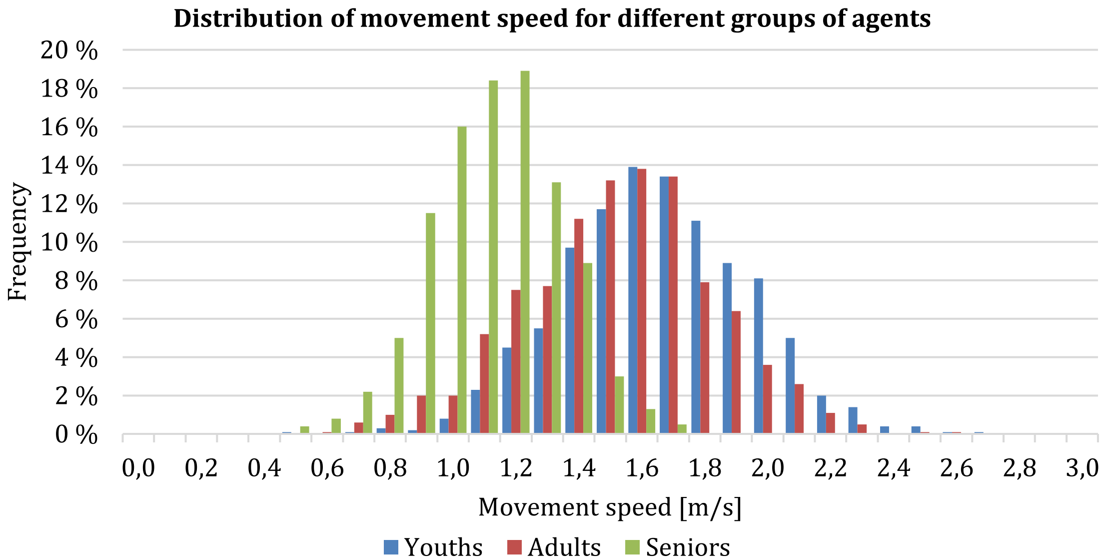

Figure 9: Distribution of movement speeds for different groups of agents – youths (20%), adults (70%), and seniors (10%).

The pre-movement time was derived using the same sources. The key is to maintain a log-normal distribution that corresponds to the available empirical knowledge. The resulting distribution has the parameters $\mu = 4$ and $\sigma = 0.5$ in Fig. 10. The mean value of the pre-movement time is then of about 60 s with a standard deviation of about 30 s. The values of 5% and 95% quantiles, i.e. 20 s and 120 s, were used as the boundary values for the simulation settings (green colored region).

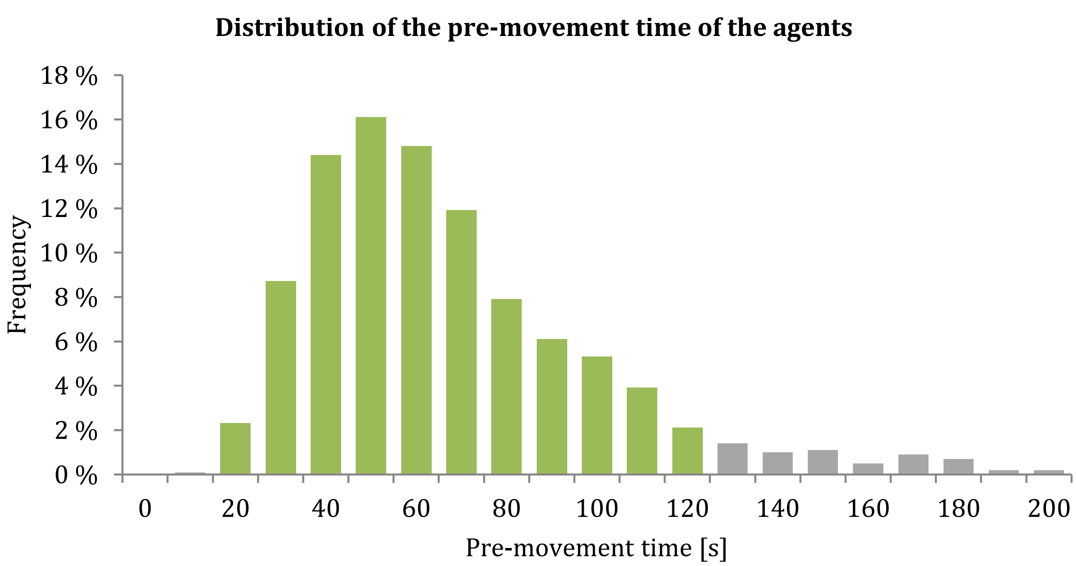

Figure 10: Distribution of the pre-movement time of the agents. The green region has been used for the simulation.

The initial occupancy is based on the documents for the original fire safety assessment of the building with the basic value of 6,000 commuters in the building. Our analysis then complements other real occupancies in the range of 1,000 to 10,000 commuters, with a step of 1,000 commuters to cover all relevant daily, weekly or annual variations. Agents are distributed in the area with a density of 0 - 2 agents/m^2 according to the real experience of the security managers, as described in Fig. 11.

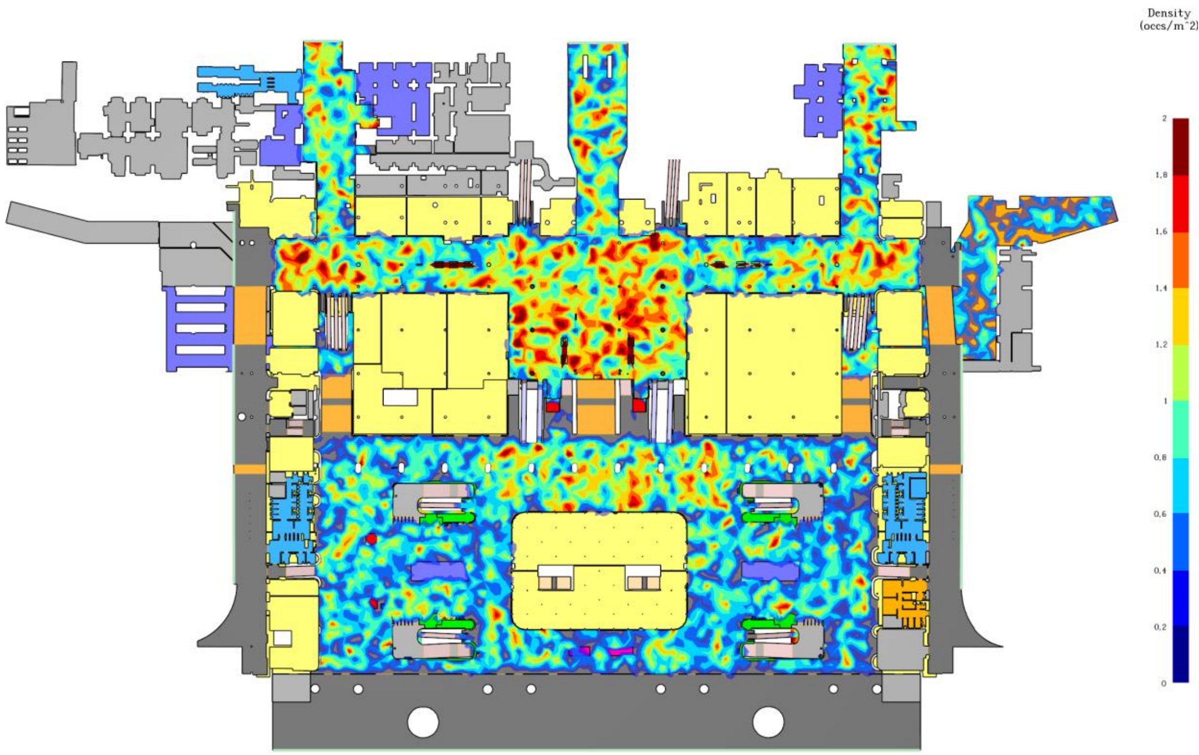

Figure 11: Initial distribution of the agents within the railway station.

Simulation outputs

Both the distribution of agents in the station and the distribution of their parameters within the population have a significant impact on the evacuation time, so we used the Monte Carlo approach. The individual scenarios were gradually loaded by increasing occupancy. For each scenario and occupancy level, we run tens of simulations with a random distribution of agents and statistical distribution of their parameters. We focused on the following results:

- Evacuation Time: The moment when the last agent leaves the station, considering various quantiles like Q95 (mean value + 1.6449 * standard deviation of total evacuation time), described by graphs and tables. This is a standard metric used in fire safety assessment. An example is shown in Fig. 12.
- Maximum Density: Displayed graphically as a heat map to find parts of the station where a critical density has formed at ANY time during the evacuation. An example of such a display is shown in Fig. 13. The color of the agents on the picture corresponds to the time remaining until they leave the station.
- Maximum Time to Exit: Displayed graphically as a heat map. It identifies places in the building from which evacuation is most complicated and where the security manager should focus its actions at first. An example is shown in Fig. 14.
- Maximum Usage: Displayed graphically as a heat map. The value is important especially in combination with the maximum density because it shows how long the congestion prevailed. The longer the congestion, the higher the frustration of people, and the greater the risk of

injury or panic. The result is the next important information for security managers. An example is shown in Fig. 15.

- For the client, we have also created a flight through an object in various situations, which can be observed in VR. An example is shown in Fig. 16.

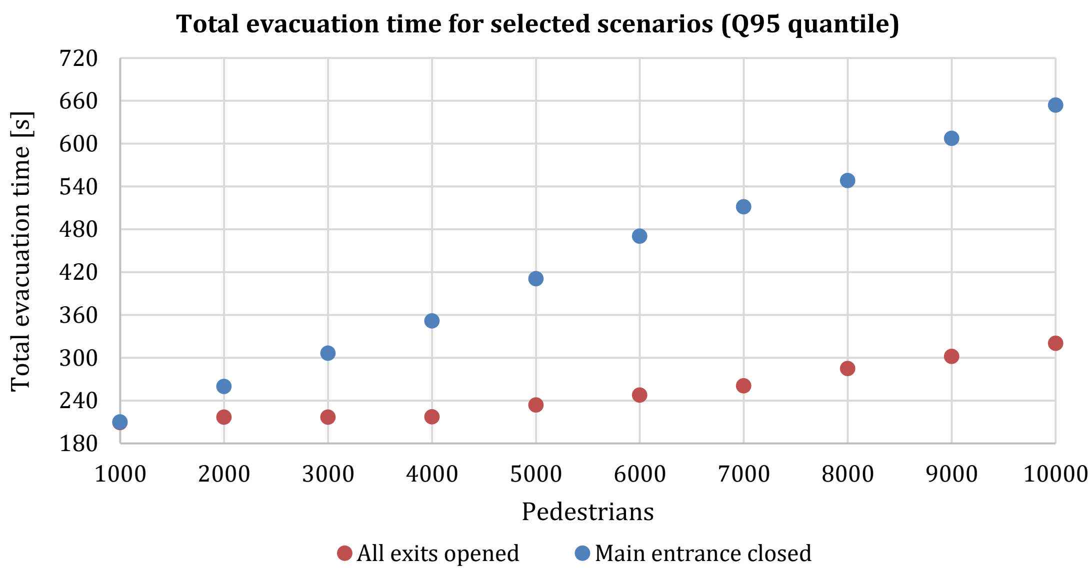

Figure 12: Total evacuation time for selected scenarios: all exits opened and closed the main entrance.

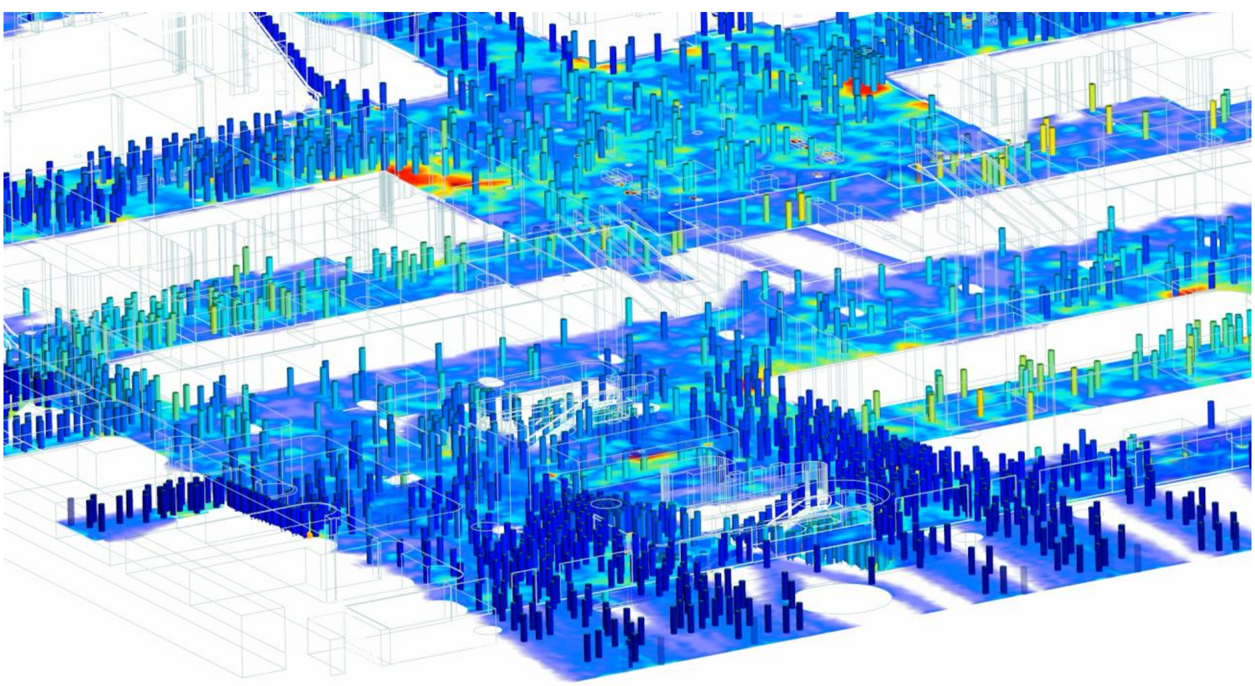

Figure 13: Maximum density helps to find parts of the station where a critical density has formed at any time during the evacuation. The color of the agents on the picture corresponds to the time remaining until they leave the station.

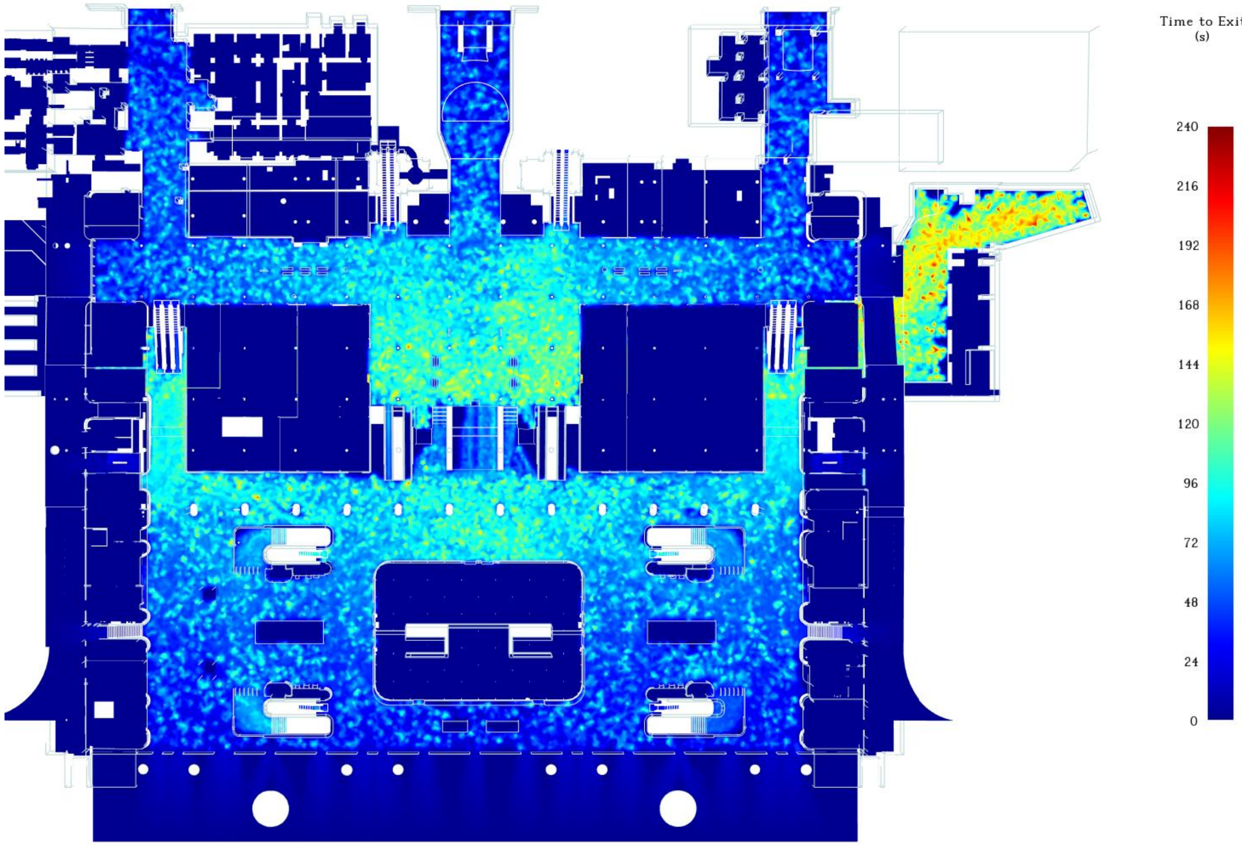

Figure 14: Maximum Time to Exit identifies places in the building from which evacuation is most complicated and where the security manager should focus its actions at first.

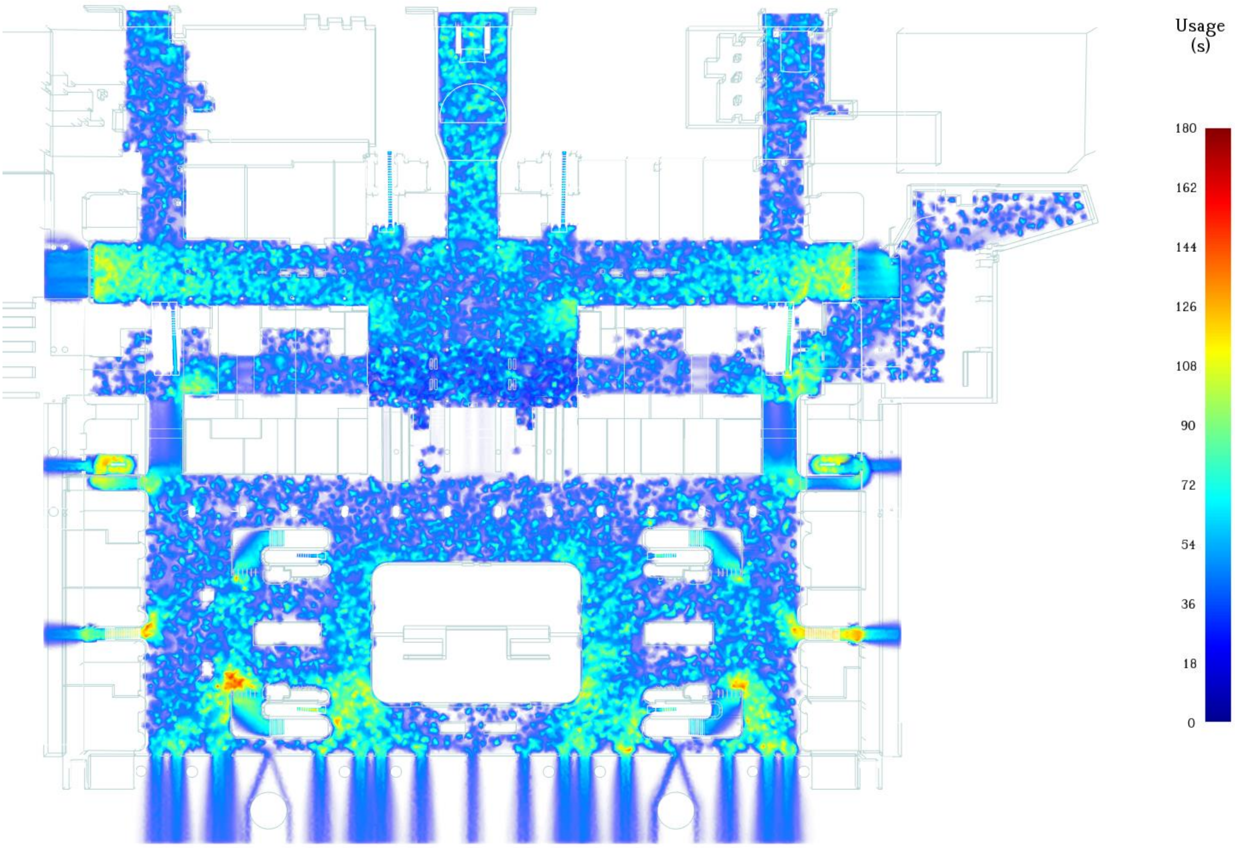

Figure 15: Maximum Usage shows how long the congestion prevailed. The longer the congestion, the higher the frustration of people, and the greater the risk of injury or panic.

Figure 16: A flight through an object in various situations, which can be observed in VR.

We analyzed a total of 7 different scenarios, each with a capacity of 1,000 to 10,000 people, for each occupancy tens of simulation runs with random input parameters. This means several thousands of individual simulations. This procedure would not be possible without advanced automation, in our case using scripts in the R statistical language. We use to change the Pathfinder Input File to achieve the following changes in particular:

- Change the number of agents.
- Change the parameters of agents.
- Change random seed.
- Open or close the doors

The results have been processed using the same approach. Besides the third-party software tools, it was also important to deploy a sufficiently powerful computing server. In our case, it was dual CPU Intel Xeon with 24 cores for multi-threaded processing of Pathfinder simulations. Without this platform, it would not be possible to carry out simulation tests in a reasonable time.

CONCLUSION

The soft targets' protection is a long-term issue especially in developed countries, which are the primary target of terrorist attacks and similar threats. The development of simulation tools has enabled a new level of accuracy for the risk analysis applied by security professionals.
When assessing, we must apply the correct method of risk analysis and interpret these risks in the environment of simulation tools. An example is the occurrence of the shooter outside of the object, which we interpret by closing specific escape routes. Among the simulation results, in addition to the evacuation time, we must also include other outputs that are important for security managers, for example heatmap of time to exit
Further development will depend also on the level of digitalization of the construction industry. A very good example is the Building Information Models (BIM), which we applied in another of our studies of soft targets, the Prague subway station in Fig. 17. Support for key these standards like IFC (Industry Foundation Classes) by simulation tools significantly speeds up the analysis, makes it less expensive, and enables much more attractive visualization. This will enable us to further replace an assessment through prescriptive codes wherever it makes sense.

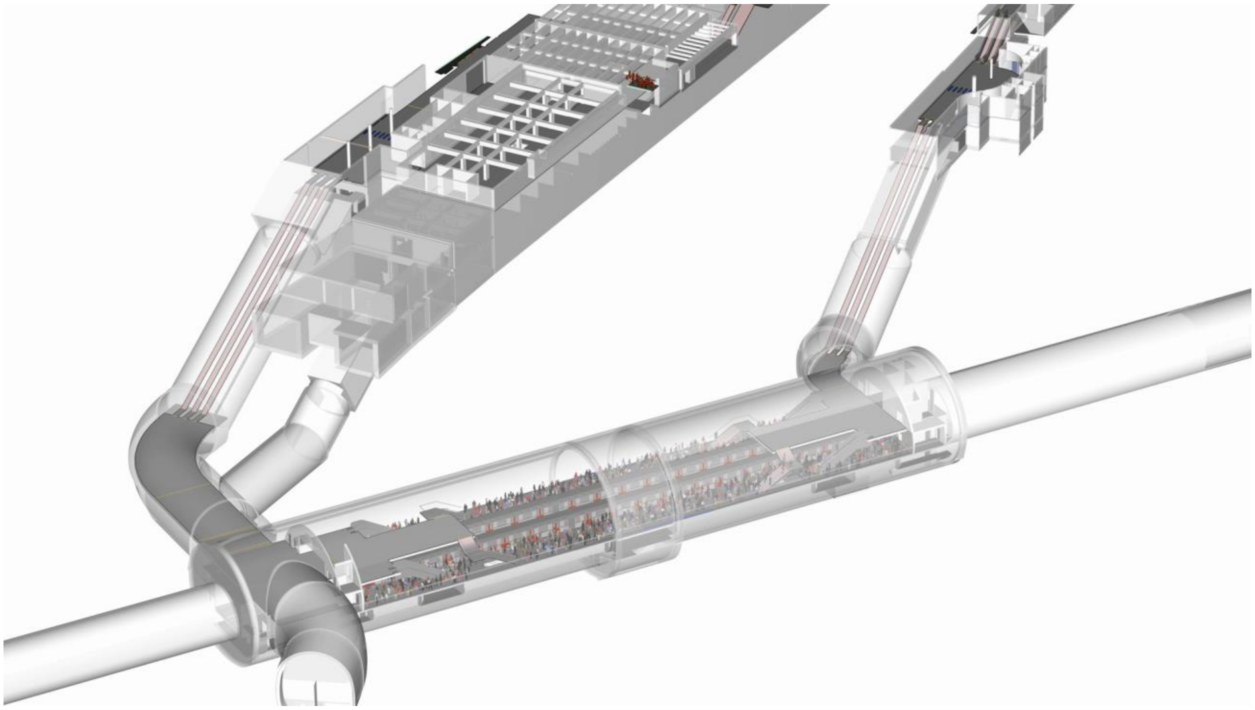

Figure 17: Simulation of the Prague subway station using Building Information Model (BIM).

REFERENCES

[1] ČSN 73 0802 Požární bezpečnost staveb – Nevýrobní objekty (Fire safety of buildings - Non-production facilities), 2009.

[2] Thunderhead Engineering Consultants, Inc., "Pathfinder Technical Reference Manual", available online [2020-08-20]: https://support.thunderheadeng.com/docs/pathfinder/2020-3/technical-reference-manual.

[3] Schröder, B. (2017), "Multivariate Methods for Life Safety Analysis in Case of Fire," IAS Band, Volume 34, ISBN 978-3-95806-254-2, available online [2020-08-20]: http://elpub.bib.uni-wuppertal.de/servlets/DerivateServlet/Derivate-7013/dd1611.pdf

[4] Galea, E. R., Deere, S. J., Hopkin, C. G. (2015), "A study of response behaviour in a Theatre during a live performance," *In: Proceedings of the 6th International Symposium on Human Behaviour in Fire*. 6th Interscience Communications Ltd, London, pp. 385-398. ISBN 978-0-9933933-0-3.

[5] Lovreglio, R., Kuligowski, E., Gwynne, S., Boyce, K. (2019), "A pre-evacuation database for use in egress simulations," *Fire Safety Journal*, **105**, April 2019, pp. 107-128.

[6] Hurley, M. J., et al. (2015): "SFPE Handbook of Fire Protection Engineering". Springer, 2015. ISBN: ISBN 978-1-4939-2564-3.