High parametric CFD-analysis of fire scenarios in underground train stations using statistical methods and climate modelling

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MOTIVATION

Public transport is an essential component to cope with the growing demand for mobility in urban areas. Rail mounted transportation pertains to the most powerful systems and is often realised underground. Among spacious tunnel systems, underground train stations are complex facilities with challenging structural features for preventive and defensive fire protection. After all, these facilities are frequented by large crowds, which primarily depend on self-rescue during an event of fire.

OBJECTIVES

Usually the fire safety level of a structure is described by overall safety objectives. The attainment of these objectives is proven by satisfying predefined performance criteria i.e. gas temperatures or smoke layer heights that determine the available safe escape times of certain escape route components. Among various engineering philosophies, a potential approach comprises a qualitative and a quantitative phase of analysis [5]:

The qualitative analysis results in a variable amount of probable scenarios whose individual parameter sets need to be investigated in the quantitative phase of analysis. For this purpose, CFD models are applied increasingly. Here, it is a challenge to define scenarios that are supposed to cover the expected sample spaces at its best. In practice, this process is rather realised by expert judgement than by utilizing systematic methods. With awareness of various restricted resources, this work demonstrates a potential approach to overcome large parameter spaces in fire safety engineering.

Among these methodological aspects, two other factors are investigated in more detail: On the one hand, climatic effects are often neglected within fire safety assessments. On the other hand, most of the published investigations rely on one certain station [4, 9]. This contribution provides a more generalised approach based on statistical data about typical structures and dimensions of underground train stations in Germany.

STRUCTURAL STANDARD TYPES

At the beginning of 2014, an ascertainment of 40 underground train stations in Germany was conducted [2]. The examined stations do not belong to pure metro systems but to light rail systems that are run both at the surface and underground. This service concept is very common in Germany. The objective of this work was to get a principal overview of characteristics like typical structures, dimensions, escape way topologies, fire and smoke compartments and many others. The results of this work were condensed to a couple of standard types that represent typical structural features and dimensions based on statistical distributions.

The number of levels varied from one to three, whereby the majority of the examined stations comprise two levels. Further on, a number of two tracks was identified as the most common shape of the platform level. Considering the investigations presented in this paper, the following most prominent station type shall be examined in more detail:

Standard Type A

Standard type A represents an underground station with two tracks, which are separated by a central platform. On each face side of the platform level, a stairway leads to a distribution level. Each distribution level comprises two further stairways, which connect the station with the surface (see Figure 1). These shapes could be identified in 60 % of all recorded cases.

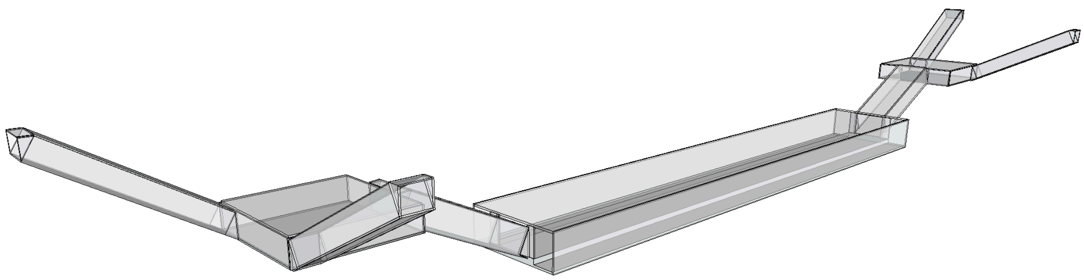

Figure 1: Standard Type A is characterized by two tracks separated by a central platform. Two stairways lead to intermediate distribution levels each of them comprising two stairways towards the surface.

Dimensions

The recorded data sets have been analyzed in order to extract representative dimensions for the single structural features (see Table 1).

Table 1: Standard Type A - Structural Features

Component	Representative	Minimum	Maximum
Platform			
Width	9 m	3.2 m	12 m
Number of stairways	2	1	4
Platform level			
Length	102 m	59.5 m	118 m
Width	16 m	13.1 m	17.3 m
Height	3.5 m	3 m	9.25 m
Distribution level			
Height	3 m	2.5 m	3.4 m
Number of stairways	2	1	5

CLIMATE MODELLING

The specific characteristics of underground rail infrastructures often implicate complex airflow regimes that can affect fire safety considerations drastically. Commonly, it is supposed that these airflows are predominantly induced by the so-called piston effect caused by moving trains. Based on this assumption, the consideration of climate effects is often neglected with the argument that the train traffic is stopped immediately in case of a fire.

However, the investigations of [3] and [10] clearly proved that airflows in underground train stations do not depend exclusively on train movements. In field studies that were conducted in Dortmund, Germany, it has been shown that background airflows establish one to three minutes after the train service is ceased. The shape of background airflows is mainly influenced by the ambient weather conditions. In detail, the temperature differences between the underground train station and the environment as well as within the underground train station have been yielded as the main influencing factor.

In general, it has been found, that higher temperature gradients result in higher flow velocities. This is especially the case during the winter period as the underground temperature profiles are less dynamic than the ambient ones and partially strong chimney effects establish. In contrast, the summer period is rather characterized by more localised temperature differences and more or less stable stratification phenomena. These conditions lead to airflows with minor velocities that are prone for flow reversals. In this case, the background airflow is predominantly driven by the temperature differences within the underground train station. With regard to accidents, the importance of further investigations about interactions between background airflows and those which are thermally driven by e.g. a fire has already been pointed out [11].

Implementation in FDS

Different approaches have been examined to model different climatic conditions in a simplified geometry with FDS 6.1. One attempt employed boundary conditions with explicit properties defining dynamic pressures. Another approach utilised temperature regions and gradients which reproduced the principal results of measured data [3] in the most satisfying way (see Chapter Results).

Utilising standard type A, the definition of different temperature regions and boundary conditions within the computational domain was conducted according to Figure 2:

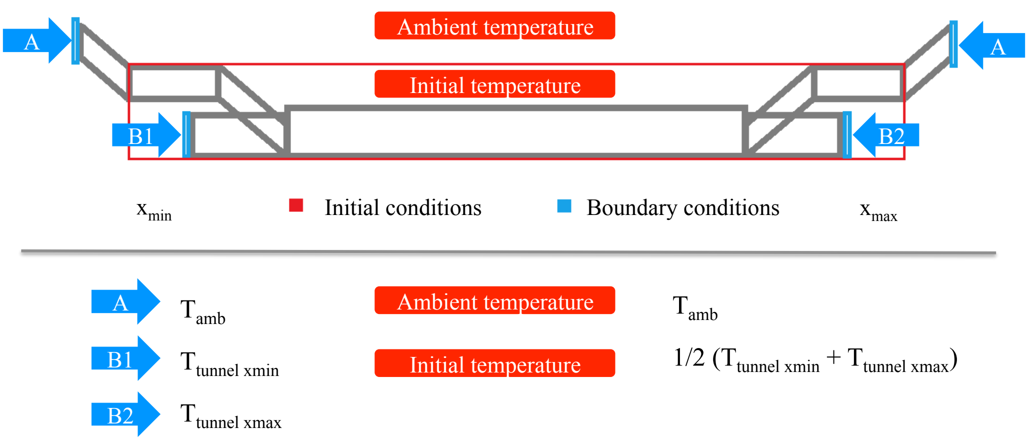

Figure 2: Implementation of climatic conditions utilizing both initial and boundary conditions. Three different temperature magnitudes have been applied to model climatic conditions at the surface (T_{amb}), at the tunnel portals ($T_{tunnel\ xmin}$ and $T_{tunnel\ xmax}$) and inside the station (mean of $T_{tunnel\ xmin}$ and $T_{tunnel\ xmax}$).

At first the mesh boundaries at the stairways that connect the distribution levels with the environment were furnished with ambient temperature conditions T_{amb}. The ambient temperature is assumed to be equal at both exit stairways.

Further on, temperature conditions were set to the mesh boundaries at the tunnel portals. Regarding to the insights of [3, 10, 11] two differing temperatures $T_{tunnel\,xmin}$ and $T_{tunnel\,xmax}$ were applied to the portals to slightly induce horizontal airflows. This approach assumes the tunnel temperatures to be both warmer and colder than the platform temperature. In contrast to that, the stations temperatures are usually higher than the tunnel temperatures [10]. However, long-term temperature measurements are only available for the tunnel systems.
In order to speed up the transient effect, an initial region was defined. It covers the whole platform level, the intermediate stairways and the distribution levels. The belonging initial temperature was assumed as the mean of both tunnel temperatures.

Based on this approach, a vertical as well as a horizontal temperature difference can be implemented into the computational domain. Hereby, the above-mentioned temperature criteria are chosen based on measured data [1, 3]. For the principal investigation of climatic effects, the magnitudes have been varied uniformly distributed in a range from -10 to 30 °C for T_{amb} and between 15 and 25 °C for $T_{tunnel\,xmin}$ and $T_{tunnel\,xmax}$. However, for the final parameter choice alternative distributions will be considered. (see Chapter PARAMETER SAMPLING).

Results

Qualitatively, the modelling approach described above produced satisfactory results regarding the principal airflow conditions in underground train stations. Especially distinctive airflow regimes during winter conditions as well as relatively stable stratification phenomena with minor velocities during summer conditions could be reproduced. Figure 3 visualises the longitudinal velocity (u-vel) within the simplified geometry for exemplary winter and summer conditions:

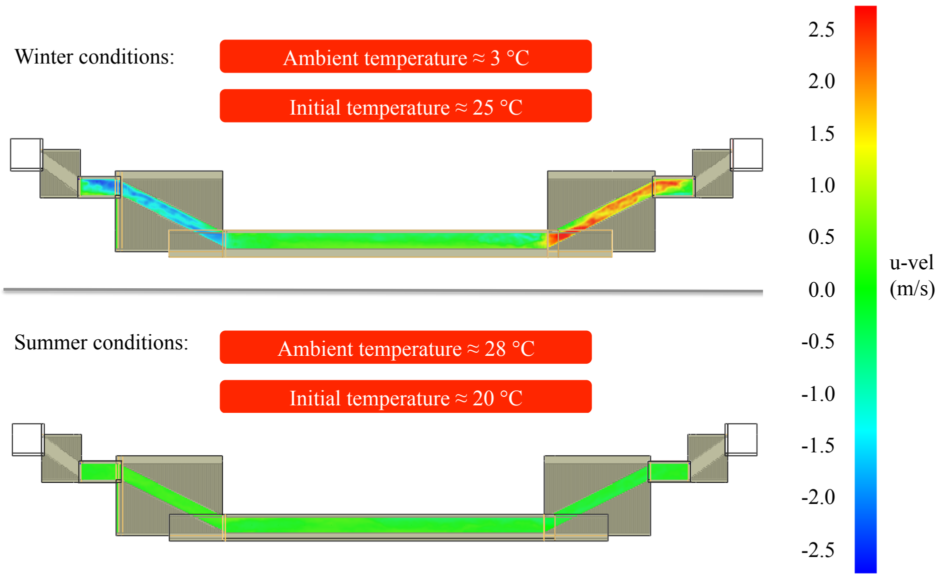

Figure 3: Principal airflow regimes during winter and summer conditions. Lower surface temperatures induce vertical air exchange from the platform level towards the surface. Higher surface temperatures result in stratification with minor airflows. Differing tunnel temperatures induce horizontal airflows within the platform level.

The temperature differences during winter conditions obviously provoke airflow regimes that lead to a steady air exchange from the platform level to the environment. Additionally, the shape of the airflows at each stairway is slightly influenced by the horizontal temperature difference between the tunnel portals. In case of summer conditions, warm ambient air and cold air in the underground system stratify. This process is accompanied by minor airflows that are predominantly driven by horizontal temperature differences.

A quantitative comparison between modelling approach and field data can be conducted by utilising airflow velocities in the tunnel system. Figure 4 illustrates regression lines for several service modes belonging to the measurements in [3]. The scatter plot opposes calculated airflow velocities nearby the tunnel portals at x_{max} to the field data:

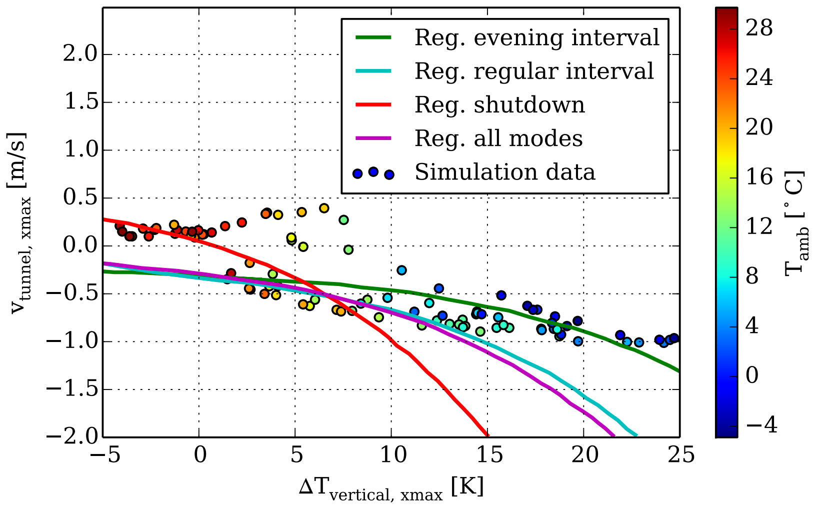

Figure 4: Comparison of field data regressions and simulation data. The scatter plot opposes airflow velocities at a tunnel portal against vertical temperature differences [3].

The absolute velocities recorded by [3] varied in a range from zero up to two meter per second. The simulations concluded absolute velocities only up to one meters per second. There are various reasons that could cause this discrepancy: For example, further climatic phenomena like wind at the surface, ambient pressure or humidity are neglected within this approach. Further on, one needs to consider that the comparison is based on simulation data obtained from a fictional standard type and field measurements at one individual station. However, the principal dependency between horizontal temperature difference and airflow velocity can be reproduced.

PARAMETER SAMPLING

The parameters described below conclude a wide range of possible combinations that cannot be completely assessed with full-scale simulations. It is the aim to perform a design of experiment that enables the approximation of a response utilising a smaller number of simulations. For this purpose, so-called Latin hypercube designs have become quite popular over the last two decades [12].

Latin hypercube design provides a space-filling sampling within the considered domain. Here, it is capable to consider statistical distributions as well as the coverage of varying design spaces within one sampling. There is no strict mathematical rule that determines the size of the sample according to the number of factors [8]. To outline a first approach, a sample size with n=100 combinations is applied for the sampling process.

Finally, planning of input configuration as well as statistical analysis is mandatory for the design of experiments. The sampling process comprises the seven parameters shown in

Figure 5. The parameters can bee classified into climate, design fire and structure. Further insights into each parameter are described below.

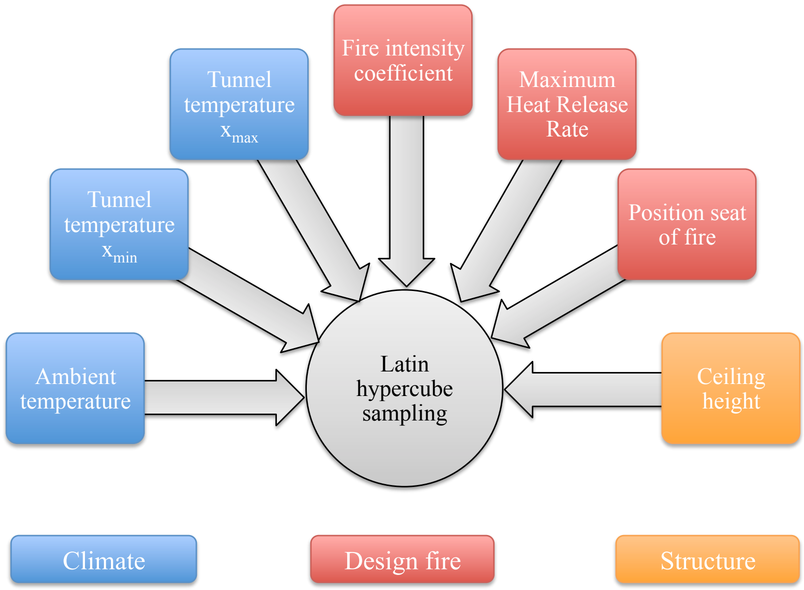

Figure 5: Parameters that were included in the sampling process. A classification of the parameters can be conducted as follows: climate, design fire and structure.

Climate

The climate data was gained from measurements in Düsseldorf and Dortmund. Both cities are located in the same area. Figure 6 comprises field data of minimum and maximum ambient temperatures at Düsseldorf over a period of one year. The dataset could be fitted with a normal distribution. The corresponding μ- and σ- values for T_{amb} are transferred to the sampling process. Figure 7 shows tunnel temperatures that have been recorded in Dortmund from July to February. Concerning these data, it is not possible to apply a certain distribution to the sampling process. For this reason, a uniform distribution from 10 to 20 °C for $T_{tunnel\ xmin}$ and $T_{tunnel\ xmax}$ has been implemented into the sampling process.

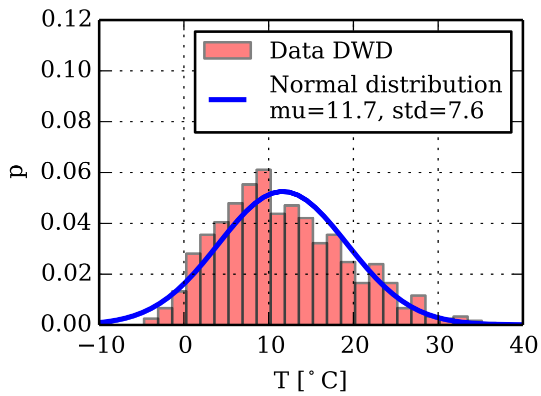

Figure 6: Ambient temperature histogram comprising the maximum and minimum temperatures measured by the Deutscher Wetterdienst (DWD) at Düsseldorf during the period from May 29th 2013 to May 29th 2014 [1].

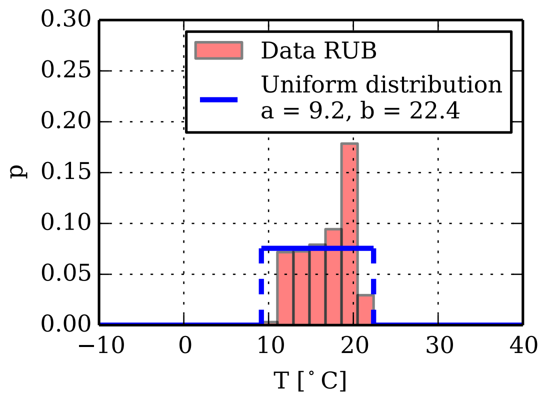

Figure 7: Tunnel temperature histogram showing field data about tunnel temperatures that were recorded by the Ruhr-Universität Bochum (RUB) at Dortmund from July 8th 2005 until February 28th 2006 [3].

Design Fire

It is the aim to use a minimal amount of parameters for modelling a wide range of design fires. Thus, the heat release within the computational domain utilises an αt^2-Ansatz realised by a time-dependent growth of the area of fire. Only the fire intensity coefficient α and the maximum heat release rate $\dot{Q}_{max}$ have been considered within the sampling. The corresponding specific heat release rate q'' is calculated as quotient of the maximal heat release rate and the carriage area $A_{carriage}$ (Equation 1):

$$q'' = \frac{\dot{Q}_{max}}{A_{carriage}} \qquad \text{Equation 1}$$

In accordance with the studies of [7], a constant fire load Q of 50 GJ per carriage is assumed. Further on, the end time of the continuous fire stage $t_{End\,\dot{Q}_{max}}$ is calculated after a conversion of 70 % of the fire load, as shown in Equation 2. In this context $t_{Begin\,\dot{Q}_{max}}$ is the moment when the maximum heat release rate is reached.

$$t_{End\,\dot{Q}_{max}} = t_{Begin\,\dot{Q}_{max}} + \left(\frac{Q \cdot 0.7 - \alpha \cdot \frac{1}{3} \cdot t_{Begin\,\dot{Q}_{max}}^{\;3}}{\dot{Q}_{max}} \right) \qquad \text{Equation 2}$$

The stage of dying fire contains a linear decrease of the heat release rate. The duration of the dying stage Δt_{dying} is calculated with Equation 3:

$$\Delta t_{dying} = \frac{Q \cdot 0.6}{\dot{Q}_{max}} \qquad \text{Equation 3}$$

According to the approach described above, the fire intensity coefficient is varied from 0.012 to 0.188 KW/s^2 to represent medium up to ultra-fast fire growth rates. The maximum heat release rate ranges from 20 to 60 MW. These parameter bounds consider the recommendations presented in [7] and are supposed to be extracted uniformly distributed.

The seat of fire is assumed to be located inside one single carriage. Its location is varied uniformly distributed within six sections of the platform level as shown in Figure 8:

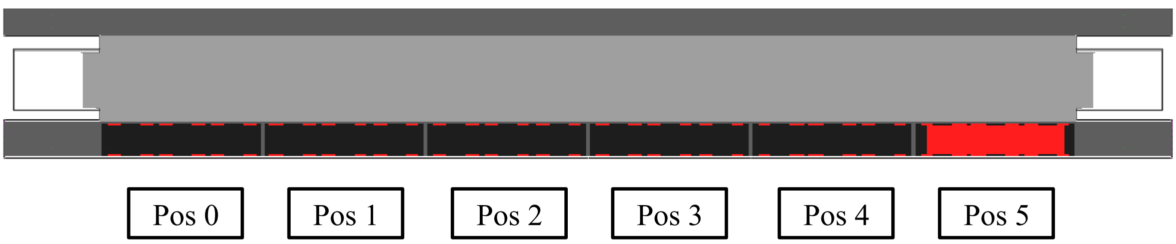

Figure 8: Top view on six carriages placed on the platform level. The red carriage visualizes the location of the seat of fire. Each sample contains a parameter defining the location of the seat of fire between zero and five.

Structure

Out of various structural data from [2], the ceiling height is worth considering for fire safety aspects. The investigations resulted in ceiling heights in a range from three to nine meters above the platform edge. Figure 9 visualizes the accumulation of heights smaller than five meters. For this reason, a Weibull distribution is applied to the sampling process.

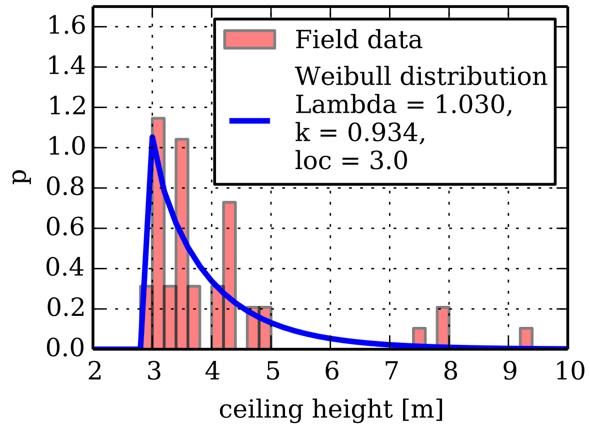

Figure 9: Ceiling height histogram showing dimensions from three to nine meters [2]. A Weibull fit represents the accumulation between three and five meters.

FIRE SIMULATION

According to the sampling process, 100 simulations have been conducted for the considered standard type A. The parameter sampling utilized the Latin hypercube design method. The PyDOE-module (Python Design of Experiments) has been used for that. The automated input file generation is realised via one single XML-file (Extensible Markup Language) and a Python-Parser that converts each parameter set into an fds-file.

The simulations have been executed with FDS 6.1 (SVN 19410) utilising OpenMP+MPI hybrid parallelisation on 32 Intel-Nehalem-cores each. The computational domain consists of 16 regular meshes, whereas each one is discretised by a cell size of 20x20x20 cm^3. To cover the self-rescue period, the simulation time after ignition amounts to 900 seconds. Prior ignition, an additional delay time of 240 seconds is applied to bridge the transient effect of the climatic conditions so that the overall simulation time is 1140 seconds. The heat release is modelled by a simplified αt^2-Ansatz based on a propane combustion reaction (see section Design Fire). All structural surfaces are modelled with material properties of concrete. According to the recommendations of [7], the carriage doors of the entire train and the windows of the burning carriage are supposed to be open. Output data is essentially produced to quantify the propagation of hot gases as well as smoke layer heights. The overall production process is visualized in Figure 10:

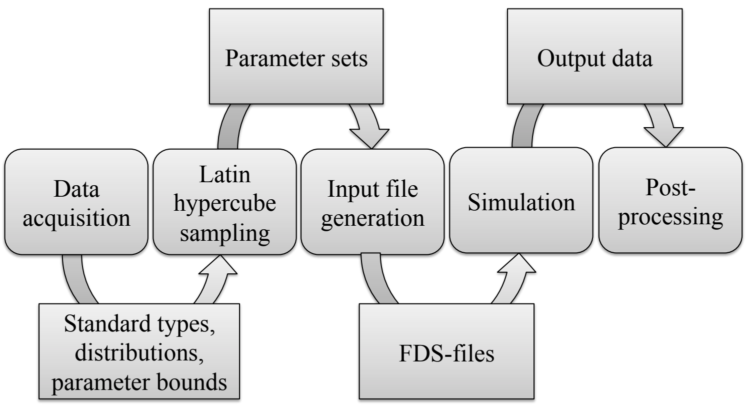

Figure 10: Production process consisting data acquisition and analysis, Python-based Latin hypercube sampling, XML-based input file generation, execution of simulations and final post-processing.

RESULTS

For the substantiation of life safety, factors like gas temperatures as well as optical and toxicological characteristics of smoke have to be considered [5]. The assessment of smoke characteristics is excluded in the scope of this work. As a start, the analyses below rely on the distribution of hot gases inside an underground train station structure. The analyses refer to the left and right edges of the platform level as shown in Figure 11. Especially the measuring points located on the left and right edge of the platform are of high importance to the period of self-rescue. Here, the local conditions terminate the availability of the escape routes leading to the surface.

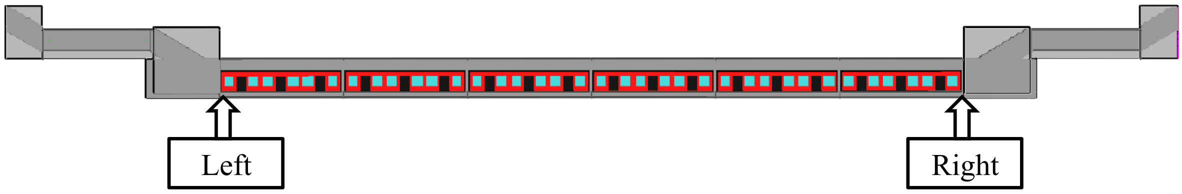

Figure 11: Location of measurement points at the left and right edge of the platform level.

The left side of Figure 12 shows the time sequences of the gas temperatures measured at a height of 1.8 meter. On the right, histograms illustrate the distributions of the calculated points in time when the tenability criteria are exceeded.

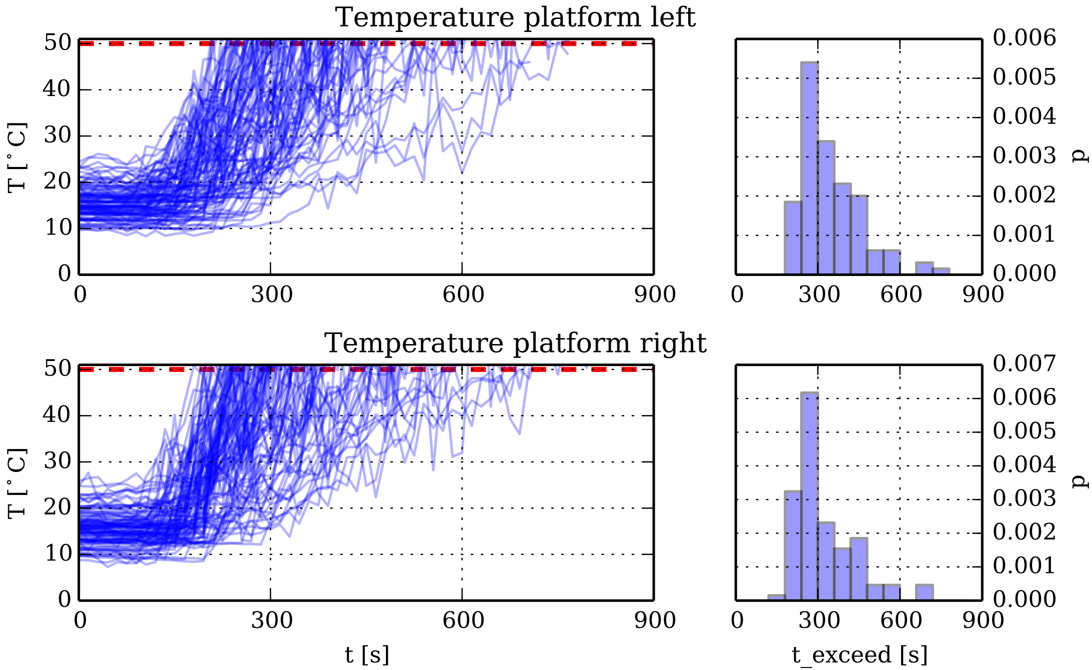

Figure 12: Temperature sequences recorded on the left and right of the platform level. The red dashed lines illustrate the tenability temperature of 50 °C for a length of stay of 15 minutes as proposed in [5]. For each location, histograms illustrate the distributions of the calculated points in time when tenability criteria are exceeded.

The time axis ranges from zero to 900 seconds. It covers the time range between the beginning of αt^2 and the end of the period of self-rescue. The upper bound of the temperature axis visualizes the tenability temperature of 50 °C for a length of stay of 15 minutes that is proposed in [5]. Further on, the more or less constant temperatures up to 150 seconds illustrate the differing initial temperatures within the platform level. The diagrams clearly show the wide spread of durations for the availability of certain escape route components. In concrete terms, a minimal duration of only 179 seconds has been observed. In the maximum case, the tenability criterion is exceeded after 680 seconds.

The results outlined above allow the principal identification of worst credible scenarios. One possible strategy is, to utilize the absolute minimum exceeding time for the determination of the available safe escape. For this purpose, the appropriate parameter samples must be analyzed in more detail. Especially the availability of the second escape route should be considered. Table 2 lists the samples that were identified as the most critical parameter sets:

Table 2: Overview of the five most critical samples regarding to the exceeding time of tenability criteria on the right edge of the platform level. Additionally, the exceeding time of the opposite measurement point is shown.

Sample ID	**022**	**043**	**095**	**077**	**046**
Tunnel temperature x_{min} (°C)	13.45	13.99	15.05	14.53	10.08
Tunnel temperature x_{max} (°C)	16.42	11.48	12.32	16.15	18.38
Ambient temperature (°C)	16.76	11.62	25.87	19.77	22.09
Maximum heat release rate (MW)	20.1	37.4	22.7	41.7	54.4
Fire intensity coefficient (KW/s^2)	0.19	0.14	0.15	0.19	0.16
Position seat of fire	3	5	3	4	3
Ceiling height (m)	3.2	3.0	3.4	3.2	3.0
$t_{exceed, right}$ (s)	179	193	197	199	207
$t_{exceed, left}$ (s)	206	334	219	233	231

Another conceivable approach is the statistical processing of the simulation results that can be transferred to probabilistic approaches for assessing life safety as proposed by [6].
For a more general understanding, the individual influences of the design fire as well as of the modeled climatic conditions shall be investigated. For this purpose, the focus is on the right side of the platform level where the minimum available safe escape time has been calculated.
The scatter plot in Figure 13 opposes the fire intensity coefficient, the exceeding time and the heat release rate at the time point of exceeding. Figure 14 illustrates the correlation of the vertical temperature difference between the platform level and the surface, the exceeding time and the fire intensity coefficient.

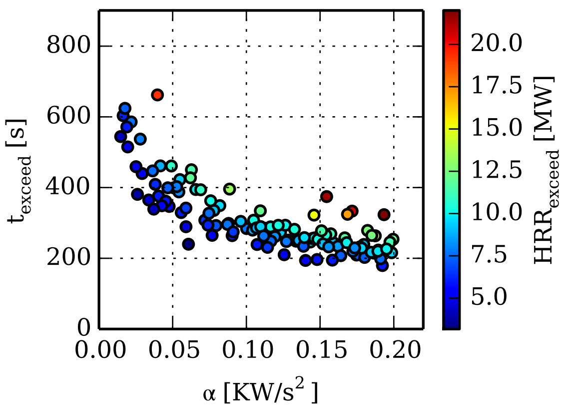

Figure 13: Scatter plot illustrating the correlation between exceeding time, fire intensity coefficient and heat release rate at the exceeding time.

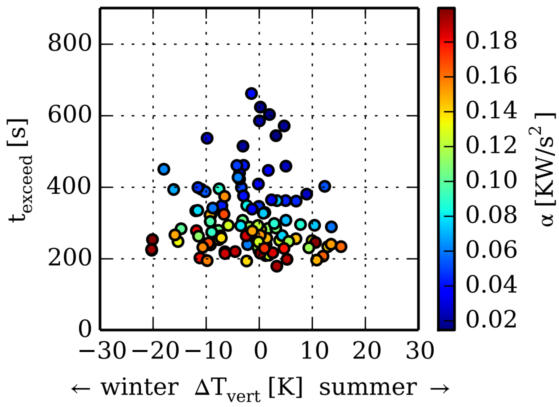

Figure 14: Scatter plot opposing exceeding time of tenability, vertical temperature difference between platform and surface and fire intensity coefficient.

Figure 13 shows a clear correlation between the fire intensity coefficient and exceeding time. The exceeding time ranges between 179 and 680 seconds. It becomes apparent that increasing fire intensity coefficients result in decreasing exceeding times. Obliviously, the measured heat release rates are relatively low at the minimum time points of exceeding. One can conclude from this that the heat release rate has subordinate significance,

The plot in Figure 14 does not conclude an unambiguous correlation between the vertical temperature difference between the platform level and the surface and the exceeding time. Nevertheless, a cluster of high exceeding times can be observed in the area around zero Kelvin temperature difference. In consideration of the fire intensity coefficient, it becomes obvious that the exceeding times of parameter sets with low fire intensity coefficients depend on the vertical temperature difference between platform level and surface. In other words, temperature differences that represent winter and summer conditions result in lower exceeding times.

CONCLUSIONS

This work deals with high parametric fire scenario analysis for underground train stations. For this purpose, several train stations in Germany have been captured to assess representative standard types. Based on field data, varying climatic conditions have been reproduced satisfactorily with FDS. Utilizing a systematic sampling strategy, it has been shown that high dimensional parameter spaces can be investigated effectively. For that purpose, statistical processing of field data and planning of input generation are mandatory for the design of experiment. Regarding to the amount of data and variations, automated processing for input file generation, job execution and post-processing is indispensable. The simulation results show a wide range of 179 to 680 seconds when tenability criteria are exceeded. Regarding to the determination of the available safe escape time, this work proposes a potential strategy to identify worst credible scenarios in fire safety engineering. Finally, for a more general understanding, the influence of selected parameters on the overall system is investigated. Here, the fire intensity coefficient has been identified as the most important parameter. Regarding to the climate modeling, it has been found that climatic effects can influence the determination of performance criteria. This is especially the case for low temperature differences between platform level and surface.

OUTLOOK

This work concludes the demand for further consideration of climatic conditions in fire safety engineering. Especially in the scope of underground train stations, the influences of surface wind and atmospheric pressure need further investigation.

Regarding to the post-processing the quantification and ranking of correlations as well as surrogate modeling needs further effort. For this purpose, the impact of both, smaller and larger sampling sizes has to bee investigated in more detail.

As a start, the analyses rely on the propagation and stratification of hot gases inside a structure. The outlined methodology can be transferred to the assessment of other performance criteria. In concrete terms, the consideration of both optical and toxicological smoke characteristics in conjunction with different fuels should be conducted. Further on, the investigation of selected smoke management strategies could be implemented into the sampling process.

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