International Journal of Innovative Research and Scientific Studies, 8(6) 2025, pages: 884-898

IJIRSS International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Use of the FDS program for effective determination of spacing distances when dealing with fire safety solution for buildings, Slovak case study

Dorota Hodúlová[1*], Patrik Mitrenga[2], Stanislava Gašpercová[3]

[1,2,3]*Department of Fire Engineering, Faculty of Security Engineering, University of Zilina, Slovakia.*

Corresponding author: Dorota Hodúlová (*Email: dorota.hodulova@uniza.sk*)

Abstract

Fire safety solutions for buildings in Slovakia are addressed by legislation and Slovak technical standards, which are not legally binding, but their wording is mandatory if they are referred to in an implementing regulation. Fire safety solutions for buildings in Slovakia are therefore mainly limited by legislation and technical standards. The use of fire models in fire safety solutions for buildings is common worldwide, but these tools are not used in Slovakia. Their use is not prohibited by law, but it is always necessary to prove the applicability and correctness of the outputs. The paper deals with a case study of Slovak implementation of fire models when discussing the stand-off distances from fully fire-opened areas. The research addresses fire safety solutions for buildings under the conditions of the Slovak Republic. To utilize fire models in practice, the threshold conditions for the use of the selected FDS fire model needed to be established. This process is called a validation program, conducted based on the utilized simulation method. Subsequently, a general model for determining the stand-off distances from fully fire-opened areas was established. This model was verified by comparing the values of stand-off distances obtained through simulations and values derived from the prescriptive approach, which determines the stand-off distances in Slovakia following generally binding legal regulations and standards. Subsequently, an accurate general model for the solution of stand-off distances was created, which is validated with the technical standards in the Slovak Republic.

Keywords: FDS, Fire models, Fire safety solutions for buildings, Slovak case study, Stand-off distances.

DOI: 10.53894/ijirss.v8i6.9762
Funding: This work is supported by the University of Žilina, Slovakia (Grant number: 16961).
History: Received: 8 July 2025 / **Revised:** 11 August 2025 / **Accepted:** 13 August 2025 / **Published:** 10 September 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Publisher: Innovative Research Publishing

1. Introduction

Nowadays, there has been a steep increase in the construction of new buildings, followed by a directly proportional decrease in the number of building plots open for construction without addressing the issue of fire safety in different types of construction. As a result, a solution regarding the problem of fire spread between neighboring buildings needs to be considered even more [1]. In order to efficiently prevent the spread of fire among buildings, one must know not only the distance between them but also the behavior and course of the fire itself. Through fire hazardous areas, we can determine the approximate distance needed between two buildings to prevent the spread of fire [2]. However, the fire itself is influenced by various factors; furthermore, a slight change in one of them might significantly alter its course. Therefore, there are no means to effectively predict fire behavior in enclosed spaces, although it is possible to estimate it using the tools available. [3]. One such tool is the fire model. Fire models are classified as a technology that enables fire simulations [4, 5], especially in enclosed spaces. This technology enables us to predict the behavior and progression of fires, allowing us to efficiently combat their outbreaks and thereby eliminate property damage and, most importantly, protect the lives and health of occupants inside said buildings. However, in terms of fire safety solutions for buildings, the implementation of fire models into practice remains unknown, although the only thing needed for their employment is to set the threshold conditions for the individual areas of said solutions. Then, under these conditions, similar results as found in the prescriptive approach would be obtained.

The issue of implementing fire models into fire safety solutions for buildings is in high demand worldwide. Some countries have already adopted this approach. New Zealand utilises the B–RISK programme, which demonstrates the compliance of fire safety design solutions for buildings with current legal regulations [6, 7]. In 2017, scientists from Pesic, et al. [8] conducted research called *Simulation of Fire Spread Between Residential Buildings Regarding Safe Separation Distances* [8]. The focus of their research was the determination of the optimal stand-off distance needed to prevent the fire from spreading between two neighbouring residential buildings by utilising the FDS programme. In 2021, Dúbravská, et al. [9] addressed the *Use of CFD in fire hazardous area prediction* [10]. The aim of their research was to assess the impact of individual user settings in FDS simulations on the change in the resultant heat flux density values, which are used to determine the stand-off distances. The research compared the results of radiant heat determined by the prescriptive approach based on Kirchhoff's Law, Stefan–Boltzmann Law, Planck's Law, and Lambert's Law with simulation results when selected parameters are changed [10]. In Slovakia, the issue of the implementation of fire models into the fire safety solutions for buildings is being addressed, as proven by the works of Kadlica [11-13] and other authors [14-17]. Matej Kadlic focused on *the impact of variability and uncertainty of input parameters on the quality of fire model outputs*. He also discussed the issue of the applicability and plausibility of fire models in engineering practices. Within his research, he analyzed the input parameters and specified the ranges of sensitivity analysis values. This analysis was then used to assess the impact of input uncertainty and variability on the outputs [13].

The aim of the contribution of the Slovak case study is to demonstrate, verify, and validate the application of the FDS fire model to determine stand-off distances in fire safety solutions in Slovakia. An integral part of this is the processing of sensitivity analysis for measuring separation distances between buildings and their subsequent verification under the binding legal regulations of the Slovak Republic. Specifically, the paper addresses the impact of selected parameters of fire models on the simulation computational time and the size of the stand-off distances.

2. Materials, Methods and Results

The following part of this paper discusses the description of stand-off distance solutions in Slovakia and their methodology by utilising the fire models, specifically the FDS programme.

2.1 Solution of Stand-Off Distances under the Conditions of the Slovak Republic

Fire hazardous area Regulation No. 94/2004 Coll [18]; STN 92 0201 – 3 [19] and Dúbravská, et al. [9] denotes a space created around a burning fire section or structure involving a risk of fire spread caused by radiant heat or collapsing parts of the structure, which could transfer the fire to another building or another fire section of the same building. Fire hazardous area in a building is determined according to the fire risk. Fire risk Regulation No. 94/2004 Coll [18]; Mózer [20] and Mračková, et al. [21] is defined as a presumable fire intensity in the fire section or its part. The fire risk is represented by the equivalent duration of the fire (min.) for production buildings, fire load calculation ($kg \cdot m^{-2}$) for non-production buildings, the index of stored materials, and the economic risk index for warehouses in a single-storey building [21]. The fire hazardous area of a fire section in a construction object is restricted by the area drawn in a stand-off distance *d* parallel with the opened fire area of the fire section under assessment [18]. On the sides, the fire hazardous area is enclosed by cylindrical surfaces with a radius equal to the stand-off distance, the axes of which are aligned with the boundaries of the fire hazardous area, which, in turn, emerge from the boundaries of the open fire area, forming a 160° angle [18, 22]. The exact procedure for determining the stand-off distances is provided in Regulation No. 94/2004 Coll [18] and Hodúlová and Gašpercová [23]. The depiction of the fire-hazardous area is shown in Figure 1.

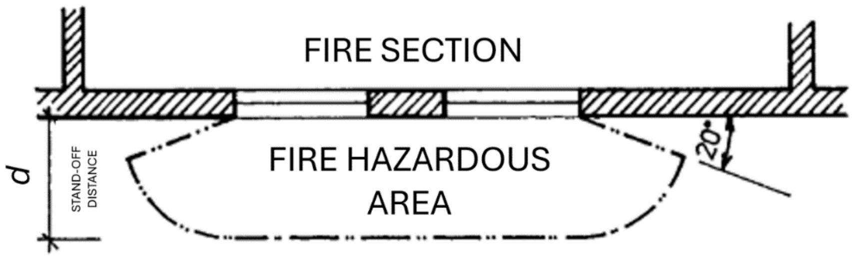

Figure 1.
Depiction of the fire hazardous area Regulation No. 94/2004 Coll [18].

Analysis of the issues regarding stand-off distance solutions in Slovakia follows generally binding legal regulations and technical standards related to the general issues of fire safety solutions for buildings. The main legal regulations for the development of project documentation on fire safety solutions for buildings in Slovakia are:

- *Act. No. 314/2001 Coll., on protection against fires as amended* [24]
- *Decree of the Ministry of the Interior of the Slovak Republic No. 121/2002 Coll., on fire prevention as amended* [25]
- *Act. No. 25/2025 CollBuilding Act* [26]
- *Decree of the Ministry of the Interior of the Slovak Republic No. 94/2004 Coll., establishing technical requirements for fire safety in the construction and use of buildings as amended* [18]
- *Decree of the Ministry of the Interior of the Slovak Republic No. 699/2001 Coll. on the provision of water for extinguishing fires in buildings as amended* [27].

Further legal regulations, arising from the design of specific buildings, are referred to in the above-mentioned legislation and standards.

The European Union employs Eurocodes [28] and Introduction and use of Eurocodes in the Slovak Republic [29] which concerns itself with the design of structures and their durability under specific conditions. However, there is not a single method of dealing with fire safety solutions for buildings in the European Union, since each country addresses this issue with its own regulations [30, 31]. Fire safety solutions for buildings in Slovakia is governed by Slovak Technical Standards (STS), which are not legally binding; however, they are mandatory if they are referred to by an implementing regulation:

- *STN 92 0201 – 1: Fire safety solutions for buildings – Fire risk, size of fire section* [32]
- *STN 92 0201 – 2: Fire safety solutions for buildings – Building structures* [33]
- *STN 92 0201 – 3: Fire safety solutions for buildings – Escape routes and evacuation* [19]
- *STN 92 0201 – 4: Fire safety solutions for buildings – Stand-off distances* [34]
- *STN 92 0400: Water supply for firefighting* [35]
- *STN 92 0202 – 1: Equipment of buildings with fire extinguishers* [36]
- *STN 92 0241: Occupation of buildings by persons* [37]
- STN EN 1991 – 1 – 2 (73 0035) – Eurocode 1: Loads on structures – Part 1 –2: General loads – Loads on structures subjected to fire [38].

Further STS arising from the design of specific buildings, referred to in the above-mentioned legislation and standards.

To define the objective, the paper shall further discuss only the fire-hazardous area and its determination. Fire-hazardous areas, in other words, stand-off distances, are addressed by STS standard 92 0201 – 4 [34], which follows other standards of the STN 92 0201 series [38]. All standards utilised in fire safety solutions for buildings in Slovakia follow [22] publications. Stand-off distances specifically are discussed in Volume 27 [22]. The fire safety solution for buildings in [22] book follows the Czech technical standard (CTS) 73 08XX. Volume 27 specifically follows the CTS 73 0804 [39], which is a newer, modified version of the CTS 73 0802 [39] standard. Theoretical assumptions for stand-off distance calculations according to Reichel can be found in his publication [22] and theoretical assumptions for stand-off distance calculations according to STS 92 0201 – 4 can be found in the respective standard [34].

2.2. Addressing Stand-off Distances with Fire Models

Fire models are designed as fire simulation tools, used when discussing fire safety solutions for buildings [40]. Fire models [41, 42] are divided into two major groups, *Physical* and *Mathematical*, which are further subdivided according to their application. There is a countless number of fire models. Each of them, first and foremost, aims to simulate fire and smoke transport, albeit each emphasizes different parameters of their development [43]

- FDS is a software designed to model the spread of fire and combustion products in an enclosed space. To use this software requires considerable skill [44]
- *PyroSim* is the graphical user interface of the FDS, which is quite easy to use [45]
- *CFAST* is a two-zone fire model, which divides the fire section into two zones with the assumption of a different temperature and density of combustion products in each zone [46, 47]
- *Autodesk CFD Simulation* is a programme used for the simulation of fire, smoke, human safety evaluation and monitoring of selected fire parameters [48]

- *B – RISK* is designed to model the spread of fire in buildings and monitor the activation and operation of fire equipment. The program allows visualization of geometry and simulation outputs. B – RISK operates in accordance with New Zealand building regulations [7].

FDS software is a computer programme designed to solve problems in the fire engineering area and is also a tool for investigating the basic dynamics of fire and combustion. FDS [44] can be used in studies focused on smoke control, activation of fire protection equipment and simulations of fires in enclosed spaces [44, 49].

2.3. Addressing Stand-off Distances in FDS in General

The main precondition for space modeling in FDS is the design of the *Computational grid. This grid is composed of computational cells* that are assigned dimensions. A single model can contain multiple computational grids, the cells of which should have consistent proportions if they are in contact. When implementing the FDS fire model into stand-off distance solutions, one computational grid is sufficient. The size of the computational grid is determined based on the number of openings to be considered, their sizes, and relative distances. The cell size of the computational grid should be configured to an appropriate ratio of 1:1:1, i.e., the cell should have the same dimensions in all directions to optimize calculations. Correct configuration of these initial parameters plays a vital role in the calculation of the transfer of heat, fire, and combustion products, which occur individually in the cells and simultaneously in the whole computational grid, to obtain the most accurate results and visualizations [44, 50].

The sides of the computational grid are defined as inert surfaces, i.e., they are not subject to chemical reactions, as is required when designing the stand-off distances. To model the space most accurately, it is also necessary to define all sides of the computational grid as open areas, except for one, which represents the inert surface and simulates the side containing the fire open areas. When considering both fully fire-open and partially fire-open areas within the stand-off distances, the surface of the assessed side can be modified. In such cases, a material analysis of the building would also be required. However, when examining the stand-off distances from the fully fire-open areas, a material analysis of structures is not necessary.

When addressing the stand-off distances from fully fire-open areas, the inert surface is equipped with openings, the so-called radiant surfaces, which simulate openings in the structures from which heat escapes by flow and radiation. The number and dimensions of the radiant surface depend on the actual number and dimensions of openings found in the assessed structure. The fire, the amount of heat leaked in the radiant surface, can be simulated by setting the temperature (°C) or the area heat flux density (kW/m^2). These parameters can be set as time variables or parameters with a constant value. When dealing with stand-off distances, it is preferable to use constant values, using the expected maximum quantity value achieved over the entire course of the fire. In determining radiant surface values using temperature, this temperature is defined based on the standard temperature curve (1), which is dependent on the standard fire duration τe (min) for production buildings**,** or equivalent to this value in terms of the calculated fire load for non-production buildings p_v (kg/m^{-2}). In determining radiant surface values using the area heat flux density, the value of this quantity is defined based on the equation (2), whose input data are derived from the standard temperature curve (1) and based on the equivalent fire duration time or calculated fire load [34, 51].

$$T_N = 20 + 345\log(8t + 1) \qquad (1)$$
$$q = (T_N + 273)^4.\ 5{,}67.10^{-11} \qquad (2)$$

where: T_N standard gas temperature in °C

t value of standard fire duration time τ_e (min) for production buildings, or equivalent to this value, the calculated fire load for non-production buildings, p_v (kg.m^{-2})

q area heat flux density (kW.m^{-2})

The stand-off distance is determined based on the quantity being measured by the measuring equipment. The FDS supports 11 types of devices that can be used to record quantities related to thermal exposure of surfaces. These devices can measure the individual components of energy transfer differently, or they may differ in their placement, either on a fixed surface or in the air. All devices are described in detail in the *Fire Dynamics Simulator User´s Guide, Chapter 22.10.12 Heat Flux* [44]. When dealing with stand-off distance solutions, the best course of action is to use the *Gauge Heat Flux Gas* device, which records both radiant and flowing heat components, and its placement is not dependent on the fixed surface – it can be positioned in open space. The number of these devices is optional but depends on the size of the fire open area, as well as the selected distance from the radiant surface. Estimating the distances of the devices from the radiant surface and the influence of other parameters on the measurement results are addressed in the sensitivity analysis.

To estimate the stand-off distance, the *Slice File Parameter* in the input file must be defined, which enables the recording of the selected quantities of the gas phase. In the case of stand-off distances, it is the total heat intensity radiating from the radiant surface. The said quantity is recorded through a plane set in the middle of the radiant surface, either vertically or horizontally, depending on how the stand-off distance will be measured. The standoff distance reference is based on the determination of the threshold value 18.5 kW.m^{-2} [32] and its 2D rendering in the already simulated space. FDS enables the design of the 3D scalar quantities of the gas phase, which can assist during the rendition of the stand-off distance in 3D. This rendition is carried out through the *Isosurface Parameter* command, which is assigned to record the total heat intensity in the space with an 18.5 kW·m^{-2} value. An example of stand-off distance rendition in FDS in 2D and 3D is provided in Figure 2.

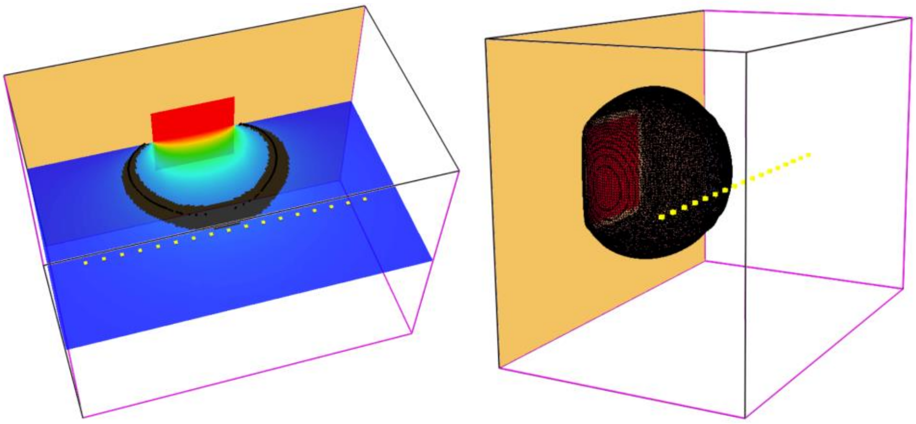

Figure 2.
Rendering of stand-off distances in FDS in 2D (left) and 3D (right).

2.3. Sensitivity Analysis

To apply fire models in practice and make them usable for determining separation distances from buildings, a significant number of simulations are required. These simulations should investigate the influence of individual input parameters on the overall computational time and the accuracy of determining the magnitude of the stand-off distance from the building. Such a procedure is called sensitivity analysis or validation. Based on the knowledge and experience with the FDS program, along with the information from the *Fire Dynamics Simulator User´s Guide* [44], the following parameters in the Table 1 have the greatest impact on the simulations' computational time, the accuracy of the readings and the size of the stand-off distances.

Table 1.
Description of the input parameters examined in the verification.

Parameter	Unit	Description
The size of computational cells	Depending on the cell dimension m, cm, mm	The size of computational cells in the computational grid
Path Length	meter (m)	This parameter is necessary for determining and recording the values of radiation transfer in the fire area. When calculating heat flux, this parameter indicates the distance between the fire and the measuring device (target).
Number of Radiation Angles	-	This parameter enhances the spatial and temporal accuracy of the discrete radiation transfer equation, thereby affecting the visualization of critical values in determining stand-off distances. The fewer the radiation angles, the more the visualization resembles a star (more pronounced star shape); conversely, the higher the number, the smoother the visualization of the critical value (resembling an oval).
Time Step Increment and Angle Increment	-	These parameters influence the frequency of the recorded radiation outputs. The default value of the time step increment is 3, and the angle increment is 5. Following this scenario, the radiation transfer equation is updated every 15 time steps, and the values are thus recorded. If both parameters' values equal 1, the values will be recorded every 1 time step.
Humidity	%	This parameter reaches values ranging between 0–100, the default value being 40%

Source: McGrattan, et al. [44]

The verification was focused on investigating the influence of the above-mentioned parameters on the overall computational time of the simulations (Chap. 2.3.1)and the size of the stand-off distances (Chap. 2.3.2).

2.3.1. Impact of Selected Parameters on the Simulations' Computational Time

The main simulation area was formed by a computational grid, with dimensions 3 (width) x 3 (length) x 2 (height) meters. The size of the computational cells was 5 x 5 x 5 centimeters; therefore, there were 60 computational cells in the width of the grid, 60 in length, and 40 in height. All sides of the computational grid, except for one, which represented the inert surface and contained the heat source, were defined as open areas. The heat source was a radiant surface with a constant temperature of 900°C, this value being equivalent to the calculated fire load, p_v = 45 kg.m^{-2}, which represents an average value of the said load in residential buildings. The radiant surface was dimensioned 1 x 1 m and placed in the centre of the inert surface. To record and examine the stand-off distances, a *Slice File Output* with a 1 m recording height, which represents the mid-height of the computational grid and thus the radiating surface as well, and an *Isosurface File*

Output with a recording value of 18.5 kW.m^{-2} were created. The area was then equipped with measuring devices. The device selected was the *Gauge Heat Flux Gas* since it can both flux and radiation and can be placed in the open area, i.e., it is not constrained by a fixed surface. Nine of said devices were placed at 1.4 m from the heat source with a mutual distance of 0.2 m. The simulation time has been set to 10 seconds. At approximately 6 seconds, the heat radiating from the source stabilizes. Nevertheless, the simulation time has been increased to 10 seconds to allow for possible variations in the radiation. In the basic model, parameters that do not influence the computational time of simulations, the precision of readings, and the length of the separation distances were left at the default values. An example of an input file is listed in Appendix A.

Based on the results stated in Table 2 describing the individual parameters, it can be said that only the *Path Length* parameter did not influence the simulation time, since all five simulations lasted 4 minutes and 10 seconds. The most significant change in simulation time was caused by the size of the computational cells, as the simulation with the thickest grid (75 mm) was completed in a few seconds, while the simulation with the finest grid (10 mm) lasted more than 30 hours.

The *Number of Radiation Angles* parameter also had a significant impact on the simulation's computational time. In this case, operating with 2,500 solid angles, the computational time varied up to 600%, with the default value of 400. Should the number of solid angles increase, so could the computational time. The question remains whether increasing the number of solid angles would still be necessary given the quality of the results, which may be the subject of further research.

Time Step Increment and *Angle Increment* significantly influenced the length of the simulation, i.e., up to +400%. With a time step increment and angle increment ratio of 3:5, the simulation lasted 4 minutes and 10 seconds, and with a ratio of 1:1, the simulation time was up to 17 minutes.

The relative air humidity had the lowest impact on the simulations' computational time, at only 27%. With the relative air humidity at zero, the simulation time was 4 minutes and 10 seconds, but with this parameter increased to a maximum (100%), the simulation time was 5 minutes and 45 seconds. Naturally, when determining the relative air humidity, it is necessary to consider the space that is being simulated and the conditions that are present in such space in the real environment, to prevent unnecessary deviation from reality and thus inaccuracies in the results.

Table 2.
Results of the influence of selected parameters on the computational time of simulations.

Tested Parameter	Range	Simulation Time		Change in Simulation Length
		Minimum	Maximum	
Cell Size	10, 25, 50, 75 mm	Seconds	Days	Simulation time from seconds to days
Path Length	0.1 – 3 m	4:10 min.	4:10 min.	0 %
Number of Radiation Angles	100 – 2 500	4:10 min.	28 min.	+ 600 %
Time Step Increment and Angle Increment	1:1 – 3:5	4:10 min.	17 min.	+ 400 %
Humidity	0 – 100 %	4:10 min.	05:45 min.	+ 27 %

2.3.2. Influence of Selected Parameters on the Length of the Stand-off Distances

The following section describes the influence of selected FDS parameters on the dimensions of monitored stand-off distances. Each parameter was assessed individually. In all the models presented, some input parameters were modified, while others remained unchanged. Parameters that were altered are discussed in the corresponding sections, whereas those that retained their default values are not addressed. The parameters that have not been modified in any of the models but need to be defined at the beginning are listed below:

- The basic model consists of five sides that form an open surface and one inert surface. Within this area, there is always a radiant surface representing a fully fire-open area. The size and number of radiant surfaces vary depending on the parameter in question, although their temperature remains constant at 900°C;
- The model includes a defined *Slice File Output*, positioned at the midpoint of the computational grid's height, and an *Isosurface File Output* with a recorded value of 18.5 kW·m^{-2}.
- *Gauge Heat Flux Gas* is the type of measuring device used throughout;
- The simulation's computational time is set to 6 seconds, since at this time point, the heat radiating from the source has already stabilized.

2.3.2.1. Time Step Increment and Angle Increment Parameter Influence

The set dimensions of the computational grid were 3 (width) x 3 (length) x 2 (height) meters, and the size of the computational cells was set to 5 x 5 x 5 centimeters. The source of heat was a 1 x 1 meter radiant surface placed in the center of the inert surface. Nine measuring devices were positioned 1.6 meters from the radiant surface, as the estimated stand-off distance based on precise calculations was 1.2 meters. There was a 0.2 meter relative distance between the devices. To assess the influence of altered *Time Step Increment* and *Angle Increment* parameters, 15 simulations were conducted. The *Time Step Increment* parameter ranged from 1 to 3, and the *Angle Increment* from 1 to 5, with all possible combinations of these parameters included in the simulations. Other simulation parameters not specified remained at the program's default values.

Based on the results found in Table 3, which lists the influence of selected parameters on the size of the stand-off distance in the FDS program, it can be said that this parameter did not influence the stand-off distances in any way. However, since these parameters affect the frequency of the recorded radiation outputs, it is recommended that their values in the simulations are not left at the default program values on the contrary, they should be changed to *Time Step Increment 1* and *Angle Increment 1* values, to record radiation every time step.

Table 3.
Results of the investigation of the influence of the Time Step Increment and Angle Increment parameters.

Time Step Increment	Angle Increment	Distance [m]		Difference
		Prescriptive Approach	FDS	
1	1	1.2	1.2	0%
	2		1.2	0%
	3		1.2	0%
	4		1.2	0%
	5		1.2	0%
2	1		1.2	0%
	2		1.2	0%
	3		1.2	0%
	4		1.2	0%
	5		1.2	0%
3	1		1.2	0%
	2		1.2	0%
	3		1.2	0%
	4		1.2	0%
	5		1.2	0%

2.3.2.2. Humidity Parameter Influence

When investigating the influence of the *Humidity* parameter, the basic simulation area was the same as in the *Time Step Increment* and *Angle Increment Parameter Influence* section of this paper. The investigation of this parameter used *Time Step Increment 1* and *Angle Increment 1* values. To monitor the influence of the selected parameter, 11 simulations were conducted, and the *Humidity* parameter was varied from 0% to 100% in 10% intervals. The other simulation parameters not mentioned remained at the program's default values.

Regarding the partial results, it must be mentioned that under normal conditions, the *humidity* ranges from 70% to 80%, although this value can vary depending on factors such as the weather or the time of year. Based on the results found in Table 4, for *humidity* values of 30%–50%, the resulting stand-off distance values determined from the FDS are identical to those determined by the prescriptive procedure, the calculation. As the *humidity* value decreases, the stand-off distance measured from the simulations increases by 15 cm, or 11%, compared to the prescriptive procedure. Conversely, as the *humidity* value increases, the overall stand-off distance from the radiant surface decreases compared to the prescriptive procedure; the difference can reach as many as 10 cm, which is 9%.

These results show that *humidity* influences the final stand-off distances determined by the FDS program. As a safety precaution, the best approach would be to use a *humidity* of 0% in simulations. However, it is always ideal to work with the estimated real value. In cases where this parameter cannot be accurately determined, the default value of 40% is recommended.

Table 4.
Results of the investigation of the influence of the parameter Humidity.

Humidity [%]	Distance [m]		Difference
	Prescriptive Approach	FDS	
0	1.2	1.35	11%
10		1.30	8%
20		1.25	4%
30, 40, 50		1.20	0%
60, 70, 80,90		1.15	-4%
100		1.10	-9%

2.3.2.3. Impact of Path Length and Number of Radiation Angles Parameter

The basic simulation space concerning the influence of the *Path Length* and *Number of Radiation Angles* parameters on the size of stand-off distances was comprised of a computational grid with dimensions of 4 (width) x 4 (length) x 3 (height) meters**.** The set size of the computational cells was 2.5 x 2.5 x 2.5 centimeters since it was assumed that the parameters could significantly impact the determination of the overall stand-off distance. Therefore, a smaller computational cell size was chosen for these simulations to obtain the most accurate readings possible. To determine the effect of changes in individual parameters on the resulting stand-off distance, baseline models were created with three different radiant surface sizes. These surfaces were always located in the center of the inert surface. Seventeen measuring devices were placed at various distances from the radiant surface, since the parameter under investigation, *Path Length*, represents the distance between the measuring device and the radiant surface. The mutual distance between devices was constant, i.e., 0.2 meters.

A total of 84 simulations were conducted to evaluate the impact of the specified parameters. Three variations in the size of the radiant surface were tested: 1 x 1 m, 1.5 x 1.5 m, and 2 x 2 m. For each variation, seven changes in the *Path Length* parameter were applied, resulting in combined variants. In the case of a 1 x 1 m radiant surface, *Path Length* values were determined by calculating the stand-off distance, which was set to 1.25 m. These values were then systematically increased and decreased from this baseline to explore the parameter's variability. For the 1.5 x 1.5 m surface, the stand-off distance was 1.85 m, establishing the basic *Path Length* value at 1.85 m. Similarly, for the 2 x 2 m surface, the stand-off distance was 2.5 m, and the basic *Path Length* was set accordingly. These adjustments ensured comprehensive assessment of the parameter variations for each surface size.

Along with monitoring and comparing the stand-off distance values in the combined radiant surface sizes and Path Length parameters, the *Number of Radiation Angles* parameter was also varied. As mentioned before, its default value is 400. Experience and information on the FDS programme have shown that the smaller the number of solid radiation angles, the less accurate the resulting stand-off distance values can be, although the resulting simulation time is shorter. Subsequently, four values of the *Number of Radiation Angles* parameter were selected in combination with other parameters, i.e., 500, 1,000, 1,500, and 2,000 radiation angles. Appendix B – Table B1 shows the simulation results.

Based on the above-mentioned results, it can be said that the *Number of Radiation Angles* parameter does not influence the value of the stand-off distance at the 2.5 x 2.5 x 2.5 cm computational grid. However, given the knowledge already gained about how the program works, it can be argued that this parameter may influence the way the program renders the stand-off distances concerning the shape of the final stand-off distance, i.e., whether it is more of an ellipse or a star in shape. In the case of star-shaped formations, the prominences could cause differences in stand-off distances ranging from 0 cm to 5 cm. Figure 3 shows the difference in the rendering of stand-off distances for the *Number of Radiation Angles* values.

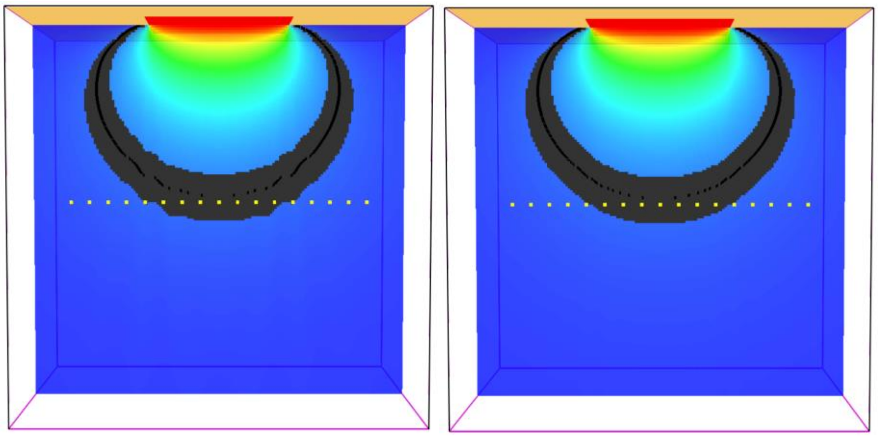

Figure 3.
The difference in rendering of stand-off distances for *Number of Radiation Angles* 500 (left) and 1,500 (right).

Further discoveries showed that the *Path Length* parameter has a demonstrable impact on the overall value of the resulting stand-off distance. The lower the value of *Path Length* in FDS, the lower the resulting stand-off value when compared to the value noted for the greater *Path Length*. The difference between the lowest and highest stand-off distance value from the FDS results with a 1 x 1 m radiant surface was 2.5%. For a 1.5 x 1.5 m radiant surface, the difference was 5.4%, and for a 2 x 2 m radiant surface, the difference was 3.2%. Moreover, it can be seen that the difference between the stand-off distance value obtained through exact calculation and the value obtained from the FDS ranged from 0% to 6%, reflecting a difference between 3 cm and 10 cm. Given the stated facts, it can be said that the higher the *Path Length* parameter value, the higher the value of the resulting stand-off distance. In terms of fire safety, this fact favors safety, although it is always better to be close to reality; thus, higher values of this parameter are desirable in simulations.

2.3.2.4. Impact of Computational Cell Size Parameter

Eighteen simulations were conducted to examine the influence of computational cell size parameters on the stand-off distances. These simulations were categorized into three primary groups based on the size of the radiant surface from which the stand-off distances were measured. The radiant surfaces measured 1 x 1 m, 1.5 x 1.5 m, and 2 x 2 m, respectively. Six simulations were performed for each surface type, utilizing various sizes of computational cells. Each area with different cell sizes was described individually, as the size of the computational grid was adjusted according to the cell sizes and their distribution. The descriptions of these individual simulation areas, based on the size of the computational cell, are listed in Table 5. Figure 4 shows the difference in the rendering of the area with the varied size of the computational cell's dimensions.

Table 5.
Simulation areas depending on the size of the computational cell's edge.

Size of the cell edge [mm]	Dimensions of the computational grid		
	Width [m]	Length [m]	Height [m]
25	4.0	4.0	3.0
30	3.99	3.99	3.0
35	3.99	3.99	2.94
40	4.0	4.0	3.0
45	3.96	3.96	2.97
50	4.0	4.0	3.0

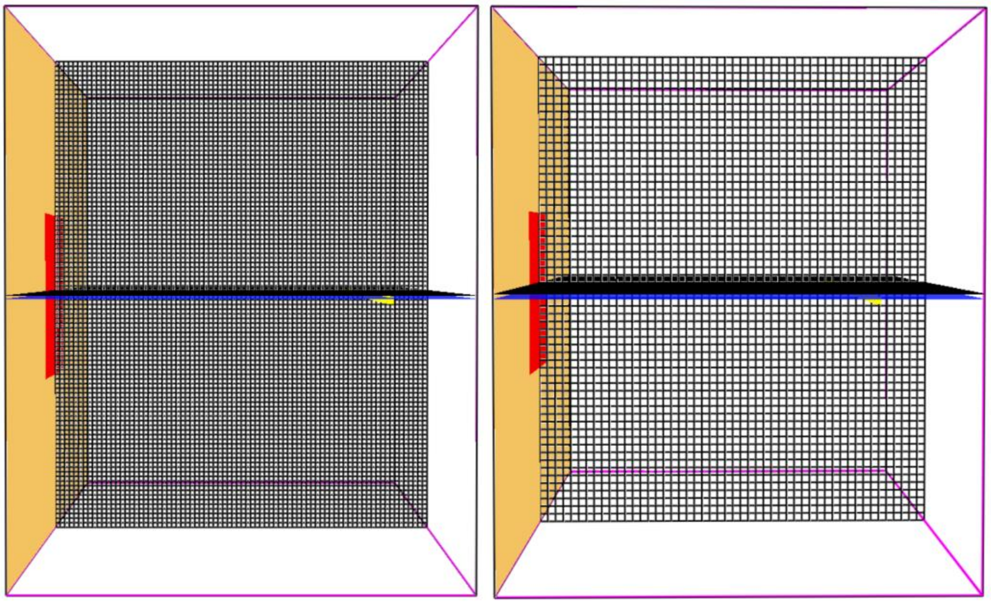

Figure 4.
Rendering of the area with varied sizes of the computational cell’s edge – 30 mm (left) and 50 mm (right).

Seventeen measuring devices were distributed in the area with a mutual distance of 0.2 m. The *Path Length* parameter for the given area always had a maximum value, which was adjusted to the largest dimensions of the computational grid, and the *Number of Radiation Angles* parameter had a value of 500. Table 6 shows the results of the investigation regarding the influence *Size of the computational cells* parameter on the space-off distances.

Table 6.
Results of the investigation of the influence of the parameter Size of the computational cells.

Opening [m]	Size of the cell edge [mm]	Distance [m]		Difference	Simulation Time [s]
		Prescriptive Approach	FDS		
1x1	25	1.25	1.20	-4%	23.5
	30		1.23	-2%	11.6
	35		1.23	-2%	6.0
	40		1.24	-1%	3.1
	45		1.26	1%	2.2
	50		1.25	0%	1.3
1.5x1.5	25	1.85	1.85	0%	27.0
	30		1.86	1%	12.0
	35		1.89	2%	6.3
	40		1.84	-1%	3.6
	45		1.85	0%	2.3
	50		1.85	0%	1.5
2x2	25	2.50	2.43	-3%	30.0
	30		2.43	-3%	12.3
	35		2.42	-4%	6.6
	40		2.44	-2%	4.0
	45		2.48	-1%	2.3
	50		2.45	-2%	1.6

Given the results presented in Table 6, it is possible to conclude that the size of the computational cells had a moderate influence on the size of the resulting stand-off distances. The differences varied from 0 to 7 cm, which constitutes a difference between 0% and 4% in the simulations we have defined. Given these results, it cannot be stated that shrinking or expanding the computational grid had a specific impact on the resulting stand-off distance, as no particular trend was observed that was repeated between simulations with different radiant surface sizes. However, regarding the presented results, it can be argued that the difference in the results of the stand-off distances may be caused by the size of the computational cells, since the results can be obtained only in the intervals of the computational cell sizes.

Based on the results presented in the *Impact of Selected Parameters on the Simulations' Computational Time* chapter, it is evident that the size of the computational cells significantly impacts the overall computational time of the simulations, which can range from seconds to days. However, since the effect of this parameter was investigated in the aforementioned chapter at default values of the other parameters, the total computational times of the simulations were examined from the output files of the individual simulations, which are listed in Table 6. This fact implies that the size of computational cells can extend the simulation time from 1.5 hours to more than a day, representing a twentyfold increase in computing time.

From these results, it can be assumed that the most appropriate size of computational cells to use in future simulations will be 5.0 cm, since no significant impact of changing this size was detected. This decision can also reduce the overall computational time of simulations, which is useful for the implementation of fire models in practice.

2.3.2.5. Impact of the Number of Measuring Devices Parameter

The dimensions of the model's computation grid were 4 (width) x 4 (length) x 3 (height) meters. The size of computational cells was set to 5 x 5 x 5 centimeters. These simulations were divided into three primary categories depending on the size of the radiant surface from which the stand-off distances were taken. The radiant surfaces measured 1 x 1 meter, 1.5 x 1.5 meters, and 2 x 2 meters, respectively. Seven simulations were created for each of these surface types, operating with various numbers of measuring devices and, therefore, different distances between them. The measuring devices were placed at the following numbers and distances from each other:

- Seventeen measuring devices, the distance between devices is 0.2 m;
- Fourteen measuring devices, the distance between devices is 0.25 m;
- Twelve measuring devices, the distance between devices is 0.3 m;
- Ten measuring devices, the distance between devices is 0.35 m;
- Nine measuring devices, the distance between devices is 0.4 m;
- Eight measuring devices, the distance between devices is 0.45 m;
- Seven measuring devices, the distance between devices is 0.5 m.

The devices were placed at a distance of 4.0 m, so the *Path Length* for the given area was at a maximum. The *Number of Radiation Angles* has been determined to be 500. Table 7 shows the results of the investigation regarding the influence of the number of measuring devices on the stand-off distance determination.

Table 7.
Results of the investigation of the influence of the parameter *Number of Measuring Devices*

Opening [m]	**Number of measuring devices**	**Distance between devices [m]**	**Distance [m]**	
			Prescriptive Approach	**FDS**
1x1	17	0.20	1.25	1.25
	14	0.25		1.25
	12	0.30		1.25
	10	0.35		1.25
	9	0.40		1.25
	8	0.45		1.25
	7	0.50		1.25
1.5x1.5	17	0.20	1.85	1.85
	14	0.25		1.85
	12	0.30		1.85
	10	0.35		1.85
	9	0.40		1.85
	8	0.45		1.85
	7	0.50		1.85
2x2	17	0.20	2.5	2.45
	14	0.25		2.45
	12	0.30		2.45
	10	0.35		2.45
	9	0.40		2.45
	8	0.45		2.45
	7	0.50		2.45

Following the results obtained from the simulations investigating the influence of the number of measuring devices on the resulting stand-off distance, it was concluded that the parameter does not influence stand-off distance results regarding the radiant surface for the given simulation parameters. Differences may occur if the simulation uses only 2 or 3 measuring devices or if the computational grid adjusts its cell size to e.g., 1 cm. In such cases, the determination of resulting stand-off distances could become subject to slight changes, but these should be considered mainly with the possibility of obtaining results in intervals of computational cell sizes. With significantly fewer measuring devices, there is a chance of inaccurate calculations and subsequent deviations in stand-off distance determinations. When investigating this parameter, the focus was on the overall computational time of simulations for different numbers of measuring devices. Following the results, it was determined that the number of measuring devices does not influence the simulations' computational time. In the simulations, the difference in said times did not exceed 5 minutes, which may have been caused by changes in the performance of the computer running the simulations.

2.4. Implementation of the FDS Fire Model into Practice

All results obtained from the sensitivity analysis needed to be processed, followed by the design of a general model for addressing stand-off distances from buildings using fire models. This model was created because, in a real space, the values of the stand-off distances can be verified on multiple openings simultaneously, either horizontally or vertically, not only on one singular opening. The designed model was used to verify the stand-off distance values according to STN 92 0201 – 4, Table 4 [32]. Thus, it is possible to confirm or disprove the correct setting of the fire model and the possibility of its implementation in practice in the Slovak Republic.

2.5. General Model for the Solution of Stand-off Distances

The general model for the solution of stand-off distances was comprised of a computational grid with dimensions of 8 (width) x 10 (length) x 5 (height) meters. The size of the computational cells was set to 5 x 5 x 5 centimeters, as this size is sufficient for obtaining accurate readings of the stand-off distances. For a given size of computational cells, there were 160 cells in the width of the grid, 200 in the length, and 100 in the height. The sides of the computational grid—except for one, which represented the inert surface and was equipped with a radiant surface—were defined as open areas simulating the exterior. The size of the radiant surface varied depending on the size values of fully fired open areas in STN 92 0201 – 4, Table 4 [32]. Following the standard, these openings were between 0.5 m and 4.5 m in length, and between 0.5 m and 3.0 m in height in all possible variants, while the change in lengths happened in 0.5 m intervals. The amount of heat radiating from the radiant surface was also determined by the standard and its specified values. Following the standard for openings, the fire risk is presented by values 10, 20, 30, 40, 50, 60, 80, 100, 120 and 180 $kg.m^{-2}$ or min., depending on the structure type [32]. The represented fire risk values were converted to temperature values (°C) according to equation (1).

A *Slice File Output* with a 2.5 m recording height was created to monitor and determine the stand-off distances, along with an *Isosurface File Output* with an 18.5 kW/m^{-2} recording height. Fifteen measuring devices, *Gauge Heat Flux Gas* specifically, were located in the area, with a mutual distance of 0.5 m. The devices were placed at two different distances from the radiant surface, depending on the estimated stand-off distance according to STN [32]. The *Path Length* parameter represents the distance of the measuring devices from the radiant surface, e. g. 5.5 m and 7.5 m.

The *Number of Radiation Angles* parameter was set to 500, *Time Step Increment*, along with *Angle Increment* parameters to a value of 1, following the conducted sensitivity analysis. The *Humidity* parameter has been left at the program's default value, e.g., 40%. The set duration of the simulations was 6 seconds.

3. Results

In total, up to 540 simulations were run to verify the stand-off distance values. Due to an extensive amount of data, Table 8 lists only several selected stand-off distance comparison values.

Table 8.
Resulting values of the comparison of stand-off distances according to STN and FDS.

Length of the opening [m]	Height of the opening [m]	Fire risk (pv [kg.m^{-2}] or te [min.])							
		10		**40**		**80**		**180**	
		678 °C		**885 °C**		**988°C**		**1,110 °C**	
		STN	**FDS**	**STN**	**FDS**	**STN**	**FDS**	**STN**	**FDS**
0.5	0.5	0.30	0.35	0.60	0.60	0.70	0.75	0.90	0.95
		14%		0%		7%		5%	
1.0	1.0	0.70	0.70	1.20	1.20	1.50	1.60	1.80	1.85
		0%		0%		6%		3%	
2.0	2.5	1.50	1.60	2.70	2.65	3.50	3.45	4.00	3.95
		6%		-2%		-1%		-1%	
3.0	2.5	1.90	1.85	3.30	3.25	4.30	4.15	4.90	4.70
		-3%		-2%		-4%		-4%	
3.5	2.0	1.80	1.85	3.50	3.50	4.60	4.45	5.30	5.05
		5%		0%		-3%		-5%	
4.5	3.0	2.50	2.55	4.40	4.70	5.40	5.20	6.60	6.10
		2%		-2%		-4%		-8%	

The results obtained from the simulations show that the FDS program is suitable for dealing with stand-off distances from fully fire-open areas, only when all input parameters are set correctly. The biggest difference – i.e., the FDS value was higher than the STN value – was 0.25 m and 0.3 m. These differences were recorded especially with larger openings representing a fully fire-open area **–** that is, the openings were 4.0 and 4.5 in length. Percentage-wise, these differences ranged from 8% to 19%. These differences may be explained as follows: if there is a difference in stand-off distances for smaller openings, where a smaller stand-off distance is assumed, then the proportional difference in measured values is greater than for larger openings, where a larger stand-off distance is assumed. For example, a 0.5 x 0.5 m opening with a fire risk value of 10 (678 °C) had a stand-off distance according to STN of 0.3 m and according to FDS of 0.35 m. Therefore, the difference was only 0.05 m, but that translates to up to 14%. The same difference, i.e., 0.05 m, was recorded at the 4.5 x 3.0 m opening with a fire risk value of 10 (678 °C). The stand-off distance following the standard was 2.5 m, and following the FDS was 2.55 m – the difference, therefore, being 2%. This difference phenomenon is observed throughout the assessment of stand-off distance values; thus, it was necessary to consider not only the resulting percentage value of the difference but also the value of the difference in metres.

There was also a difference between the values in a considerable number of cases, where the value of the resulting stand-off distance from the FDS was lower than the one in the standard. In such cases, the percentage difference was marked as negative. Similar outcomes can be observed mainly at openings with lengths of 1.5 m and higher. Concerning this case, the differences ranged from 0.05 m to 0.5 m, which translates to a 1–8% difference.

4. Conclusion

Based on the given results, it can be stated that fire models can be suitably incorporated into the solution of stand-off distances from the fully fire-open areas of fire safety solutions for buildings in Slovakia. Within this implementation, it is always necessary to consider all the variables involved in the problem of the solution that can affect it, even in the smallest way. For this reason, a sensitivity analysis was needed, which became the focus of this paper. The said analysis did not just concentrate on one particular case of solving the stand-off distances problem, but on solving the problem as a whole.

The first partial objective of the paper was to conduct a sensitivity analysis and determine the parameters that affect the output data. This objective has been fulfilled, followed by the determination of input parameters that influence the deduction of stand-off distances from the FDS program. The range within which the parameters influence the results was successfully identified, thus providing knowledge for a more efficient and accurate setting of individual input parameters for future use. Furthermore, it was possible to establish the basis for a general model regarding the solution of stand-off distances from fully fire-open areas. This model can be viewed as the first step in implementing fire models into the solution of stand-off distances in Slovakia, since using these models for fire safety in Slovakia is not supported by any legislation. Given the unique design of each structure, many cases require individual fire safety assessments—here, fire models could be of significant use.

The second partial objective of the paper was to verify the values of stand-off distances from the fully fire-open areas. This verification was possible based on the established general model. Based on the verification of the FDS, the values of the input parameters to the FDS model were determined, and then a general model of the spacing solution was developed:

- The size of the computational cells in the computational grid → 50 mm;
- Path Length → possible maximum;
- Number of spatial radiation angles (Number Radiation Angles) → 500;
- Time Step Increment and Angle Increment → 1:1;
- Relative humidity (Humidity) → 40%.

The general model was designed as the basis for continuing further research and thus achieving a more comprehensive take on the already mentioned objective.

Based on the results stand-off distance comparison according to FDS and STN 920201 – 4, Table 4 [32] values, it can be said that the established model provides a sufficient basis for the implementation of fire models into practice. Naturally, a considerable number of simulations still need to be run to specify and modify the various input parameters of the model to ensure that the general model approaches or fully reflects the actual conditions as closely as possible.

The objective defined at the beginning of the paper is considered fulfilled. The suitability of using fire models in solving a specific aspect of fire safety in Slovakia, namely, stand-off distances, has been demonstrated. Following the results of the validation and verification of the settings, it can be concluded that fire models are suitable for practical implementation in the Slovak Republic. Nevertheless, a considerable number of simulations still need to be conducted; therefore, further research is necessary to achieve broader objectives, such as the general implementation of fire models in practice rather than focusing on a single area.

Abbreviations

CFAST Consolidated Fire and Smoke Transport
FDS Fire Dynamics Simulator
STN Slovak Technical Standard

References

[1] K. Lu, L. Hu, M. Delichatsios, F. Tang, Z. Qiu, and L. He, "Merging behavior of facade flames ejected from two windows of an under-ventilated compartment fire," *Proceedings of the combustion institute,* vol. 35, no. 3, pp. 2615-2622, 2015.
[2] S. Gannouni, "Critical velocity for preventing thermal backlayering flow in tunnel fire using longitudinal ventilation system: Effect of floor-fire separation distance," *International Journal of Thermal Sciences,* vol. 171, p. 107192, 2022.
[3] W. Shannon, C. Anand, B. Shotorban, and S. Mahalingam, "Fire behavior in multiple burning shrubs separated horizontally and vertically," *Fire safety journal,* vol. 118, p. 103236, 2020.
[4] Z. Wang, L. Yu, and J. Ji, "Numerical investigation on the asymmetric flow characteristics of two propane fires of unequal heat release rate in open space," *Fire Technology,* vol. 57, pp. 2181-2203, 2021.
[5] Y. Li, Z. Kuang, Z. Fan, and J. Shuai, "Evaluation of the safe separation distances of hydrogen-blended natural gas pipelines in a jet fire scenario," *International Journal of Hydrogen Energy,* vol. 48, no. 49, pp. 18804-18815, 2023.
[6] B. RISK, "Design fire pool," 2023. https://www.branz.co.nz/fire-safety-design/b-risk/
[7] Fire safety regulatory framework, "Fire safety regulatory framework," 2023. https://fireandemergency.nz/businesses-and-landlords/building-and-designing-for-fire-safety/fire-safety-regulatory-framework/
[8] D. Pesic, D. Zigar, M. Raos, and I. Anghel, "Simulation of fire spread between residential buildings regarding safe separation distance," *Tehnički vjesnik,* vol. 24, no. 4, pp. 1137-1145, 2017.
[9] K. Dúbravská, Ľ. Tereňová, and D. Špilák, *Fire safety of buildings*. Zvolen, Slovakia: Technical University in Zvolen, 2024.
[10] Use of CFD in fire hazardous area prediction, "Use of CFD in fire hazard prediction," 2023. https://www.tzb-info.cz/pozarni-bezpecnost-staveb/23115-vyuziti-cfd-pri-predikci-pozarne-nebezpecneho-prostoru
[11] M. Kadlic and V. Mózer, "Impact of selected fire-modelling input parameters on the safe available evacuation," *Krízový manažment,* vol. 16, no. 1, pp. 5–13, 2017.
[12] M. Kadlic and P. Magdolenová, "Evaluation of selected input parameters in tunnel fire modelling," *Transportation research procedia,* vol. 40, pp. 1412-1417, 2019.
[13] M. Kadlic, "The impact of variability and uncertainty of input parameters on the quality of fire model outputs," Dissertation Thesis. University of Žilina, Faculty of Security Engineering, Žilina, Slovakia, 2019.
[14] D. Hodúlová, "Computer fire simulation," Bachelor Thesis. University of Žilina, Faculty of Security Engineering, Žilina, Slovakia, 2020.
[15] P. Magdolenová, "Advanced modelling of the impact of fire on building structures," Dissertation Thesis, University of Zilina, Faculty of Security Engineering, Zilina, Slovakia, 2021.
[16] D. Hodúlová, "Modelling car fires in confined spaces," Diploma Thesis, University of Zilina, Faculty of Security Engineering, Zilina, Slovakia, 2022.
[17] J. Zoleík, "Modeling of fires on the water surface during the passage of the KB-160 floating device," Diploma Thesis, University of Zilina, Faculty of Security Engineering, Zilina, Slovakia, 2022.
[18] Regulation No. 94/2004 Coll, "Decree of the ministry of the interior of the slovak republic establishing technical requirements for fire safety in the construction and use of buildings. Bratislava, Slovakia," 2004. https://www.zakonypreludi.sk/zz/2004-94
[19] STN 92 0201 – 3, *Fire safety in buildings -Escape routes and evacuation*. Bratislava, Slovania: Slovak Standards Institute, 2000.
[20] V. Mózer, *Fire safety of buildings*. Bratislava, Slovakia: Eurostav, 2017.
[21] E. Mračková, I. Chromek, Ľ. Tereňová, and I. Marková, *Protection against fires*, 2nd ed. Zvolen, Slovakia: Technical University in Zvolen, 2015.
[22] V. Reichel, *Preventing damage -designing for fire safety in manufacturing facilities - Volume 27 - part IV*. Prague: Česká Státni Pojišťovna: Czech Republic, 1989.
[23] D. Hodúlová and S. Gašpercová, "Solving spacing distances of a selected object using a prescriptive approach and modelling tools," *SPEKTRUM*, vol. 23, no. 2, pp. 7–10, 2023.
[24] Act No. 314/2001 Coll, "Act No. 314/2001 coll., on protection against fires. Bratislava, Slovakia," 2001. https://www.zakonypreludi.sk/zz/2001-314
[25] Regulation No. 121/2002 Coll, "Decree of the ministry of the interior of the slovak republic on fire prevention. Bratislava, Slovakia," 2002. https://www.zakonypreludi.sk/zz/2002-121
[26] Act No. 25/2025 Coll, "Building act. Bratislava, Slovakia," 2025. https://www.slov-lex.sk/ezbierky/pravne-predpisy/SK/ZZ/2025/25/
[27] Regulation No. 699/2001 Coll, "Decree of the ministry of the interior of the slovak republic on the provision of water for extinguishing fires in buildings. Bratislava, Slovakia," Regulation No. 699/2001 Coll, 2001.

[28] Eurocodes, "Eurocodes," 2025. https://www.normoff.gov.sk/stranka/661/eurokody/
[29] Introduction and use of Eurocodes in the Slovak Republic, "Introduction and use of eurocodes in the slovak republic ", 2025. https://www.sksi.sk/buxus/docs/statika_2009_balaz.pdf
[30] Results of the EU survey on electromobility and fire safety in buildings, "Results of the EU survey on electromobility and fire safety in buildings ", 2025. https://appo.sk/vysledky-prieskumu-eu-o-elektromobilite-a-protipoziarnej-bezpecnosti-stavieb/
[31] Report on the EU legislation, "Report on the EU legislation, building codes, guidelines on fire safety of EVs recharging infrastructure in covered and above ground parkings.," 2025. https://appo.sk/engine/wp-content/uploads/2024/09/Report-on-fire-safety-of-EVs-recharging-infrastructure-parkings.pdf
[32] STN 92 0201 – 1, *Fire safety of buildings - Fire risk, size of fire compartment*. Bratislava, Slovania: Slovak Standards Institute, 2000.
[33] STN 92 0201 – 2, *Fire safety of buildings - Building structures*. Bratislava, Slovania: Slovak Standards Institute, 2007.
[34] STN 92 0201-4, *Fire safety of buildings – Spacing distances* Bratislava, Slovakia: Slovak Standards Institute, 2000.
[35] STN 92 0400, *Water supply for firefighting*. Bratislava, Slovania: Slovak Standards Institute, 2005.
[36] STN 92 0202 – 1, *Equipment of buildings with fire extinguishers*. Bratislava, Slovania: Slovak Standards Institute, 1999.
[37] STN 92 0241, *Occupation of buildings by persons*. Bratislava, Slovania: Slovak Standards Institute, 2012.
[38] STN EN 1991 – 1 – 2 (73 0035), *Eurocode 1: Loads on structures - Part 1-2: General loads - Loads on structures subjected to fire*. Bratislava, Slovania: Slovak Standards Institute, 1991.
[39] ČSN 73 0802, *Fire safety in buildings. Non-production buildings*. Bratislava, Slovania: Slovak Standards Institute, 1995.
[40] D. Špilák, *Personal communication*. Zvolen, Slovakia: Technical University 2025.
[41] V. Mózer, "On the issue of probabilistic fire risk modelling," in *Proceedings of the Dealing with Crisis Situations in Specific Environments, Zilina, Slovakia, 20–21*, 2015.
[42] Computer Fire Models, "Computer fire models," 2025. https://www.interfire.org/res_file/firemod.asp
[43] Z. F. and G. A., *Fire safety and management awareness*. Sofia; Bulgaria: IntechOpen, 2020.
[44] K. B. McGrattan, S. Hostikka, R. McDermott, J. Floyd, and C. Weinschenk, *Fire dynamics simulator – user´s guide*. Gaithersburg, Maryland: NIST – National Institute of Standards and Technology, 2013.
[45] PyroSim User Manual, "PyroSim user manual," 2025. https://support.thunderheadeng.com/docs/pyrosim/2024-2/user-manual/
[46] D. Peacock, K. B. McGrattan, G. P. Forney, and P. A. Reneke, *CFAST – consolidated fire and smoke transport (Version 7)*. Gaithersburg, Maryland: National Institute of Standards and Technology, 2015.
[47] H.-Y. Jang and C.-H. Hwang, "Evaluation of available safety egress time (ASET) in performance-based design (PBD) using CFAST," *Fire,* vol. 7, no. 4, p. 108, 2024.
[48] Autodesk CFD, "Autodesk CFD: Simulation software for engineering complex liquid, gas, and air systems," 2025. https://www.autodesk.com/products/cfd/overview?term=1-YEAR&tab=subscription
[49] P. Weisenpacher, J. Glasa, and L. Valasek, "Investigation of various fire dynamics simulator approaches to modelling airflow in road tunnel induced by longitudinal ventilation," *Fire,* vol. 8, no. 2, p. 74, 2025.
[50] H. Chen *et al.*, "Numerical simulation of passenger evacuation and heat fluxes in the waiting hall of an ultralarge railway station Hub," *Fire,* vol. 7, no. 6, p. 174, 2024.
[51] ISO 834-11, *Fire resistance tests - Elements of building construction*. Geneva, Switzerland: International Organization for Standardization, 2014.

Appendix A.

```
&HEAD CHID='basicmodel'/
&TIME T_END=10.0/
&DUMP DT_DEVC=1.0, DT_RESTART=5.0/
&MESH ID='room', IJK=30,30,20, XB=0.0,3.0,0.0,3.0,0.0,2.0/
&SURF ID='FIRE', COLOR='RED', TMP_FRONT=900/
&VENT ID='o1', SURF_ID='OPEN',XB=0.0,0.0,0.0,3.0,0.0,2.0/
&VENT ID='o2', SURF_ID='OPEN',XB=0.0,3.0,3.0,3.0,0.0,2.0/
&VENT ID='o3', SURF_ID='OPEN',XB=0.0,3.0,0.0,0.0,0.0,2.0/
&VENT ID='o4', SURF_ID='OPEN',XB=0.0,3.0,0.0,3.0,2.0,2.0/
&VENT ID='o5', SURF_ID='OPEN',XB=0.0,3.0,0.0,3.0,0.0,0.0/
&VENT ID='fire1', SURF_ID='FIRE',XB=3.0,3.0,1.0,2.0,0.5,1.5/
&DEVC ID='ghfg1', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,0.7,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg2', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,0.9,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg3', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,1.1,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg4', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,3.1,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg5', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,5.1,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg6', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,7.1,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg7', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,9.1,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg8', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,2.1,1.0, ORIENTATION=1.0,0.0,0.0/
&DEVC ID='ghfg9', QUANTITY='GAUGE HEAT FLUX GAS',XYZ=1.4,2.3,1.0, ORIENTATION=1.0,0.0,0.0/
&SLCF QUANTITY='INTEGRATED INTENSITY', VECTOR=.TRUE., CELL_CENTERED=.TRUE., ID='ID',
PBZ=1.0/
&ISOF QUANTITY='INTEGRATED INTENSITY', VALUE=18.5/ &TAIL/
```

Appendix B.

Table B1. Results of the investigation of the influence of the Path Length and Number of Radiation Angles Parameters.

Opening	Pathlength [m]	Distance [m] Prescriptive Approach	Number Radiation Angles 500 Distance [m] FDS	Difference	Number of Radiation Angles 1000 Distance [m] FDS	Difference	Number of Radiation Angles 1500 Distance [m] FDS	Difference	Number of Radiation Angles 2000 Distance [m] FDS	Difference
1x1	0.50	1.25	1.20	-4%	1.20	-4%	1.20	-4%	1.20	-4%
	0.75		1.23	-2%	1.23	-2%	1.23	-2%	1.23	-2%
	1.00		1.23	-2%	1.23	-2%	1.23	-2%	1.23	-2%
	1.25		1.23	-2%	1.23	-2%	1.23	-2%	1.23	-2%
	1.50		1.23	-2%	1.23	-2%	1.23	-2%	1.23	-2%
	1.75		1.23	-2%	1.23	-2%	1.23	-2%	1.23	-2%
	2.00		1.23	-2%	1.23	-2%	1.23	-2%	1.23	-2%
1.5x1.5	0.40	1.85	1.75	-6%	1.75	-6%	1.75	-6%	1.75	-6%
	0.90		1.80	-3%	1.80	-3%	1.80	-3%	1.80	-3%
	1.40		1.80	-3%	1.80	-3%	1.80	-3%	1.80	-3%
	1.90		1.83	-1%	1.83	-1%	1.83	-1%	1.83	-1%
	2.40		1.83	-1%	1.83	-1%	1.83	-1%	1.83	-1%
	2.90		1.83	-1%	1.83	-1%	1.83	-1%	1.83	-1%
	3.40		1.85	0%	1.85	0%	1.85	0%	1.85	0%

Table B1. Results of the investigation of the influence of the Path Length and Number of Radiation Angles Parameters (continuing).

Opening	Pathlength [m]	Distance [m] Prescriptive Approach	Number Radiation Angles 500 Distance [m] FDS	Difference	Number of Radiation Angles 1000 Distance [m] FDS	Difference	Number of Radiation Angles 1500 Distance [m] FDS	Difference	Number of Radiation Angles 2000 Distance [m] FDS	Difference
2x2	1.00	2.50	2.35	-6%	2.35	-6%	2.35	-6%	2.35	-6%
	1.50		2.38	-5%	2.38	-5%	2.38	-5%	2.38	-5%
	2.00		2.40	-4%	2.40	-4%	2.40	-4%	2.40	-4%
	2.55		2.43	-3%	2.43	-3%	2.43	-3%	2.43	-3%
	3.00		2.43	-3%	2.43	-3%	2.43	-3%	2.43	-3%
	3.50		2.43	-3%	2.43	-3%	2.43	-3%	2.43	-3%
	4.00		2.43	-3%	2.43	-3%	2.43	-3%	2.43	-3%