applied sciences

MDPI

Article

Fire Models as a Tool for Evaluation of Energy Balance in Burning Space Relating to Building Structures

Marianna Tomaskova [1,*], Jiri Pokorny [2], Petr Kucera [2], Michaela Balazikova [1] and Daniela Marasova, Jr. [3]

[1] Department of Safety and Production Quality, Faculty of Mechanical Engineering, Technical University of Kosice, Letna 9, 042 00 Kosice, Slovakia; michaela.balazikova@tuke.sk
[2] Faculty of Safety Engineering, VSB-Technical University of Ostrava, Lumirova 630/13, 700 30 Ostrava-Vyskovice, Czech Republic; jiri.pokorny@vsb.cz (J.P.); petr.kucera@vsb.cz (P.K.)
[3] Faculty of Mining, Technical University of Kosice, Park Komenskeho 19, 040 01 Kosice, Slovakia; daniela.marasova.2@tuke.sk
* Correspondence: marianna.tomaskova@tuke.sk

Abstract: Fire is defined as an extremely hazardous event, causing a threat to life and health of persons, but also damage to the economic sphere. It has been shown many times that fire can occur anywhere and at any time. In order to minimize the risk of fire manifestations, it is necessary to understand its course. In technical practice, computational models are used to determine the partial manifestations of fire, such as fire spread rate, smoke generation rate in the burning area, formation of toxic burning products, flame height, and others. One of the important characteristics is also the energy balance in the burning area relating to the character of burning material, access of oxygen necessary for exothermic reaction of burning, and reaction of the installed safety devices. In this paper we will point out the fire safety of the building. The FDS (Fire Dynamics Simulator) model is recently used in practice, and its advantage is the possibility to model fire even in large and atypical spaces. The contribution of this paper is the practical application of fire safety of construction using the FDS Model, to reduce the cost of fire safety for the structure being constructed. Attention was paid to evaluating how the heat energy that is released during a fire can be influenced by the installed stable fire-extinguishing equipment, taking into consideration the fire resistance of the building structures.

Keywords: fire simulation; building fire safety; prevention

check for updates

Citation: Tomaskova, M.; Pokorny, J.; Kucera, P.; Balazikova, M.; Marasova, D., Jr. Fire Models as a Tool for Evaluation of Energy Balance in Burning Space Relating to Building Structures. *Appl. Sci.* **2022**, *12*, 2505. https://doi.org/10.3390/app12052505

Academic Editors: Cesare Biserni and Asterios Bakolas

Received: 18 January 2022
Accepted: 25 February 2022
Published: 28 February 2022

1. Introduction

Fires cause loss of life, property, and natural ecosystems every year, so it is important to study them to prevent or limit the occurrence of potential fires. The basic principle of fire prevention is to create and develop the conditions to ensure effective protection of life and health of persons and property from fires, as well as their effective management, including the provision of assistance during such events. The area of fire prevention and the provision of basic fire prevention measures is currently addressed in a number of ways, in particular, the roles, responsibilities, and competences contained in fire protection legislation. Computer simulation of fires makes it possible to test different fire scenarios and to model the course and consequences of a fire under different conditions, to detect possible risks and circumstances that may lead to damage, and, where appropriate, to reduce the consequences of potential future fires. It is also one of the ways to minimize the consequences of fire and contribute to the fire safety of buildings [1].

Fires and firefighting interventions at fires represent a high cost to government budgets each year. They cause secondary damage that can be more severe than the direct consequences of fire, for example, by limiting infrastructure by closing off areas damaged by fire.

Sustainable development of the territory is also significantly related to the safety of the buildings located in the territory. The requirements for ensuring the safety of buildings within the European Union are based in particular on Regulation (EU) No 305/2011 of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. Among the characteristics that buildings must meet are fire safety requirements. These requirements include maintaining the load-bearing capacity of the structure in the event of fire, limiting the spread of fire inside and outside the building, ensuring the evacuation and rescue of persons, and ensuring the safety of rescue units [2].

To assess compliance with the specified requirements, it is necessary to characterize the development of the fire. The development of a fire is usually described by four phases, which include the initial (initiation) phase, the development phase, the fully developed phase, and the burn-out phase. All phases of a fire can be described by fire parameters, the most significant of which include fire area, fire perimeter, linear rate of spread, rate of flare-up of materials, flame height, flame temperature, heat release rate, heat flux density, and others. Using the fire phases and their parameters, the dynamics of the developing fire and its predicted effects on the surrounding environment, i.e., the building structure, can be described [3–6].

Smoke is produced and spread during a fire, which also has negative consequences. Toxic substances present in smoke can cause poisoning of people in smoke-infested buildings in confined spaces.

The presence of smoke reduces visibility and, therefore, the ability to orient oneself in space, which can make it significantly more difficult or impossible to find escape routes and, as a consequence, cause panic among people escaping. Fire is a phenomenon that involves many physical and chemical processes such as the propagation of radiation, combustion, heat radiation, turbulent flow of gases, and others. Due to the intensification of fire, it is necessary to study the course of fire and its consequences, to seek means of increasing the safety of objects threatened by fire.

The course of a fire can be determined by standardized or specific procedures. Standardized procedures may include computational or experimental approaches presented by technical standards [7]. Specific procedures can be understood as the use of methods other than standardized methods. Fire models that can be used to describe, in part or comprehensively, the course of a fire are used here [8].

Computer simulations of fire based on empirical and scientific knowledge are comparable to real fire experiments. A significant advantage in comparison to fire tests is the non-destructiveness and flexibility of fire simulations. A fire can be modeled in an identical space under different conditions (e.g., with different fire initiation sources) without major costs. Computer simulation, fire progression, and consequence modeling are an important part of improving fire safety [9].

One of the crucial properties of building structures is their fire resistance, i.e., the time for which the building structures are able to resist the effects of fire. There are various high quality and effective products and systems that ensure the integrity and load-bearing capacity of the affected structures, before the action of fire or its spread, for the period of evacuation of the building.

In terms of fire resistance of building structures, in the event of a fire, the building and its equipment must provide:

- load-bearing capacity for the period specified in the project;
- the ability to limit the spread of fire and smoke in the building;
- the ability to limit the spread of fire to adjacent buildings;
- the possibility of evacuating people from the building;
- the safety of the emergency services.

Fire resistance is a rate of a building's durability in the event of a fire. The measure of fire resistance is the time (in minutes) from the first contact of the system with fire until it reaches one of the three limiting criteria:

- fire load capacity—R;
- integrity thermal insulation capacity—I [10].

Simulation and training technologies offer new opportunities to improve the quality of, for example, teaching at universities. The introduction of new progressive teaching is based on simulation and situational methods. Simulation methods create the playful character of the situation without the confrontational character as it is in reality. It facilitates students to move forward and gain insight. Situational methods are problem-solving procedures of model situations. Their basis is based on actual emergencies or crises that have happened in the past. Article [11] emphasizes the use of simulations in preparing students to handle emergencies at the tactical, operational, and strategic management levels [11].

The present shows that it is also necessary to observe the manifestations and behavior of past fires. By studying documentation of past fires, it is possible to predict under what circumstances a fire will occur in a similar environment and under similar conditions, how it will spread, and how it can be located and extinguished as quickly as possible. Nevertheless, the spread of a fire is influenced by a number of other circumstances and parameters, such as climatic conditions (temperature, airflow, ventilation, humidity, pressure), environment (interior, exterior, obstructions, openings), fuel type, and quantity. Therefore, it should be noted that in approximately the same environment a fire may behave differently, and, thus, based on knowledge from past fires, it is only possible to determine the occurrence and spread of potentially threatening fires approximately, even for buildings and conditions of similar types.

The working environment, temperature changes and humidity must be controlled in all production processes and places where employees are present. Paper [12] objectively assessed employee exposure to microclimatic environmental factors in the workplace. The data were collected in real working conditions. Thermal stress due to cold and heat exposure at each location was assessed using the wet bulb globe temperature (WBGT) indicator. Indoor air quality indicators consist of indoor temperature, air quality, lighting, dust levels, as well as chemical and biological factors. These data can also be used in fire simulation [13].

Fires in a confined space are common emergencies in our company. However, the difficulty of dealing with this complicated emergency situation by fire and rescue personnel can have fatal consequences for their employees. There is, therefore, a significant demand for new methods and technologies to deal with this life-threatening emergency. Modeling and simulation techniques have been adopted to conduct research due to the complexity of obtaining a database of actual cases related to this phenomenon. Paper [14] reviews the literature related to modeling and simulation of shelter fires with respect to the fire-jumping phenomenon. Furthermore, the related literature for comparing thermal camera images with computed images is summarized. Finally, the suitability of Artificial Intelligence (AI) techniques for predicting the fire jumping in closed premises is investigated [14].

The objective of the research in [15] is to solve the problem of fire evacuation from a student house using a numerical method. In research with an evacuation function (FDS + Evac.), Fire Dynamics Simulator software was used. The problem being investigated is related to a building that has an outdoor center. The building features include five floors, with two exterior fire staircases located on two sides of the building. In addition, there is a single exit to the exterior of the building, and the fire suppression system is not installed inside the building.

Among various types of disasters, fire poses a significant threat to life and property in urban and rural areas. Protection of hospitals from fire is very important due to the presence of affected persons, lack of awareness, and expensive apparatuses and devices in hospitals. This study focused on the simulation of fire in a hospital [16]. In daily life, emergency services such as firefighters, paramedics, and police play an important role. Rescuers often forget about their own safety in their work. Overall, this issue is neglected in these services, especially during the actual intervention. In many cases, it is the imperfect process of each rescue activity, or even the failure to use personal protective equipment. In [17], a group of fire and rescue officers is specified, which respects the basic rules of OHS in their activities such as fires, road accidents, natural disasters, and many others.

According to [18], mathematical models of fire have two main areas of their use. First, it is the design and verification of the fire safety of a building and next, they are a tool for simulating the development of a fire in the time interval between the occurrence of a fire and its extinction. One of the essential capabilities of mathematical models is the simulation of smoke movement and the determination of its temperature and concentration. Evidence of this capability is provided by simulations of buildings such as the Xanadu shopping and entertainment center in Spain, the mass garages in Annecy, France, or the Wembley stadium. In the Czech and Slovak republics, mathematical models are mainly used for this purpose in the design of railway and road tunnels.

Innovativeness of this article is based on the following aspects: on the methodological procedure used for creation of the fire scenarios and on the subsequent specification of design fires and on their assessment by three basic variants, i.e., by the simplified analysis, by the mathematical zonal model CFAST, and by the mathematical model of computational fluid dynamics FDS. These procedures were applied to various types of operations, which are characterized by different fire dynamics, assuming simultaneous acting of the sprinkler fire extinguisher. The authors do not dispute that mathematical modeling of fire is, nowadays, an actual trend in solving some of the problematic areas of fire safety for buildings. However, the authors emphasize in the presented case study a relevant fact: just the combination of mathematical modeling of fire with the simultaneous application of active fire-extinguishing equipment is a progressive solution that can lead to significant economic savings in solving of these buildings. This solution is suitable, especially in complicated operations.

The authors demonstrate, on a presented case study, a perspective of the fire model application in the real process of building projection using active elements of the fire protection (in this case, it is the sprinkler protection).

1. Mathematical Models for Reconstruction and Investigation

The aim of the paper is to present a case study that demonstrates the perspective of using fire models for fire resistance assessment of building structures. The main idea of this case study is the evaluation of energy balance in the burning area and influence of the installed stable fire-extinguishing equipment on the energy balance, taking into consideration fire resistance of the building structures. The presented study confirms a fact that in addition to the standard proposal procedures it is meaningful to use the simplified calculations, but above all also the mathematical models of fire. In the cases when a stable fire-extinguishing system is also installed, more detailed evaluation procedures (i.e., simplified calculations or fire models) can lead to a significant reduction in the costs necessary to ensure the required fire resistance of the building structures, while maintaining their defined properties.

2. Materials and Methods

The fire resistance of building structures may be assessed by test, calculation, or a combination of both. With nominal or parametric temperature curves, simplified and improved fire models are used for thermal analysis of structures. For the purpose of the case study, the different variants usable for the assessment of the fire resistance of building structures will be described below. The described variants present standard procedures and specific procedures. At the same time, the procedures that were used in the case study are presented.

2.1. Fire Resistance of Structures Determined by Nominal Temperature Curves

Fire resistance tests of building structures are carried out in accredited laboratories where temperature curves are used. Nominal temperature curves include the standard temperature curve, the external fire curve, the hydrocarbon curve, and the slow fire curve [19]. The norm temperature curve has the widest use.

The norm temperature curve has an empirical basis; it is also referred to as the "cellulose curve" and simplistically describes the situation after the total ignition of substances in space. Specific temperature curves are used for specific buildings where a significantly different temperature evolution of the fire development can be assumed. Characteristic curves are, e.g., tunnel temperature curves RABT or RWS.

2.2. Fire Resistance of Structures Determined by Parametric Temperature Curves

Parametric temperature curves are a simple calculation method that determines the temperature history of a fire for different ventilation coefficients, fire load densities, and different physical properties of the structures bounding the fire compartment. The equations for determining the parametric temperature curves were derived based on the thermal equilibrium equation, which describes the overall temperature balance in the space where the fire develops.

The use of parametric temperature curves is very limited, and their use is recommended only for fires with cellulose-type fire loads and for relatively small spaces (up to 500 m^2 of floor area with a maximum clearance of 4 m). It is also possible to apply them to fire compartments with horizontal openings in floors or ceilings [19,20].

2.3. Simplified and Improved Fire Models

Simplified fire models represent simple computational techniques for describing fire, based on the determination of a design fire load value that takes into account the density of the characteristic fire load and coefficients reflecting the influence of the fire hazard and the influence of active fire safety equipment [21].

A uniform or non-uniform distribution of temperatures as a function of time is assumed. Unequal temperature distribution is characteristic of the phases of fire development.

A uniform temperature distribution generally corresponds to a fully developed fire situation. There is presented, as an example of the simplified fire model, a calculation of heat release rate without influence of fire extinguishing (i.e., without activation of the sprinkler protection or without intervention of fire brigade etc.). This example is based on a simplified description of fire development, which is divided into three main phases.

The fire growth phase—this first phase is usually described in a simplified form by means of t-quadratic equation, which is applied in the modified form [7]:

$$Q = 10^3 \left(\frac{t}{t_\alpha} \right)^2, \tag{1}$$

where Q is heat release rate (kW),

t time (s),
t_α time interval, which is necessary to reach the heat release rate value 1 MW (s).

The fully developed fire phase—the second phase is characterized by the reached maximum value of the released heat (i.e., by its constant value), whereby the fire in this phase is controlled either using ventilation or by amount of fuel) [3,7].

An example of fire, which is controlled by the amount of fuel, is presented by calculation of the heat release rate value Q (kW), according to the following relation:

$$Q = RHR_f \cdot A_{fi}, \tag{2}$$

where A_{fi} is maximum area of fire (m^2),

RHR_f maximum heat release rate produced by 1 m^2 of fire, which is controlled by the amount of fuel (kW·m^{-2}).

The case of fire, which is controlled using ventilation, is illustrated by calculation of the maximum heat release rate $Q_{\max}$ (MW), as follows:

$$Q_{\max} = 0.10 \cdot \mathrm{m} \cdot H_u \cdot A_v \sqrt{(h_{eq})} \tag{3}$$

where m is coefficient of burning (-), usually m = 0.8,

H_u the pure calorific value of wood (MJ·kg^{-1}), H_u = 17.5 MJ·kg^{-1},
A_v area of nozzles (m^2),
h_{eq} average height of nozzles (m).

The burning-out phase—the last phase is typically a linear decrease. This phase begins after burn-out of 70% fire loading, and it is finished in the moment of complete burn-out.

Advanced fire models are fire models based on the assessment of changes in energy, mass and momentum in the space where the fire develops. These include single-zone models, two-zone models, and Computational Fluid Dynamics (CFD)-based models [21].

2.4. Fire Models Selected for the Case Study

It is essential to select the appropriate fire model for each task. The choice of the model is closely related to the following areas:

- the objectives of the solution (evaluation);
- the extent and quality of the input data;
- the extent and quality of the required output data;
- visualisation quality requirements;
- the characteristics of the model and its potential to address the stated objectives.

The Model of Fire and Smoke Transport (CFAST) and the Fire Dynamics Simulator (FDS) were chosen for further evaluation. The CFAST and FDS models enable to perform simulations when entering different sources of fire. In this case, the so-called t-square fire was used, which is characterized by different fire dynamics for various groups of production and operations. However, this is only one option. As was previously mentioned, the used fire models allow to perform simulations for different fire sources. In general, it is possible to use more centers of fires, not just only one. It can be stated that only the fire model FDS enables to distinguish the different sources of fire, for which it also allows to perform a parallel calculation, i.e., it enables to apply more than one processor in the calculation process.

Of course, each of the fire models has its own specific advantages and disadvantages. The type of the solved task, the scope and quality of the input data, and the required scope and quality of the input data are the decisive aspects necessary for a proper choice of the suitable fire model. The fact whether the model is currently being developed and verified on a long-term basis is absolutely substantial. When evaluating the performance of the fire models (this affects the choice of the model itself), it is also necessary to take into account the basic attributes on which the model is based, i.e., what kinds of the sub-models are used in order to solve the sub-processes and what are the limits of the model. In their response, the authors presented only the basic aspects related to the choice of a suitable model and to assessment of its performance.

The turbulence was simulated using the Large Eddy Simulation (LES) method. The "most used" mathematical CFD fire model—the FDS program—is based on this approach.

CFAST is a two-zone fire model used to calculate the evolving distribution of smoke, fire gases and temperature throughout compartments of a building during a fire. These can range from very small containment vessels, on the order of 1 m^3 to large spaces on the order of 1000 m^3 [22,23].

The modeling equations used in CFAST take the mathematical form of an initial value problem for a system of ordinary differential equations (ODEs). These equations are derived using the conservation of mass, the conservation of energy (equivalently the first law of thermodynamics), the ideal gas law and relations for density and internal energy. These equations predict as functions of time quantities such as pressure, layer height and temperatures given the accumulation of mass and enthalpy in the two layers. The CFAST model then consists of a set of ODEs to compute the environment in each compartment and a collection of algorithms to compute the mass and enthalpy source terms required by the ODEs [22–24].

Fire models based on Computational Fluid Dynamics [24] are widely used for the assessment of fire development. One of the most promising models based on this foundation is the FDS model. The model was developed at the National Institute of Standards and Technology in the USA [25] in collaboration with the Technical Research Centre of Finland in Finland [13]. The FDS model has been validated during its development and is also now being further developed.

To facilitate the work, it is possible to use the graphical interfaces PyroSim [14] or Blender FDS [15].

FDS solves numerically the Navier–Stokes equations for temperature-controlled flow, with emphasis on heat and smoke transfer from the fire.

The FDS program applies the so-called network method for a numerical solution of the partial differential equations. This method is very robust, but it requires a regular network. Creating of a quality calculation network is a basic prerequisite for a quality CFD simulation. For the solved type of the task, it is possible to consider the edge length of the computing cell in tens of centimeters. For this study, the calculation network with the dimensions 10 cm $\times$ 10 cm $\times$ 10 cm (cubic shape) was chosen in the FDS program. This network is considered to be the most suitable and optimal for the simulation process, and at the same time it allows numerically approximate the fire well enough in terms of spatial scale. The choice of network for purposes of this study was, therefore, optimal in order to achieve the right results. In the cases where it is not defined a calculation network suitable with regard to the simulation, the results obtained from the simulation can be significantly "misrepresented".

It is a model that allows to simulate many fire parameters, e.g., determination of the heat release rate and its sub-fractions, the flow of gases induced by the fire, determination of the concentration of substances released by the fire, etc. The model can be used to simulate fires in various objects, e.g., buildings or technical equipment (e.g., cars). All input data are entered by means of a single text input file. The output is multiple files where the output data are stored. The model can be visualized with Smokeview (SMV) software [11].

2.5. Description of the Case Study

2.5.1. Characteristics of Operation

The contribution of fire models to the assessment of the fire resistance of building structures is described by a case study of a manufacturing plant where steel platforms are located.

The production plant is a large-scale automotive paint shop. In the production area, there are paint lines that run longitudinally through the space under evaluation. The lines are a large-scale painting and drying facility.

Walking platforms are located in the production area to allow people to traverse the installed production equipment. Each of the platforms has plan dimensions of 16/16 m and a clear height of 5.5 m. The supporting structure of the platforms consists of vertical steel columns and horizontal steel beams. The ceiling walkway structure consists of sheet metal. The perimeter structures of the platforms are open.

The platforms are designed for the movement of employees during normal operation. In the event of a fire, the platforms are also designed for the intervening firefighters.

The platforms have the character of structures that do not ensure the stability of the whole building. Due to their use by firefighting units in the event of a fire, it is necessary to ensure the fire resistance of the load-bearing structures of the platforms for the duration of the ongoing intervention, i.e., for 30 min.

The production plant is equipped with a number of fire safety devices. Among the most important are an electrical fire alarm and fixed sprinkler fire-extinguishing equipment. Fire-extinguishing equipment is located in all areas of the production plant and also under the ceiling structures of the platforms.

2.5.2. Design Fire Scenario and Design Fire

The set of possible scenarios, characterized by their probability of occurrence and expected consequences, is understood as design fire scenarios. The process of selecting fire scenarios is referred to as qualitative analysis from a fire engineering perspective. From the overall set of scenarios, the scenarios to be further evaluated are selected. As a rule, these are the scenarios with the highest probability of occurrence or the highest consequences.

A design fire is a quantitative description of the selected design fire scenarios. It is usually an expression of the heat release rate and its components, the density of the heat release rate, the temperatures, the amount of smoke generated, the pressure ratios, etc. [3,4].

The stability of the platforms was evaluated on the basis of the expected fire development in the production plant, which can be described by the so-called characteristic fire types [3,5,6].

The fire types were determined for different “groups of production and operations”, which are characteristic in the design of buildings of production facilities in the Czech Republic. Operations in production buildings are divided into seven groups (1 to 7), with the eighth group consisting of auxiliary non-production operations that also occur in production buildings (e.g., dressing rooms, sanitary facilities, offices) [26,27]. In general, as the value of the production operation increases, the amount of combustible substances increases and thus the dynamics of fire development also increases.

For the case study, the groups 4 to 7 of production and operation according to CSN 73 0804) were chosen [17]. The fire outbreak was located in the middle of the platform at floor level. The heat release rate for each production and plant group were then determined in accordance with EN 1991-1-2 [7].

The sprinkler heads were located at a clear height of 5.4 m and their reaction temperature was 68 °C. The distance between the sprinkler heads was 3 m.

2.5.3. Methods of Assessment

The stability of the platforms during fire development was assessed by the following procedures:

- simplified analysis (empirical calculations);
- the CFAST fire zone model with the Smokeview graphical extension;
- the FDS model with Smokeview graphical extension and PyroSim interface support.

The CFAST zonal fire model and the FDS model have been described in previous sections of this paper. The results of the mathematical fire models were compared with the simplified analysis prepared by empirical calculations.

In the simplified calculations, the under-floor flow relationships derived by Alpert [6,18,19] were used to determine the temperatures under the horizontal platform structure. Based on the determined temperatures, the sprinkler head response time t_{act} (s) was determined [20,21].

The sprinkler head response time is generally considered to be the time of reaching the maximum-maximum value of the heat release rate and, therefore, the maximum ambient temperature reached. At the same time, the heat transfer to the steel structure of the platform was evaluated.

2.5.4. Determination of Limit Criteria

In the case study, the focus was on the environmental and surface temperatures of the steel structures. The course of the ambient temperatures is significantly influenced by the response of the sprinkler heads in the area under evaluation [28,29].

The fire resistance of the horizontal steel platform structure elements was evaluated in the case study. These are the elements that ensure the stability of the platform and the fire resistance R(t) can be evaluated on the basis of exceeding the limiting temperatures.

The critical temperature of the load-bearing steel elements depends on their degree of use (load on the structure). In the case of heavily loaded structures, the critical temperature is generally considered to be 463 °C.

The surface temperature of the structures evaluated in the case study will be related to this limiting temperature.

2.5.5. Determined Output Values

The following output values were determined by these procedures:

- the activation time and temperature history of the nearest sprinkler head;
- the maximum temperature and environmental temperature profile at the steel platform ceiling;
- the maximum temperature and temperature history of the horizontal steel-bearing structure.

The output values determined by the above methods were then compared and evaluated.

3. Results

The display of the structure geometry and visualization at the time of sprinkler head activation in CFAST and FDS is shown in Figure 1.

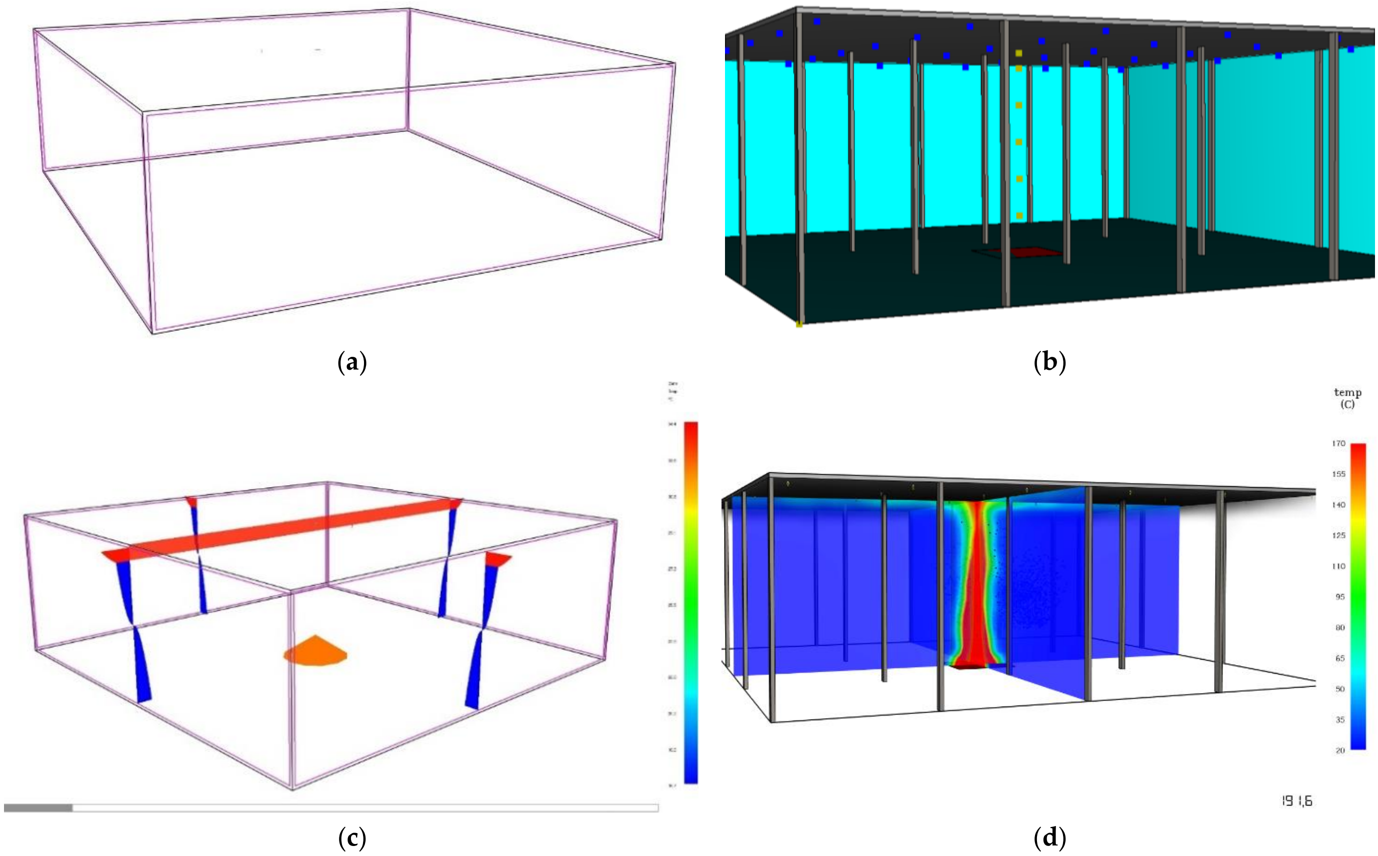


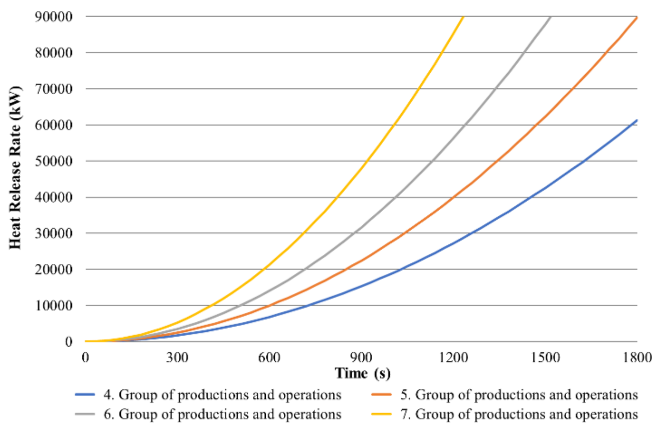
Figure 1. Visualization of the fire progress in the CFAST and FDS programs, where: (**a**) display of the structure geometry in the CFAST program; (**b**) display of the structure geometry in the FDS program; (**c**) visualization at the time of sprinkler head activation in the CFAST program; (**d**) visualization at the time of sprinkler head activation in the FDS program.

The heat release rate for each group of productions and operations without and with sprinkler response are shown in Figure 2.

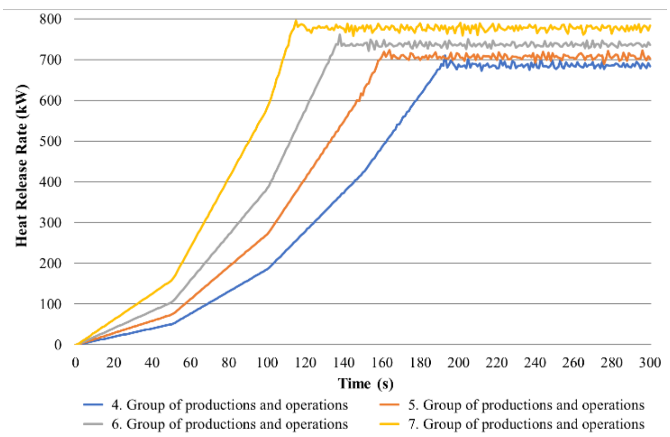
The results determined by the previously described methods are summarized in Table 1.

Table 1. Summary of the resulting values of sprinkler protection activation by individual calculation procedures.

Method of Calculation	Group of Productions and Operations			
	4th Group	5th Group	6th Group	7th Group
Simplified analysis (empirical calculations)				
Sprinkler head activation time t_{act} (s)	216	180	156	132
Maximum ambient temperature at the location of the steel platform ceiling (°C)	116	118	121	125
Maximum temperature of the horizontal bearing structure of the platform (°C)	30	28	27	26
CFAST (version 7.6.0)				
Sprinkler head activation time t_{act} (s)	205	140	110	80
Maximum ambient temperature at the location of the steel platform ceiling (°C)	85	85	86	90
Maximum temperature of the horizontal bearing structure of the platform (°C)	29	28	28	29
FDS (version 6.7.5)				
Sprinkler head activation time t_{act} (s)	190	159	136	113
Maximum ambient temperature at the location of the steel platform ceiling (°C)	169	145	156	162
Maximum temperature of the horizontal bearing structure of the platform (°C)	43	40	40	39



(**a**)



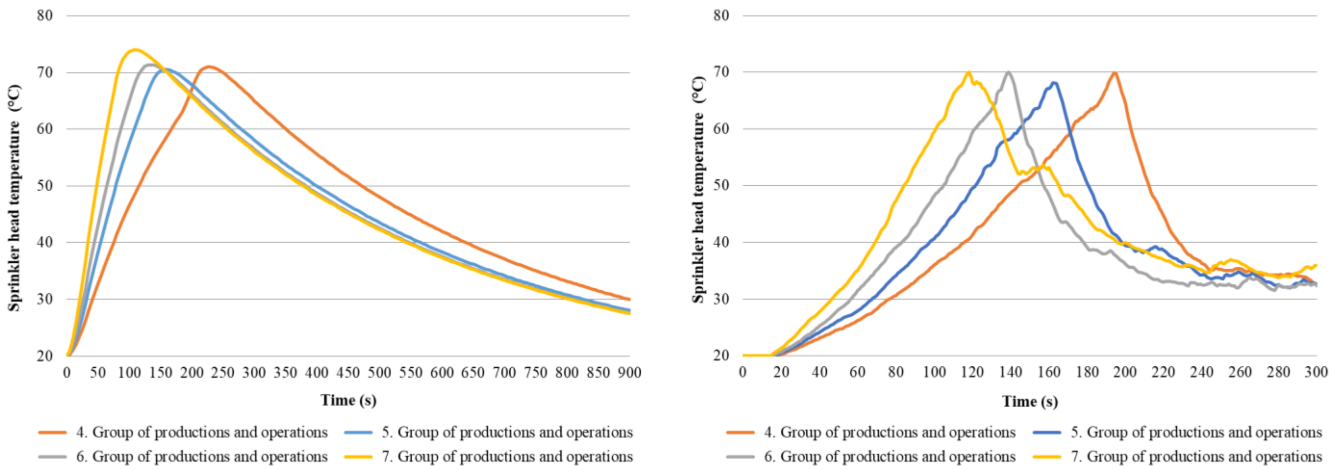
(**b**)

Figure 2. Heat release rate for each production and plant group, where: (**a**) heat release rate without sprinkler response; (**b**) heat release rate with sprinkler response as determined in the FDS program.

The sprinkler head temperature courses determined by the CFAST and FDS models are shown in Figure 3.

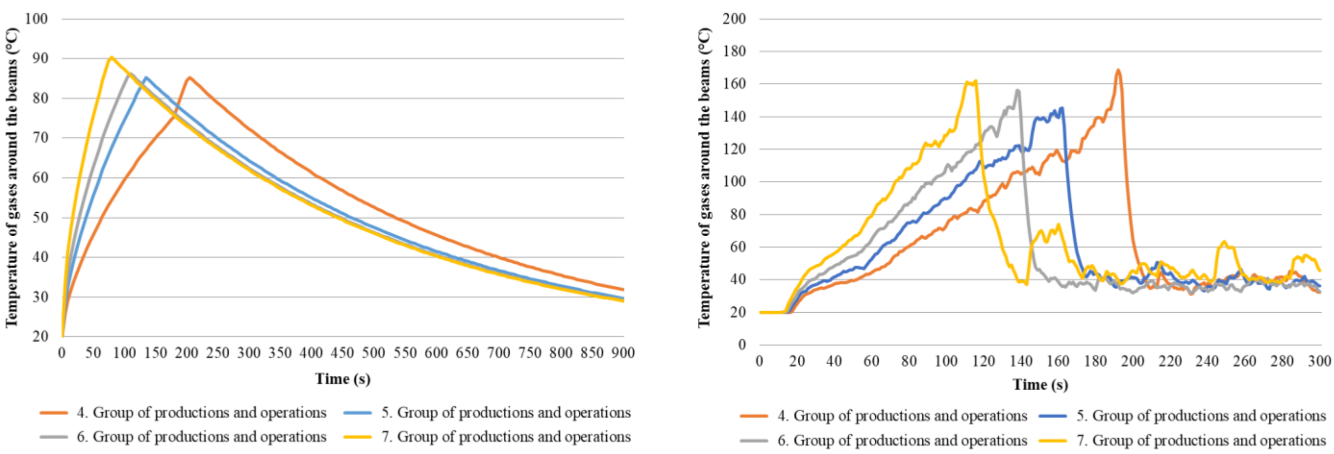
The course of gas temperatures in the vicinity of the platform beams determined by the CFAST and FDS models is shown in Figure 4.

The temperature course on the surface of the horizontal steel structure determined by the CFAST and FDS models is shown in Figure 5.



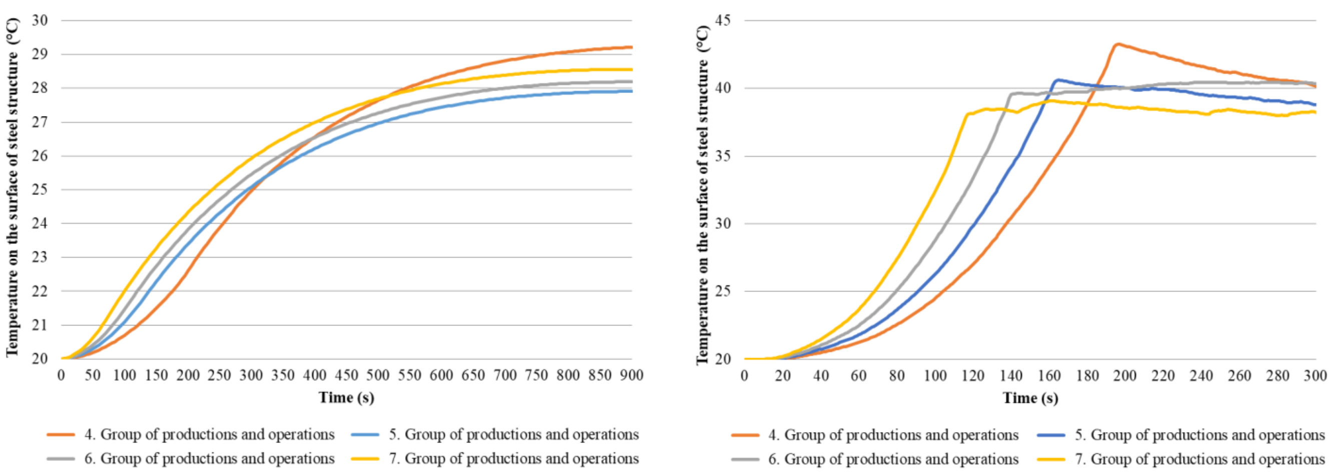
(**a**) (**b**)

Figure 3. Sprinkler head temperature courses, where: (**a**) sprinkler head temperature determined by the CFAST model; (**b**) sprinkler head temperature determined by the FDS model.



(**a**) (**b**)

Figure 4. Temperature course of gases around the platform beams, they should be listed as: (**a**) temperature course determined by the CFAST model; (**b**) temperature course determined by the FDS model.



(**a**) (**b**)

Figure 5. Temperature course of gases at the surface of a horizontal steel structure, where: (**a**) temperature course determined by the CFAST model; (**b**) temperature course determined by the FDS model.

The presented results show that the highest sprinkler head activation times were achieved by manual calculations. Shorter sprinkler head activation times are achieved by both the CFAST and FDS models. The sprinkler head activation times determined by both the CFAST and FDS models are highly similar.

Lower ambient temperatures below the horizontal ceiling structure due to sprinkler head activation are achieved by simplified analysis and the CFAST model. The calculations show high agreement. The FDS model has been used to determine the highest temperature levels. The temperature drop determined by the CFAST model is more gradual, the temperature drop determined by the FDS model is faster (almost step change).

The lower surface temperatures of the horizontal structure were obtained by unified analysis and the CFAST model. The calculations show a high agreement. The highest temperatures were determined by the FDS model.

4. Conclusions

It is evident from Figure 2 that the value of heat release flow depends on two basic aspects, namely on the group of productions and operations and on influence of the stable fire-extinguishing equipment. Presence of the stable extinguishing equipment significantly reduces the heat release flow.

In terms of the monitored attributes, which are the activation time of the nearest sprinkler head, the maximum ambient temperature at the steel platform ceiling and the maximum temperature of the horizontal platform structure, it can generally be stated that the results of all the compared methods achieve relatively good agreement. This fact demonstrates the good applicability of all the methods used in Figures 3 and 4.

When evaluating the activation time of the nearest sprinkler head, the simplified calculation methods achieve the highest values. The CFAST and FDS models were found to have lower head activation times. The simplified computational procedures demonstrate the expected conservative nature of this task.

The temperature drop after sprinkler head activation is more progressive in the FDS model than in the CFAST model. This is due to the gradual opening of more sprinkler heads in the FDS model. For the CFAST model, only one sprinkler head was triggered.

When determining the maximum ambient temperature at the steel platform ceiling, the results determined by the FDS model are the highest, followed by the simplified calculation results and finally the CFAST model results. The difference in the observed maximum ambient temperatures at the steel platform ceiling location between CFAST and FDS is due to the fact that CFAST assumes an average value for the upper hot combustion products layer, whereas FDS records temperatures at each location in the environment under consideration. The locally recorded maximum temperatures at the steel ceiling location (below the ceiling) are higher in the FDS model for this reason. The fact that the simplified calculations reach the second highest values is consistent with the expected results of the conservative calculations.

The surface temperatures of the steel structure reach good consistency in all evaluation methods. The results of the simplified calculation models and the CFAST model are almost identical (they only differ in units of degrees). Higher values are obtained with the FDS model. This is related to the higher maximum ambient temperatures at the steel platform ceiling location, which are due to the FDS model calculation technique.

In general, it can be concluded that all methods achieve "good consistency of results" and are useful for the determination of the parameters evaluated. It can be recommended that the simplified calculation methods should be used more for preliminary evaluations. The CFAST zonal model also deserves recognition. Although it is a simple computational model, the results of which can be obtained with simple input data, short simulation times, and very simple operation, it, nevertheless, achieves relevant values in Figure 5.

The FDS model is one of the most sophisticated computational models in terms of the methods compared. It may be surprising that in some situations it achieves less favorable values than the simplified or zonal models, but this is due to the more detailed assessment of some of the accompanying fire phenomena. The FDS model is, clearly, very promising. However, it is also necessary to highlight the fact that the use of the FDS model is rather complicated, especially if some of the extensions that make it easy to use are not used. Moreover, the actual simulation is demanding on the hardware that is used for the calculation, where the actual simulation can take hours or even days.

The main benefit of the current models is a close approximation to the real conditions of fire, thanks to abilities to define the boundary conditions as well as thanks to a possibility to formulate the process of burning, process of heat dissipation in space and its transfer to structure of building, the process of extinguishing, etc. A user of the fire models has at their disposal a considerable variability in entering the input parameters. These parameters can be useful, for example, in the case of changes occurred during projection or realization of the building. Within the case study, the authors chose mathematical models that have been developed and verified for a long time (they are promising). The presented study confirms a fact that in addition to the standard proposal procedures it is meaningful to use the simplified calculations, but above all also the mathematical models of fire. In the cases where a stable fire-extinguishing system is also installed, more detailed evaluation procedures (i.e., simplified calculations or fire models) can lead to a significant reduction in the costs necessary to ensure the required fire resistance of the building structures, while maintaining their defined properties.

Evaluation of the heat release flow in the burning area, its possible reduction using the installed stable extinguishing equipment and solution of the energy balance inside the burning area create a base for determination of the temperature field in the given area and also temperatures of the building structures. Thermal loading of the building structures is a starting point for fire resistance evaluation concerning these structures, whereby the fire models described in this article are suitable tools for evaluation of the energy balance in the burning area and for following determination of the temperatures.

The CFAST model and the FDS model were used in this article. These models are qualitatively different. The CFAST model is a zonal fire model and the FDS model is a field type model. The authors purposefully chose just these models. They were developed by the National Institute of Standards and Technology in the USA. Nowadays, both models are constantly being developed and tested for a long time. In general, they are very promising fire models. Validation of the models was not performed in this article because it was not a part of the given study.

In this case, the so-called t-square fire was used, characterized by the different fire dynamics for different groups of production and operations. A solid fuel fire (PMMA reference material) was chosen. The combustion model considers a simplified combustion reaction, where the resulting gases contain water vapor, CO_2, CO, and soot [30–32].

Author Contributions: Conceptualization, M.B. and M.T.; Funding acquisition, J.P.; Supervision, P.K.; Writing—original draft, M.B.; Writing—review & editing, M.T., D.M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financed by the Slovak Research and Development Agency under Contract Projects: No. APVV-19-0367, KEGA 013TUKE-4/2020, APVV-18-0248.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. BlenderFDS. Available online: https://blenderfds.org/ (accessed on 24 August 2021).
2. *ČSN 73 0802*; Fire Protection of Buildings—Non-Industrial Buildings. Úřad Pro Technickou Normalizaci, Metrologii a Státní Zkušebnictví: Praha, Czech Republic, 2020. Available online: http://www.technicke-normy-csn.cz/730802-csn-73-0802_4_16712.html (accessed on 24 August 2021).

3. *ČSN 73 0804*; Fire Protection of Buildings—Industrial Buildings. Úřad Pro Technickou Normalizaci, Metrologii a Státní Zkušebnictví: Praha, Czech Republic, 2020. Available online: http://www.technicke-normy-csn.cz/730804-csn-73-0804_4_17716.html (accessed on 24 August 2021).
4. Lumnitzer, E.; Andrejiová, M.; Goga Bodnárová, A. Verification of the impact of the used type of excitation noise in determining the acoustic properties of separating constructions. *Measurement* **2016**, *78*, 83–89. [CrossRef]
5. *EN 1991-1-2*; Eurocode 1: Actions on Structures—Part 1-2: General Actions—Actions on Structures Exposed to Fire. CEN/TC 250 Structural Eurocodes. The European Union: Belgium, Brussels, 2002. Available online: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.2.2002.pdf (accessed on 24 August 2021).
6. Evans, D. *Sprinkler Fire Suppression Algorithm for Hazard*; NISTIR 5254; U.S. Department of Commerce, Technology Administration: Gaithersburg, MD, USA, 1993. Available online: https://nvlpubs.nist.gov/nistpubs/Legacy/IR/nistir5254.pdf (accessed on 24 August 2021).
7. FDS-SMV. Fire Dynamics Simulator. Available online: https://pages.nist.gov/fds-smv/ (accessed on 24 August 2021).
8. *Fire Model Survey of Computer Models for Fire and Smoke*; Combustion Science & Engineering, Inc.: Columbia, MD, USA, 2003; Available online: http://www.firemodelsurvey.com/ (accessed on 24 August 2021).
9. Hurley, M. *SFPE Handbook of Fire Protection Engineering*; Springer Science + Business Media: New York, NY, USA, 2015; ISBN 978-1-4939-2564-3. [CrossRef]
10. Karlsson, B.; Quintiere, J. *Enclosure Fire Dynamics*, 1st ed.; CRC Press: Boca Raton, FL, USA, 1999. [CrossRef]
11. Kučera, P.; Peyzdová, Z. *Fundamentals of Mathematical Modeling of Fire*; Sdružení Požárního a Bezpečnostního Inženýrství: Ostrava, Czech Republic, 2010; ISBN 978-80-7385-095-1. Available online: http://www.pbs-knihy.sk/073-ZAKLADY-MATEMATICKEHO-MODELOVANI-POZARU-d79.htm (accessed on 24 August 2021).
12. Urban, R.; Štroner, M.; Kuric, I. The use of onboard UAV GNSS navigation data for area and volume calculation. *Acta Montan. Slovaca* **2020**, *25*, 361–374.
13. Madrzykowski, D.; Vettori, R.L. A Sprinkler Fire Suppression Algorithm. *J. Fire Prot. Eng.* **1992**, *4*, 151–163. [CrossRef]
14. Malerova, L.; Pokorný, J.; Brumar, J. Teaching method focusing on Simulation. In Proceedings of the 18th International Multidisciplinary Scientific Geoconference, SGEM 2018, Albena, Bulgaria, 2–8 July 2018; Volume 18. [CrossRef]
15. Kuric, I.; Klačková, I.; Nikitin, Y.; Zajačko, I.; Císar, M.; Tucki, K. Analysis of Diagnostic Methods and Energy of Production Systems Drives. *Processes* **2021**, *9*, 843. [CrossRef]
16. Markulik, Š.; Kozel, R.; Šolc, M.; Pačaiová, H. Causal Dependence of Events Under Management System Conditions. *Mmscience J.* **2016**, *10*, 1040–1042. [CrossRef]
17. Liptai, P.; Moravec, M.; Lumnitzer, E.; Gergeľová, M. Proposal of the Sound Insulating Measures for Vibrational Sorter and Verification of the Effectiveness Measures. *Adv. Sci. Technol. Res. J.* **2017**, *11*, 196–203. [CrossRef]
18. Naser, M.Z. Properties and material models for common construction materials at elevated temperatures. *Constr. Build. Mater.* **2019**, *215*, 192–206. [CrossRef]
19. National Institute of Standards and Technology. Available online: https://www.nist.gov/ (accessed on 24 August 2021).
20. Peacock, R.D. CFAST, Fire Growth and Smoke Transport Modeling. Available online: https://www.nist.gov/el/fire-research-division-73300/product-services/consolidated-fire-and-smoke-transport-model-cfast (accessed on 24 August 2021).
21. Vranova, J.; Arenbergerova, M.; Arenberger, P.; Stanek, J.; Vrana, A.; Zivcak, J.; Rosina, J. Incidence of cutaneous malignant melanoma in the Czech Republic: The risks of sun exposure for adolescents. *Neoplasma* **2012**, *59*, 316–325. [CrossRef] [PubMed]
22. PyroSim | Thunderhead Engineering. Available online: https://www.thunderheadeng.com/pyrosim/?gclid=Cj0KCQjwmcWDBhCOARIsALgJ2QeCpMK0AtDO1vTGJV8l9mESq8NHXnGZ4NrQnBDC2Vk5gVCdw1cjlxEaAhE9EALw_wcB (accessed on 24 August 2021).
23. Sabol, R.; Klein, P.; Ryba, T.; Hvizdos, L.; Varga, R.; Rovnak, M.; Sulla, I.; Mudronova, D.; Galik, J.; Polacek, I.; et al. Novel Applications of Bistable Magnetic Microwires. *Acta Phys. Pol. A* **2017**, *131*, 1150–1152. [CrossRef]
24. *STN EN 13501-1:2007-09 (92 0850)*; Fire Classification of Construction Products and Building Elements. Part 1: Classification Using Data from Reaction to Fire Tests. Úrad pre Technickú Normalizáciu, Metrológiu a Skúšobníctvo Slovenskej Republiky: Bratislava, Slovak, 2010. Available online: https://normy.unms.sk/eshop/public/standard_detail.aspx?id=129636 (accessed on 24 August 2021).
25. Technical Research Center of Finland VTT. Available online: https://www.vttresearch.com/en (accessed on 24 August 2021).
26. Pavlenko, I.; Saga, M.; Kuric, I.; Kotliar, A.; Basova, Y.; Trojanowska, J.; Ivanov, V. Parameter Identification of Cutting Forces in Crankshaft Grinding Using Artificial Neural Networks. *Materials* **2020**, *13*, 5357. [CrossRef] [PubMed]
27. Molcanyi, M.; Bosche, B.; Kraitsy, K.; Patz, S.; Zivcak, J.; Riess, P.; Majdoub, F.; Hescheler, J.; Goldbrunner, R.; Schäfer, U. Pitfalls and fallacies interfering with correct identification of embryonic stem cells implanted into the brain after experimental traumatic injury. *J. Neurosci. Methods* **2013**, *215*, 60–70. [CrossRef] [PubMed]
28. Sabol, F.; Vasilenko, T.; Novotný, M.; Tomori, Z.; Bobrov, N.; Živčák, J.; Hudák, R.; Gál, P. Intradermal Running Suture versus 3M™ Vetbond™ Tissue Adhesive for Wound Closure in Rodents: A Biomechanical and Histological Study. *Eur. Surg. Res.* **2010**, *45*, 321–326. [CrossRef] [PubMed]
29. Pačaiová, H.; Andrejiová, M.; Balážiková, M.; Tomašková, M.; Gazda, T.; Chomová, K.; Hijj, J.; Salaj, L. Methodology for Complex Efficiency Evaluation of Machinery Safety Measures in a Production Organization. *Appl. Sci.* **2021**, *11*, 453. [CrossRef]

30. Piňosová, M.; Andrejiová, M.; Lumnitzer, E. Synergistic effect of risk factors and work environmental quality. *Qual.-Access Success.* **2018**, *19*, 154–159.
31. Piňosová, M.; Andejiová, M.; Liptai, P.; Lumnitzer, E. Objective and subjective evaluation of the risk physical factors near to conveyor system. *Adv. Sci. Technol. Res. J.* **2018**, *12*, 188–196. [CrossRef]
32. Lumnitzer, E.; Liptai, P.; Drahos, R. Measurement and Assessment of Pulsed Magnetic Fields in the Working Environment. In Proceedings of the 8th International Scientific Symposium on Electrical Power Engineering (Elektroenergetika), Stara Lesna, Slovakia, 16–18 September 2015; pp. 331–333.