ISSN: 0974-5823 Vol. 7 No. 2 February, 2022

International Journal of Mechanical Engineering

Numerical Simulation of Fire Spreading in Different Kind of Buildings: Literature Review

Suhaib Hayajneh, Jamal Naser

Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn 3122, Victoria, Australia.

Abstract

In order to examine numerical simulation of fire spreading in different kinds of buildings, the present study used a systematic review of the literature. For this purpose, studies published between 2010-2022 were chosen that highlighted the numerical simulation methods and models. The present study provides key features of FDS (Fire Dynamics and Simulator), CFD (Computational Fluid Dynamics) model, and CFAST (Consolidated Model) for the fire simulation process. FDS and CFAST are effective in providing numerical simulation, thus useful in predicting fire spreading in buildings. Moreover, software accuracy, precision and increased use of the technology are the factors that can help in reducing fire occurrences in buildings. It is also found that both FDS and CFAST are effective in providing numerical simulation, thus useful in predicting fire spreading in buildings. One of the critical findings of the literature review was that the heat release rate and pyrolysis are the core factors later used in numerical simulations by both of these models. However, the use of CFAST is limited due to its inability to show high accuracy in all types of buildings and deal with a large number of variables simultaneously. Owing to the focus of study on CFD modeling, FDS, and CFAST, the research is limited as it provided a systematic review of the literature related to these models only. Hence, it has been suggested that future researchers must consider other dimensions and models related to the fire buildings and evacuation process.

Keywords: Numerical Simulation; Fire Spreading; Fire Dynamics and Simulator; Computational Fluid Dynamics

Introduction

The progress of architectural accomplishments, as well as building technology, enables the construction of different kinds of buildings [1]. Nevertheless, there is a high risk of uncontrollable spreading of smoke within medium-high, two-story, and high-rise buildings; hence, evacuation of people is at high risk and complicated in such buildings [2]. It is observed that smoke is one of the prime causes behind the fatalities in building fires [3]. Examining and analyzing the evacuation from buildings is significant to reduce property loss, deaths, and injuries whenever emergency situations arise [4]. Compared to fires in general buildings, fire in the super high-rise, medium-high, and two-story buildings have distinctive characteristics [5]: (1) it spreads quickly, (2) boundary environments and complex building structures cause-specific fire evolution behaviors, (3) these buildings have several fire hazards, (4) fire rescue is challenging and significant time is needed to fight fire, (5) evacuation of people is not an easy task, (6), fire causes significant loss and social consequences, hence identifying measures for effectively averting the occurrence, spread, and development of fire in these kinds of buildings, ensuring the easy and safe evacuation of people, and limited the property damage and casualty is imperative [6, 7, 8, 9]. Nevertheless, studies published between 2010-2022 highlighted the numerical simulation methods and models [10-12]. The present study provides key features of FDS (Fire Dynamics and Simulator), CFD (Computational Fluid Dynamics) model, and CFAST (Consolidated Model).

Recent studies have presented several numerical fire models, which are made to approximate and illustrate the phenomena occurring in fire situations [13]. These models, according to [14], [15], [16], are based on small-level experiments and are aimed to determine the procedures taking place in the extreme fire environment. Calculations and evaluations may be performed using physical equations or through the adoption of equations that are linked to software to attain many significant parameters. The computer programs presented used are based on different types of models, complex or zone (multiple or single) models [17,18,76]. Room volume for zone models is categorized into small areas with constant conditions, where the cold ceiling, flame zones, or convection zones may be distinguished. Additionally, one of the most commonly used fire models is the Fire Dynamics Simulator (FDS), which works on concepts of computational fluid dynamics (CFD) [17]. Therefore, this method provides a significant advantage in simulating fire in different types of buildings.

According to [18], the concepts of CFD are applied for simulating full-scale story building exposed to a domestic fire. The comprehensive numerical simulation of the occurring chemical and physical phenomena allows the examination of the thermal behavior, developing flow field as well as fire spreading elements of the construction materials. Likewise, it is observed that FDS (Fire Dynamics and Simulator) codes are applied for stimulating multi-component, turbulent, and reactive flow-field development in the building. The FDS code is a tool of CFD capable of examining key fire combustion and dynamics, directed at resolving practice fire issues. Likewise, [19] mentioned that FDS codes address a type of Navier-Stokes equations relevant for low-speed numerically, with a focus on heat transfer and smoke production from fires.

Studies have used numerical simulation to explain the fire spreading in buildings; for instance, [20] applied a numerical model for estimating the spread of smoke in a medium-high level building under moveable ventilation conditions. A number of conclusions were drawn from the study. For instance, it was noted that when the building is closed completely, smoke gets accumulated in the staircase, therefore, raising the concentration of dangerous fire gases and increasing the temperature, making it challenging to perform evacuation and rescue operations effectively. Similarly, it was noted that the presence of a window towards the roof is small to remove gases and smoke from the building effectively. It was recommended that the use of mechanical ventilation is important for improving the situation in the staircase.

Methodology

The use of a qualitative approach is appropriate for this study in descriptively studying numerical simulations used during fire spreading in buildings. The quantitative approach, on the contrary, is not compatible with the current study, as it relies on using statistical and numerical tools for data analysis and producing causality statements, which is not required in this study [23]. In terms of research design, a systematic review is applied, which helps identify, choose, and critically evaluate relevant research and collect and analyze information/data from the literature included in the review. The systematic review design is correlated with the qualitative approach and, therefore, will help produce comprehensive findings. For data collection, secondary sources are applied in which high-quality journal articles are selected from the past 12 years (2010 to 2022). A total number of 10 plus journal articles are selected for the review.

Literature Review

Computational Fluid Dynamic (CFD) - A Mathematical Model for Fire Simulation

CFD or Computational Fluid Dynamics utilizes computer analysis for showing how the air or fluid moves all over the surface or in space, and in terms of fire engineering, CFD modeling depicts the spread of smoke as well as fire with the help of a detailed building's virtual representation [24]. The fire modeling based on CFD usually referred to the mathematical explanations of fire dynamics along with chemistry with a form that is appropriate for computer-based solutions.

The paper of [26] has presented a worldwide risk assessment of fire through the use of fire simulation within underground parking. The simulations are carried out using the Fire Dynamics Simulator, a Computational Fluid Dynamics (CFD) tool, on a three-dimensional model of the parking lot. This sophisticated assessment considers a number of features and aspects, including geometry, ventilation apertures (both mechanical and natural), fire detection, and fire suppression elements. The case study's output consists of a huge amount of data, including the time it took for sprinklers to activate, maximum temperatures, smoke flow, and overall fire progression. The authors' goal is to give a global evaluation of the parking's fire risk based on fire safety engineering concepts. In addition to this, the authors have used an estimated heat release rate (HRR) of a maximum of 4MW [26]. The CFD equation of energy and momentum was mathematically modeled to simulate the fire. The results of the simulation noted that the maximum temperature reaches as high as 965ºC during the fire. Also, it was affirmed that the use of such simulations could be highly effective for the designers and architects to ensure that the buildings are designed to be safer. The Fire Dynamics Simulator, i.e., CFD (Computational Fluid Dynamics), is utilized for conducting this simulation, and parking's three-dimensional model is selected for performing these simulations. It was further revealed by [26] that several factors along with parameters, for instance, ventilation openings (both natural as well as mechanical), fire suppression, geometry data, and fire detection details, play a significant role in effective numerical simulation of fire in buildings. In addition to this, [26] depicted, with the help of an extensive array of data, overall fire evolution, the time used for activation of sprinkler, smoke flow, and maximum temperatures. The authors' intention in this specific research is towards providing a worldwide risk assessment of fire within parking areas on the basis of the principles of fire safety engineering.

Moreover, [18], in their paper, also utilized CFD for appropriately describing the fire and its influence upon buildings. The major aim of the researchers in this study was to examine the gypsum dehydration phenomenon that often becomes the cause of structural damage during a fire. The structure is made up of a structural steel frame and gypsum plasterboard wall components. All building materials have temperature-dependent thermo-physical qualities. The impacts of gypsum dehydration are evaluated using two different modeling approaches: an effective specific heat model and a solid reaction kinetics model; the results are compared to a benchmark test case in which no such phenomena are modeled. Lower total heat release rates gas and wall surface temperatures are projected when the highly endothermic gypsum dehydration events are modeled, according to the findings. Furthermore, the constructed solid reaction kinetics model enables quantitative predictions of gypsum dehydration-induced water vapor formation and dispersion phenomena for the first time. The authors simulated the effects of fire on buildings using the CFD model, which enabled them to identify the major structural damage and other harms caused. The authors have assumed the building to be equipped with timber furniture that becomes the main fire load in various fire cases. Thus, timber becomes the major input for pyrolysis in the buildings during a fire and leads to a high HRR. One of the critical aspects adopted in the CFD simulation of the buildings is the use of temperature profiles. The study by [18] used a temperature profile to simulate the fire in a residential building. The temperature profile can be shown mathematically as:

$$c_{P,eff}(T) = c_{P,s}(T) + \sum_{i=1}^{2} f_i c_{P,i}(T)$$

Figure 1: Temperature Profile Used in Simulation [18]

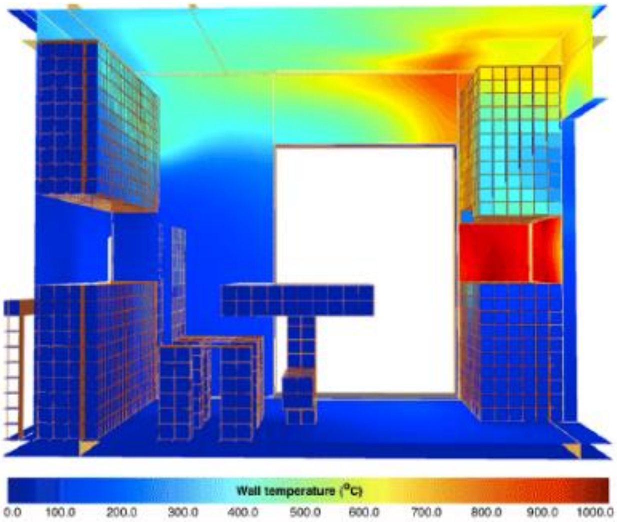

Figure 2: Simulation of Fire in a Building [18]

Furthermore, another study was conducted by McGrattan et al. [19] that aimed to examine the fire using CFD models. The authors used HRR as their main factor for CFD simulation and obtained the results based on this variable. It was noted in the results that the increase in the HRR leads to an increase in the flame height of the fire. Therefore, this means that the fire is of a higher intensity if it has a higher HRR. Besides this, the authors also noted that the HRR of the fire is dependent on various aspects of a building that mainly includes the fire load. As per the study, mass transfer during the fire enhances the rate of pyrolysis, which often depends on solid substances like wood, paper, and clothes that act as fuel. Fire is based on air, heat, and fuel, out of which the mass transfer takes place due to air and fuel. Fire produces various gases, each of which has a different mass. The transport of these gases forms the base for CFD simulation of fire in different types of buildings. The transport of these gases is also linked to their speed of movement due to the variance in their density that also causes fire to spread differently in distinguished areas of the building. Therefore, the flow of these gases enables the formation of a mass profile that can be modeled to simulate a fire event.

In another research paper by Kolaitis et al. [27], fire spreading's numerical simulation within a two-story residential building by using the CFD modeling is presented. To mimic a full-scale two-story home building subjected to a typical domestic fire, a CFD tool is employed. The complete numerical modeling of the happening physical and chemical processes enables examination of the emerging flow-field, fire spreading characteristics, and thermal behavior of construction materials. The FDS algorithm is used to model the turbulent, multi-component, and reactive flow-field that develops within the building. The building under consideration is built using a structural steel frame and drywall technology. Internal and external walls are made up of several layers of gypsum board, cement board, and insulating materials. When a gypsum board is exposed to high temperatures, water molecules trapped in its crystal lattice are liberated and transported through the board, absorbing energy and so lowering the mean wall temperature; this process is known to improve the structure's fire resistance [27]. To appropriately depict the thermal behavior of all building and furniture home materials, the real thermo-physical qualities of all construction and furniture house materials are taken into account. To simulate the fire, the authors of the study have used $C_{3.4}H_{6.2}O_{2.5}$ for modeling the pyrolysis. It was also assumed that the cooking equipment in the kitchen becomes the main cause of fire in residential buildings. The simulations led to various important findings of the fire. One of the critical findings is that after the fire erupts, the kitchen zone becomes untenable very quickly as the tolerance time of 7 minutes to 126ºC is reached in a few minutes [27]. It was also noted that the in-depth mathematical simulation of the occurring chemical as well as physical phenomena allows the developing flow-field, construction materials' thermal behavior, and fire spreading characteristics' investigation. The authors have used an enthalpy profile to simulate the fire in the building. The flow of enthalpy in the building is a critical aspect that can be numerically analyzed using the CFD model. The two-story building of 152-meter square, which is simulated; the building's behavior of fire resistance is examined by considering different alternatives as well as realistic scenarios of ventilation. Temperature predictions and gas velocity are utilized for visualizing the developing flow field and for estimating the heat flux to which every element of the building is exposed. Predicted temperatures of the wall permit the steel frame's assessment and technique of drywall construction with regard to fire resistance. Hence, through the use of this CFD modeling, the fire can be effectively simulated, which enhances the better design of the buildings. Furthermore, the research of [27] aimed towards using the CFD model for the analysis of the spread of flame over materials in the buildings. The authors studied the growth of fire as well as its spread upon ten-centimeter-thick polyurethane foam slabs. A multi-material, multi-layered model was established so as to simulate the spread of flame, and the properties of the material were accessed from numerous experiments. The results of the study found that the use of different materials in the buildings has a significant effect on the fire spread in the buildings. This spread of fire is measured majorly through the enthalpy and pressure profile that can be modeled using CFD analysis. The use of this CFD method for the spread of fire can help improve the safety of the buildings against fire.

FDS (Fire Dynamics and Simulator)

As defined by McGrattan [19], FDS is a computational fluid dynamics (CFD) method that relies on fluid mechanics and numerical calculation to model the fire behavior and predict its outcome. In order to map the evolution of fire, smoke and heat transport are considered to be important variables. FDS was initially developed by the National Institute of Standards and Technology (NIST) in 2000, but since then, it has become the most effective type of simulator within the fire community. One of the offshoots of FDS is FDS +Evac which largely focuses on the evacuation of a large number of people during the event of a fire. FDS lies on the intersectionality of heat transfer, fluid dynamics, and thermodynamics.

This is highlighted by [28], who studied fire in a single-family dwelling. The aim of the authors was to compare different fire simulator models and analyze the suitability of each model. The simulators used by the authors are FDS and CFAST. As per the authors, FDS is a field model which is very user-friendly and requires the least amount of energy and technical expertise when compared with other simulators. These results are verified by [29], who has simulated the fire using FDS in a shopping mall. The temperature and pressure profile are key parameters that are used in FDS to simulate the fire. It can be noted from the results of the FDS model that there is an increase in the HRR as time passes after the eruption of fire.

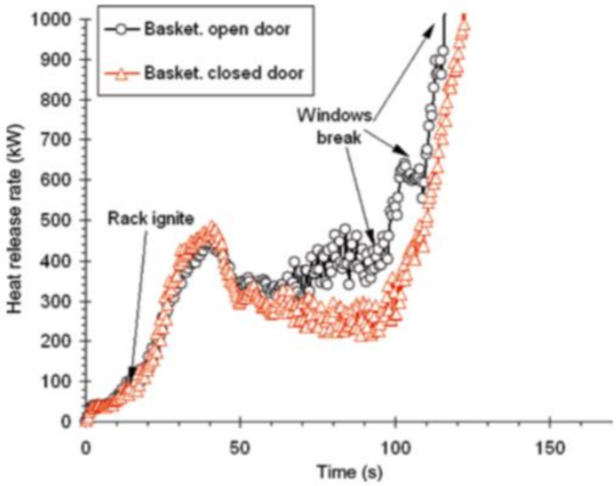

Figure 3: HRR vs. Time Elapsed [29]

Through the use of FDS, a dynamic temperature profile is developed that showcases the event of a fire in different types of buildings. The use of FDS also enables quantifying the fire in the form of temperature, pressure, and enthalpy. Therefore, these parameters simultaneously enable a great fire modeling that can be used to identify the sources/threats of fire in a building. However, the results also noted that the FDS model is limited due to the lack of validation of the transport equations, and the usage of mixture fraction suggests the possibility of a surplus of pyrolyzed gases being burnt. Nevertheless, FDS is a modern method to simulate fire and fire data can be fed into FDS, which can then analyze the pattern of fire and evacuation process. Hence, through FDS simulation, geometric coordinates, thermal properties, and location of fire sources can be effectively defined.

On the contrary, the validation of FDS is also proved by [30]. The study is based in Finland, and the experiment is conducted in a natural ventilated room. The study points out the need for calibrating the speed of combustion and the velocity of the flame. This is imperative for arriving at a validating result, and thus FDS can be recognized as a reliable method of mapping the fire. Computational fluid dynamics was employed in this work to simulate an experimental pool fire in a naturally ventilated room. The Technical Research Institute of Finland conducted an experiment in which 4.9 kg of heptane were burnt in a room 10 m wide, 10 m long, and 5 m high with natural ventilation through an open window. This scenario was simulated using Fire Dynamic Simulator (Version 6) with various meshes to evaluate the effect of grid size on numerical results. The results observed the pyrolysis of heptane and noted that there was an increase in the temperature and HRR as the time passed. Besides this, the results also noted that when the grid sizes reduce, the size of the fire grows first and then begins to diminish to an asymptotic value as the grid sizes decrease more.

In another study conducted by [31], the authors apply FDS in a horizontal space like a long tunnel. The study was aimed at exploring the impact of length in the spread of fire and evacuation. The authors of the study used FDS on five different scenarios to compare airflow velocity and temperature curves. Another critical part of this experimental study was the use of a jet fan to control the fire. Therefore, the results of this study are very useful from the perspective of fire safety and simulation. As per the results, the authors find out that during the event of a fire, the air temperature remains well below 60 degrees Celsius for the temperature range of 100 to 200m, which is tolerable by human bodies. This ensures that the humans can withstand and perform the evacuation method effectively while remaining this distance range. Furthermore, the authors confirm the validity of FDS in a horizontal length space, and the results obtained through FDS are accurate and reliable. In addition, another important finding of the study states that the positioning and spacing of jet fans are critical for the forbearance and survival of the fire extinguisher team.

In addition to this, another study was conducted by Cicione and Walls [32] to examine FDS. Based on full-scale trials, this research creates a Fire Dynamics Simulator (FDS) model to analyze fire propagation in informal communities. Fires routinely decimate informal settlements, displacing thousands of people, and with more than 1 billion people living in such locations, there is a pressing need to better understand and enhance fire safety in these regions. This study also explores the sensitivity of fire behavior to the input parameters employed in numerical simulations due to the high levels of uncertainty associated with input parameters for informal settlements. It is demonstrated that, depending on the simulation input parameters chosen, spread periods between two houses can range from 1 minute after flashover to none at all. The simulations also present that a simplified fire spread model for informal settlements is possible, particularly for steel-clad dwellings. However, a significant amount of work is required for timber-clad dwellings as the rate at which additional ventilation forms in the simulation for timber-clad dwellings is considerably slower than in reality due to the simplifications made [32]. When compared to the experiments, the simplification of using heating, ventilation, and air conditioning (HVAC) systems to model leakages caused by corrugated flutes showed good enclosure fire dynamics behavior, but it created new challenges in terms of the spread mechanism because HVAC systems do not allow electromagnetic waves to penetrate in the same way that an opening does. The authors state that although the validity of FDS is well established with the small-scale experiments and smoke movement when it comes to adjacent structures, there is a comparative lack of evidence and research. This has been taken as a point of departure by the researchers. The correlation between gas temperatures and fire development behavior shows a consistent correlation, and FDS has emerged as a good predictor of fire behavior. The results also found that the rate of HRR increases for a certain period of time and then begins to decrease after the fire erupts.

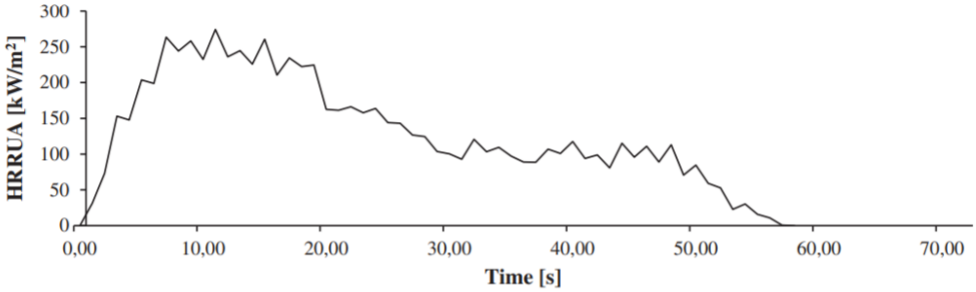

Figure 4: HRR vs. Time [32]

The study of [34] has constructed a virtual reality environment to validate the results of FDS. This particular study was set out to investigate the fire spread in a closed room. The study is very useful for firefighters and building designers as it confirms FDS as a realistic and authentic tool to predict the emergence and pattern of fire, especially in a closed setting. However, the study has criticized the application of FDS in a complex environment as it is difficult to generate geometric coordinates. Furthermore, the researchers have explained that the prediction of smoke coordinates is difficult to interpret with the movement of fire. However, the behavior and pattern of fire movement can be predicted and modeled under an FDS. The model has used furniture like chairs, sofa and tables as the main source of pyrolysis in the fire simulation, with values of thermal conductivity and ignition temperature assigned to each of them. Besides this, the study has used a combination of factors like ignition time, pressure, MLR, HRR, and chemical composition to simulate the fire and build a virtual environment [34]. A 'mixture fraction' model is mentioned by the authors for the applicability of FDS, which is largely based on fuel mixing and oxidizing phenomenon. Time and space calculations are other important tools identified in the study for the general applicability of FDS. Without these metrics, the implementation of FDS, especially in a complex environment, can be deeply flawed, putting at risk human lives. Furthermore, since the application of FDS relies on complex mathematical modeling, the prediction of fire and its behavior can be made with high accuracy.

In addition to this, the study by [22] highlights that fire propagation in super-high-rise buildings is critical for establishing practical fire prevention and evacuation measures. The fire dynamics simulator (FDS) was used to create a fire spread model, and the results were studied for a fire scenario in a single room under various conditions, a fire scenario in different functional places under the same parameters, and the spread of fire outside the room. The findings found that the key time for a fire in a shop, restaurant, or office to become a safety issue was around 200 seconds. Thus, it can be noted from these simulations of fire using FDS that the fire modeling can be very beneficial in evacuation planning of the building as it provides management of the areas that are less prone to be affected by the fire. Regardless of whether the fire spread was caused by CO mass fraction or temperature, the same sort of fire reached the crucial period required for a fire to become a safety issue faster in an office than in a restaurant or shop [22]. In ultra-high-rise structures, more attention should be devoted to fire safety in office spaces. Furthermore, visibility was a more significant element in determining the crucial time required for fire to become a hazard than CO mass fraction or temperature, and smoke affected the neighboring open region in around 60 seconds. In the event of a fire, the temperature of the staircase and its front chamber was always below the human body's tolerance threshold of 60°C.

Consolidated Model of Fire and Smoke Transport (CFAST)

CFAST or Consolidated Model of Fire and Smoke Transport is defined as an effective computer program, which is utilized by the safety officials, builders, fire investigators, builders, and engineers for stimulating the influence of potential or prior smoke as well as fires within a particular environment of the building. CFAST is further viewed as a two-zone model of fire that is used for computing the temperature, fire gases, and smoke's evolving distribution all through the building compartments during an incident of fire [35].

The study of [36] evaluated two different simulation models of the fire, i.e., field models and zone models that are recognized as CFD techniques. CFAST is considered a known zone model, which is mostly utilized to model fires within enclosures, and similarly, CFX is categorized as a CFD's general-purpose code that is used for several purposes, such as fires modeling. Their study considered a tunnel of 80 m 2 rectangular cross-section and 150 m length in order to analyze the velocity profiles along with temperature that the fire generated and was placed at a twenty-meter distance by both CFX and CFAST. For conducting simulation through CFAST, the tunnel was divided into 1-15 compartments that were of equal size, and the joining of such compartments was done by vents or openings, which had similar cross-section like the tunnel/ When the tunnel was divided into fifteen equal compartments, the position of the fire source was found at the vent's position and very high temperatures were predicted by CFAST. In addition to this, the study noted that the HRR increases with time after the fire erupts and then begins to decrease with time.

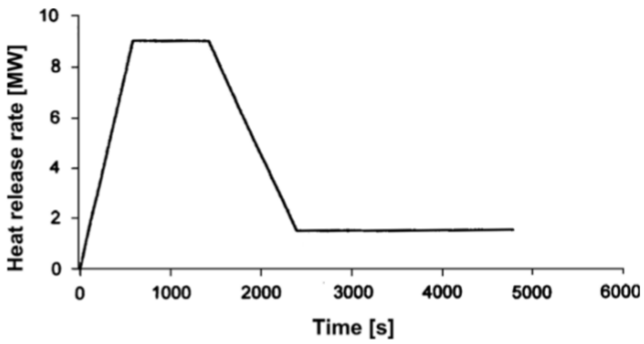

Figure 5: HRR vs. Time [36]

Moreover, it was noted that the temperature reaches 404.58 K in 24 min, after which it begins to decline as the HRR also decreases. Also, the simulations were conducted by splitting tunnels into compartments of unequal size in which the fire position lies at the compartment's center. In order to generate accurate results, it was revealed that fire source location within the compartment seems to be an essential factor. However, it was also observed that when the tunnel was split into over fifteen compartments, computational difficulty was faced. Thus, the paper of [36] thoroughly studied the temperatures, which CFX and CFAST predicted, and it is represented by their predictions that the temperature of the smoke alters with a change in pattern. It was further explored that the profiles of the temperature at specific positions are not possible to be estimated by CFAST.

Further, the research work of [28] provided the assumptions as well as results of implementing three different approaches of fire modeling in order to study different accidental fires, which occurred within single-family residences. The approaches of fire modeling that were used by the authors in their paper were a zone model, i.e., CFAST, a simplified fire growth analytical model, and a field model, i.e., FDS. The fires, which were projected include a fire in a small apartment that was initiated due to the sofa ignition, which extinguished because of depletion of oxygen; a fire in a one-story home that occurred because of the malfunctioning gas heater; and a fire in a house where the initial location was suspected by no ignition source was known. The input towards every single model was kept independent from other used models; however, it was constant with the forensic proofs [28]. The fires characteristics' predictions from the model were examined within the context of the forensic evidence for every accidental fire in order to make its comparison with the predictive capacities of the models. It was revealed in the study that though the distinction occurs within the sophistication of all modeling approaches, the obtained results were comparatively in suitable agreement, specifically in the fire's early stages. However, it is noted that the use of simpler models could be done as an initial step to approximate modeling less and for confirming the results' magnitude from complex modeling approaches. The research's results could be utilized for reaching conclusions relating to the model's complexity, which is needed for explaining a specific scenario of fire [28]. Another critical finding of this study was that the CFAST model is limited as it cannot use various factors simultaneously to simulate fire in buildings.

Furthermore, the study by [37] aimed at studying the impact of fire on the structure of the building, for which it used the CFAST model. The results of the study noted that the CFAST model was limited to the use of few variables to simulate data as it cannot handle a large dataset. The cables' integrity that is placed within the targeted room is significant in the Fire PSA due to the fact that CCDP and CDF have faced variations as per the cable integrity's results, which are dependent on the gas temperature surrounded all around. The assumptions utilized within the Fire PSA are conservative and specify that all cables along with equipment within a room will fail in the case of a fire happening in the room. However, it is important to realistically assess the risk of fire with the use of a fire simulation tool, which is considered essential within the Fire PSA. [37] in their work utilizes 8 pump-rooms in order to examine the cable integrity within the nuclear power plant and utilized zone model of the fire, i.e., CFAST. The authors estimated the gas temperature of the rooms' upper layer and performed also utilized an analysis on the basis of the model simulations' results for judging the integrity of the cable. As per the results of the analysis, the cable's integrity placed within the pump rooms' upper layer is managed, and no thermal damage has occurred. One of the significant findings of the study was that HRR is directly affiliated with flame height, which increases with time as fire erupts and then begins to decrease. Although the pattern remains the same, the intensity of a fire is dependent on the fire load and pyrolysis.

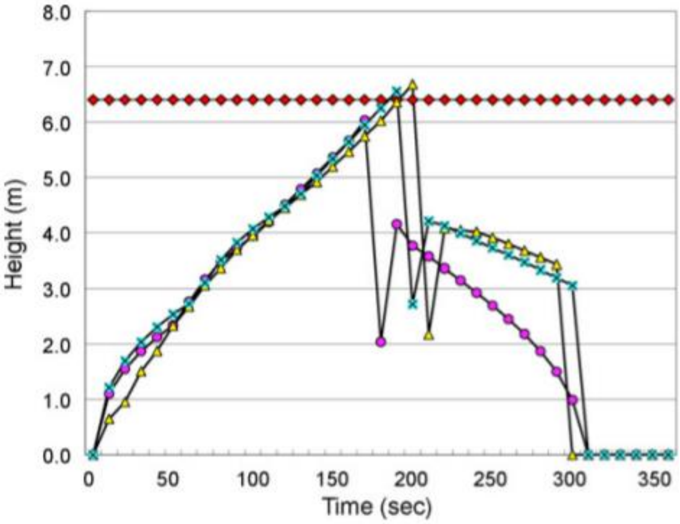

Figure 6: Flame Height vs. Time [37]

Also, a significant reduction has been observed in the CCDP, which is around half of the original CCDP. An assessment of fire safety for all pump rooms through the use of fire modeling tools is found effective in evaluating the fire scenario's consequences, developing a realistic model of Fire PSA, and reducing uncertainty. It is further observed that the ANS Fire PRA requirements could be satisfied by the fire modeling, and it could be helpful in improving the Fire PSA's quality.

Results and Discussion

The systematic review of the literature shows certain features of CFD modeling, FDS, and CFAST. The key findings as reviewed in the literature depict (Table 1).

Table 1. The certain features of CFD modeling, FDS, and CFAST

Scholars	Simulation Method	Key findings
McGrattan (2010)	CFD + FDS	FDS (computational fluid dynamics) is a type of computational fluid dynamics (CFD) that uses fluid mechanics and numerical calculations to simulate and predict fire behavior. Smoke and heat movement are regarded to be crucial elements in determining the spread of a fire. The National Institute of Standards and Technology (NIST) established FDS in 2000; however, it has already proven the greatest efficient form of the simulator in the fire world. FDS +Evac is an outgrowth of FDS that emphasizes the rescue of a significant number of individuals in the case of a fire. FDS exists at the crossroads of heat transport, fluid dynamics, and thermodynamics. Likewise, FDS is one of the most often used fire simulator systems.
Rein et al. (2014)	FDS + CFAST	The authors have presented a comparative analysis of various fire simulator models as well as an examination of each model's applicability. The authors employed the simulators FDS and CFAST. According to this study, FDS is a user-friendly field model that takes the least degree of energy and technical competence when compared to other simulators.
Khan et al. (2017)	CFD + FDS	FDS is a powerful tool, particularly when it comes to excavating dense crowds. In addition, the scientists identified FDS as a Computational fluid dynamics (CFD) that maps the fire-driven fluid flow. This means that the fire evolves in a quantifiable way, and the data generated from such simulations may be sent into FDS, which can then assess the fire pattern and evacuation procedure. The steps taken in this investigation are also noteworthy as the researchers constructed an input file on which the simulator fire is performed and then assessed the outcomes. This is accomplished by collecting geometric coordinates, establishing thermal characteristics, and determining the site of fire sources.
Pachera et al. (2015)	FDS	The scholars have identified that the rate of combustion and the velocity of the flame must be calibrated. This is necessary for obtaining a validating finding, and therefore FDS is acknowledged as

		a credible way of mapping the fire.
Weng et al. (2020)	FDS	During a fire, the overall temperature stays considerably below 60 degrees Celsius, which is endurable for adult beings. This means that humans can endure and carry out the evacuation procedure. Additionally, the researchers verify the existence of FDS in a horizontal length space and the accuracy and reliability of FDS outcomes. One significant finding of the study is that the positioning and spacing of jet fans are vital for the patience and survivability of the fire extinguisher squad.
Cicione & Walls (2021)	FDS	The time it takes for a fire to extend between two localities could fluctuate by up to one minute. According to the researchers, while the effectiveness of FDS is well proven through small-scale tests and smoke movement in neighboring structures, there is indeed a distinct shortage of scientific evidence to prove these facts. The scholars have used this as a starting point for further research in the current age. The relationship between gas temperatures and fire development behavior is persistent, and FDS has been proven as a reliable predictor of fire behavior.
Choi et al. (2011)	FDS	Scholars have identified that with the combination of AutoCAD and FDS, the usefulness of FDS may be substantially increased therefore implemented in a variety of situations.
Tzani et al. (2020)	FDS	FDS is a realistic and authentic method for predicting the appearance and pattern of fire, particularly in enclosed places. The analysis, however, challenged the use of FDS in a complex setting since it is tricky to obtain geometric dimensions. Moreover, the authors indicated that predicting smoke coordinates is difficult to understand in relation to fire movement. An FDS, on the other hand, can forecast and model the behavior and pattern of fire movement. The authors describe a mixture fraction' model for the application of FDS, which is mostly based on fuel mixing and oxidizing phenomena. Other essential tools mentioned in the study for the general applicability of FDS include time and space computations. Without these criteria, the implementation of FDS, particularly in a complex setting, can be severely defective, placing lives in danger. Moreover, because the application of FDS is based on complicated mathematical modeling, fire and its behavior can be predicted with high accuracy.
Jain et al. (2008)	CFAST	The authors have performed a comparative study of the CFAST and CFX models to examine the results of fire simulation. It was noted that CFAST is more effective than the CFX model as it was advanced. However, the CFAST model is also limited as it cannot use various factors simultaneously to simulate fire in buildings. In addition to this, it was observed that the CFAST model shows similar results as previously obtained from FDS models.
Lee et al. (2010)	CFAST	The study aimed to examine the structural changes caused by a fire in buildings, for which the CFAST model was used. It was noted that the CFAST model shows compliance with the results portrayed by the FDS model as HRR first increased and then decreased with time. Another important finding was that the CFAST model was not effective enough to handle complex simulations.

Discussion

The systematic review of the literature shows that CFD modeling, FDS, and CFAST are effective when the numerical simulations of the fire spread in a building are measured. As per [19] and [38], FDS has already proven the greatest efficient form of a simulator in the fire world. This is also supported by [39,79], who claim that the FDS system has certain numerical algorithms that help in calculating the temperature on the façade structures of various buildings. Another research by [4] also provided evidence that evacuation from buildings can be increased when effective technologies can examine these aspects. FDS has proven a highly flexible and dynamic software with accuracy and precision in the output (results) provided to the experts. Another aspect highlighted by [33] and [80] indicates that FDS can be upgraded, and Gomez et al. [41] claim that AutoCAD helps in providing a 3-dimensional perspective which helps in understanding the simulation process of the fire spread in the building. Prior to this idea and innovation, the FDS was mainly giving a 2-dimensional perspective to the experts. These findings are also comparable to the contributions made by [34,81], stating that the virtual reality environment has demonstrated the efficacy of the FDS model. It is mainly because FDS with AutoCAD aids in the prediction of fire patterns in closed areas of a building. Eventually, this improves the efficiency and the precision of the FDS model for numerical simulation of the fire spread. [31,33,73,82] have also claimed that precision is important in FDS numerical simulation as temperature recording can determine the harm that fire spread causes the human beings. If the FDS provides accuracy in measurement, the evacuation process can be accelerated, and maximum human and property loss can be prevented. These findings have been supported by [42,74,75,83], claiming that FDS precision is now a new advancement in the technology mainly supported by the integration of the FDS with the AutoCAD technology. Therefore, the FDS is quite precise and accurate when presenting numerical simulations in fire spread in various buildings.

Similarly, the CFAST model is another CFD method to simulate fire in different types of buildings. One of the key advantages of using this method is that it enables the prediction of the spread of fire in a building [37,43,66,84]. Also, it has the ability to simulate the channel taken by the fire to spread in a building. Thus, it can be effectively used for finding the potential source of fire in a building and mitigating the chances of a fire in the future. On the other hand, the review shows that [44,67,85] have highlighted the effectiveness of CFAST. They claim that this software is more suited for big-scale fire spread, mainly because of the number of measurements that can be collected and forwarded into the software. Thus a close comparison between CFAST and FDS shows that both of these models are extremely advantageous to the accurate collection of trustworthy data and simulation of fire in different types of buildings. FDS is essentially a simulator based on computational fluid dynamics, which is used to do numerical computations to predict fire behavior. It is also reasonable to suggest that FDS and CFAST have acquired global popularity owing to their accuracy and efficiency [68,69,70]. Therefore, it can be concluded that FDS and CFAST models are highly effective in getting numerical simulations of the fire spread in various buildings. Moreover, software accuracy and precision, increased use of the technology are the factors that can help in reducing fire occurrences in buildings [45,46,71]. When the numerical simulations provided by the software are timely considered, fire occurrences in buildings can be minimized, and the evacuation process is accelerated. Finally, it can be concluded that CFD modeling, FDS and CFAST are highly effective in predicting fire spreading in buildings [47,48,72]. However, it has been noted that FDS has the greatest popularity in fire simulation of the buildings as compared to other buildings.

Moreover, it was noted during the literature review that numerical simulation of fire in buildings is significantly dependent on pyrolysis and heat release rate. The use of the FDS model enables the experts to perform complex fire simulations more effectively [49,50,51]. Heat release rate when used as the major factor in the FDS model to simulate a real fire condition. In the case of buildings, simulation is majorly based on the pyrolysis of materials like wood, paper, and clothes. On the other hand, the simulation of fire using the CFAST model is limited in the case of complex events as this model is not able to cater to a large number of variables simultaneously. During the literature review, it was noted that the CFAST model is more effective in simple fire scenarios as they can be easily simulated and modeled [52,52,54]. Nevertheless, the heat release rate is still considered to be the core variable in both of these models for fire simulation. The results of the simulations FDS and CFAST model displayed that the heat release rate increases with time to a certain point after the fire erupts. However, after reaching a maximum, the heat release rate begins to decline with the increase in time [55,56,57]. This is one of the major findings of the literature review as it forms a basis of numerical fire simulation of different types of buildings. Therefore, this finding can be used to develop more effective and efficient models for fire simulation. Nonetheless, it must also be noted that different events of fires and different types of buildings lead to distinguished values of the heat release rate and different amounts of time required to reach the maximum and minimum [58,59,60,61]. The maximum value of heat release rate in a fire scenario is dependent on the type of material latest consumed as the major fire load in the building. Therefore, during the simulation and modeling of the fire in buildings, it is important to consider different materials and determine their impact on the fire [62,63,64,65]. Hence by using these findings, the numerical fires simulation of different buildings can be enhanced two obtain more accurate results.

Conclusion and Recommendations

Conclusion

The present study was based on the aim to examine numerical simulation of fire spreading in different kinds of buildings. For this purpose, the paper focused more on mid-story and high-story buildings. Therefore, it also emphasized the ways through which numerical simulation is useful in predicting smoke, temperature, and heat flow during a fire in the building. Considering it in view, the present study had three core objectives including (i) to analyze the effectiveness of numerical simulations including CFD and FDS during fire spread in buildings, (ii) to assess factors and measures which can assist in reducing fire occurrences in buildings, and (iii) to examine which of the numerical simulations is useful in predicting fire spreading in buildings. In this context, numerous contemporary projects have provided numerical fire models that are designed to demonstrate and explain the events that occur in fire conditions [13]. According to [14] and these models are founded on small studies and try to define the operations that take place in an intense fire setting. In this regard, calculations and assessments can be accomplished using physical equations or by employing equations associated with the software so that certain critical parameters can be obtained. Researchers have employed numerical simulation to assess fire spread in buildings. In this regard, one research by [20] employed a numerical model to estimate smoke dispersion in a medium-high level building with flexible ventilation. It showed that when the building is entirely closed, smoke accumulates in the stairway, growing the number of harmful fire gases and increasing the temperature. As a result, successful evacuation and rescue activities become difficult and challenging. Despite having models such as FDS that could measure the fire temperature, a study was needed to analyze the fire spreading in various building structures. This necessitated having a study that reviews the previous techniques and methods mentioned by the scholars and presents the best numerical simulation of fire spreading in different kinds of buildings.

The literature depicted that a lot of studies have focused on the FDS models. This included depicting the NIST formed the FDS model, and it lies on the intersectionality of heat transfer, fluid dynamics, and thermodynamics. Contrary to this, [29] have also supported that FDS is a remarkable tool helping in the evacuation process. [30] supports the effectiveness of FDS in Finland and proves that it is a reliable and valid way of mapping fire. [33] also, exhibit that the conventional FDS model can be boosted when new approaches such as AutoCAD with FDS are implemented. [34] the virtual reality environment has also proven the effectiveness of the FDS model. It helps in predicting the pattern of fire in a closed setting. In addition to this, it was noted that when the FDS model is used to mimic a real fire, the heat release rate is a crucial element. Building simulations rely heavily on the pyrolysis of materials such as wood, paper, and clothing. The CFAST model, on the other hand, is restricted in its ability to simulate fire in complicated situations since it cannot cater to a high number of variables at the same time. The CFAST model is more successful in basic fire scenarios, according to the literature review, since they can be easily simulated and modelled. Besides this, it has also been noted during the study that the HRR increases with time after the fire erupts, after which it begins to decrease when it has reached a maximum value.

In light of the stated research aim and objective, the study took a qualitative technique that relied on non-numerical instruments and presented a full and in-depth investigation of the research topic. The application of a qualitative technique was suitable for the research because it descriptively investigated numerical simulations employed during fire spread in buildings. The quantitative approach, on the other hand, is incompatible with the current study since it focuses on statistical and numerical techniques for data interpretation and generating causality cases, both of which are not necessary for the present investigation. In terms of research design, a systematic review is used, which aids in the identification, selection, and critical evaluation of relevant studies as well as the collection and analysis of the data from the literature contributed by the researchers. Since the systematic review design is linked to the qualitative approach and aid in the development of extensive insights, the present study employed it. Secondary sources used to obtain data, including high-quality journal publications from the previous 12 years, are chosen (2010 to 2022). In terms of inclusion criteria, only publications and journals published in the English language with public access were included in the present study. Moreover, no articles older than 2010 were chosen; therefore, publications between (2010-2022) were selected for the present study. A thematic analysis technique was employed used to examine the information, which is commonly used in qualitative studies and aids in the study of secondary data by recognizing and understanding various concepts in the study. The systematic review of the literature shows that scholars have regarded CFD modeling, FDS, and CFAST as highly effective tools when numerical simulations of the fire spread in a building are measured. The results show that FDS is highly effective in getting numerical simulations of the fire spread in various buildings as compared to CFAST. Moreover, software accuracy and precision, increased use of the technology are the factors that can help in reducing fire occurrences in buildings. When the numerical simulations provided by this software are timely considered, fire occurrences in buildings can be minimized, and the evacuation process is accelerated.

Limitations of the study

The present study is based on a systematic review of the literature to examine numerical simulation of fire spreading in different kinds of buildings. It has mainly reviewed the FDS, CFAST and CFD models. The study does not consider any other aspect than discussing the numerical simulation of fire spreading in various buildings based on the above-mentioned models. Likewise, the present study is limited as it only provides insights into the factors and measures which can assist in reducing fire occurrences in buildings and the effectiveness of the CFD and FDS models during fire spread. The study does not provide any statistical calculation or correlation between these models when considering the fore spread in various buildings. Moreover, the study does not employ primary data, adding responses from the experts and scientists to get their perspectives about the effectiveness of these models.

Recommendations

Owing to the limitations of the present study, it is suggested that future researchers must consider other dimensions and models when studying fire spread in various buildings. Future researchers must consider more tools and models than FDS and CFAST when numerical simulations are examined within the Computational Fluid Dynamics (CFD). It is suggested that future researchers should also focus on wildfire regions other than America and Australia when numerical simulations of fire simulations are studied. Likewise, the research comprising case study analysis or a mixed-method approach that considers both qualitative and quantitative data analysis can be conducted in the future. Thus, future research should look into other areas of numerical simulations and models than FDS and CFAST.

References

[1] Z. Lu, X. He, and Y. Zhou, "Performance-based seismic analysis on a super high-rise building with improved viscously damped outrigger system," *Structural Control and Health Monitoring*, vol. 25, no. 8, 2018.

[2] X. Yi, C. Lei, J. Deng, L. Ma, J. Fan, Y. Liu, L. Bai, and C.-M. Shu, "Numerical simulation of fire smoke spread in a super high-rise building for different fire scenarios," *Advances in Civil Engineering*, vol. 2019, pp. 1–11, 2019.

[3] W. Z. Black, "Smoke movement in elevator shafts during a high-rise structural fire," *Fire Safety Journal*, vol. 44, no. 2, pp. 168–182, 2009.

[4] Y.-jian Liao, G.-xuan Liao, and S.-ming Lo, "Influencing factor analysis of Ultra-tall building elevator evacuation," *Procedia Engineering*, vol. 71, pp. 583–590, 2014.

[5] L. Hu, J. A. Milke, and B. Merci, "Special issue on fire safety of high-rise buildings," *Fire Technology*, vol. 53, no. 1, pp. 1–3, 2016.

[6] T. T. Lie and J. H. McGuire, "Control of smoke in high-rise buildings," *Fire Technology*, vol. 11, no. 1, pp. 5–14, 1975.

[7] G. Hadjisophocleous and Q. Jia, "Comparison of FDS prediction of smoke movement in a 10-storey building with experimental data," *Fire Technology*, vol. 45, no. 2, pp. 163–177, 2009.

[8] Y. Wang, G. Hadjisophocleous, and E. Zalok, "Smoke movement in multi-storey buildings using cusmoke," *Safety Science*, vol. 52, pp. 13–27, 2013..

[9] A. Soltanzadeh, M. Alaghmandan, and H. Soltanzadeh, "Performance evaluation of refuge floors in combination with egress components in high-rise buildings," *Journal of Building Engineering*, vol. 19, pp. 519–529, 2018.

[10] N. Shinomiya, S. Takada, and T. Ushio, "Study on ventilation in high-rise building based on pressure differences measured at elevator doors," *Energy Procedia*, vol. 78, pp. 2712–2716, 2015.

[11] T. Pasquay, "Natural ventilation in high-rise buildings with double facades, saving or waste of energy," *Energy and Buildings*, vol. 36, no. 4, pp. 381–389, 2004.

[12] J. Zhou, J. Mao, Y. Huang, and Z. Xing, "Studies on smoke temperature distribution in a building corridor based on reduced-scale experiments," *Journal of Asian Architecture and Building Engineering*, vol. 16, no. 2, pp. 341–348, 2017.

[13] T. Baalisampang, E. Saliba, F. Salehi, V. Garaniya, and L. Chen, "Optimisation of smoke extraction system in fire scenarios using CFD modelling," *Process Safety and Environmental Protection*, vol. 149, pp. 508–517, 2021.

[14] A. Polanczyk, P. Wawrzyniak, and I. Zbicinski, "CFD analysis of Dust Explosion Relief System in the counter-current industrial spray drying tower," *Drying Technology*, vol. 31, no. 8, pp. 881–890, 2013.

[15] P. Wawrzyniak, M. Podyma, I. Zbicinski, Z. Bartczak, and J. Rabaeva, "Modeling of air flow in an industrial countercurrent spray-drying tower," *Drying Technology*, vol. 30, no. 2, pp. 217–224, 2011.

[16] A. Ziemińska-Stolarska, A. Polańczyk, and I. Zbiciński, “3-D CFD simulations of hydrodynamics in the Sulejow Dam Reservoir,” *Journal of Hydrology and Hydromechanics*, vol. 63, no. 4, pp. 334–341, 2015.

[17] W. Węgrzyński, T. Lipecki, and G. Krajewski, “Wind and fire coupled modelling—part II: Good practice guidelines,” *Fire Technology*, vol. 54, no. 5, pp. 1443–1485, 2018.

[18] D. I. Kolaitis, E. K. Asimakopoulou, and M. A. Founti, "Fire behaviour of gypsum plasterboard wall assemblies: CFD simulation of a full-scale residential building," *Case Studies in Fire Safety*, vol. 7, pp. 23–35, 2017.

[19] K. McGrattan, R. McDermott, J. Floyd, S. Hostikka, G. Forney, and H. Baum, "Computational fluid dynamics modelling of fire," *International Journal of Computational Fluid Dynamics*, vol. 26, no. 6-8, pp. 349–361, 2012.

[20] Z. Salamonowicz, M. Majder-Lopatka, A. Dmochowska, A. Piechota-Polanczyk, and A. Polanczyk, "Numerical Analysis of smoke spreading in a medium-high building under different ventilation conditions," *Atmosphere*, vol. 12, no. 6, p. 705, 2021.

[21] J. Ho Siew Kit, C. Kok Hing, B. T. Wong, V. Bong Nee Shin, L. Man Djun, and C. J. Anak Boniface, "Numerical simulation of alternative smoke control approach in a high-rise building," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 80, no. 2, pp. 1–12, 2021.

[22] H. Yi, Y. Feng, and Q. Wang, "Computational Fluid Dynamics (CFD) study of heat radiation from large liquefied petroleum gas (LPG) Pool Fires," *Journal of Loss Prevention in the Process Industries*, vol. 61, pp. 262–274, 2019.

[23] B. Lee and M. N. K. Saunders, "Conducting case study research for business and management students," 2017.

[24] C. B. Jang, S.-W. Choi, and J.-B. Baek, "CFD modeling and Fire Damage Analysis of jet fire on hydrogen pipeline in a pipe rack structure," *International Journal of Hydrogen Energy*, vol. 40, no. 45, pp. 15760–15772, 2015.

[26] D. Burlacu, I. Anghel, C. Popa, and I. Căşaru, "Fire safety evaluation of an underground car park using numerical simulation," *Mathematical Modelling in Civil Engineering*, vol. 14, no. 2, pp. 1–12, 2018.

[27] M. Founti, "Numerical simulation of fire spreading in a two-storey residential building," *Academia.edu*, 22-Apr-2021. [Online]. Available: https://www.academia.edu/47457771/Numerical_Simulation_of_Fire_Spreading_in_a_Two_Storey_Residential_Building. [Accessed: 31-Jan-2022].

[28] G. Rein, "A comparison of three models for the simulation of accidental fires," *Journal of Fire Protection Engineering*, vol. 16, no. 3, pp. 183–209, 2006.

[29] E. A. Khan, M. A. Ahmed, E. H. Khan, and S. C. Majumder, "Fire emergency evacuation simulation of a shopping mall using fire dynamic simulator (FDS)," *Journal of Chemical Engineering*, vol. 30, no. 1, pp. 32–36, 2017.

[30] M. Pachera, P. Brunello, and M. R. Castelli, 2015 “Validation of fire dynamic simulator (FDS) for pool fire ...” [Online]. Available: http://www.ecm2015.hu/papers/P4-20.pdf. [Accessed: 31-Jan-2022].

[31] M. Weng, I. Obadi, F. Wang, F. Liu, and C. Liao, "Optimal distance between jet fans used to extinguish metropolitan tunnel fires: A case study using fire dynamic simulator modeling," *Tunnelling and Underground Space Technology*, vol. 95, p. 103116, 2020.

[32] A. Cicione and R. S. Walls, "Towards a simplified fire dynamic simulator model to analyse fire spread between multiple informal settlement dwellings based on full-scale experiments," *Fire and Materials*, vol. 45, no. 6, pp. 720–736, 2020.

[33] C. B. Choi, Y. J. Jang, K. Lee, and K. S. Yang, "Fire dynamic simulator with marker particles," *Journal of computational fluids engineering*, vol. 16, no. 4, pp. 55–63, 2011.

[34] M. Tzani, J. Besharat, V. Charalampous, and C. Stylios, "Building a virtual reality fire environment based on fire dynamic simulator," *2020 International Conference on Information Technologies (InfoTech)*, 2020.

[35] R. D. Peacock, W. W. Jones, P. A. Reneke, and G. P. Forney, "CFAST-consolidated model of fire growth and Smoke Transport (version 6) :" 2005.

[36] S. Jain, S. Kumar, S. Kumar, and T. P. Sharma, "Numerical simulation of fire in a tunnel: Comparative study of CFAST and CFX predictions," *Tunnelling and Underground Space Technology*, vol. 23, no. 2, pp. 160–170, 2008.

[37] Y.-H. Lee, J.-H. Kim, and J.-E. Yang, "Application of the CFAST zone model to the fire PSA," *Nuclear Engineering and Design*, vol. 240, no. 10, pp. 3571–3576, 2010.

[38] C. Caliendo, P. Ciambelli, R. Del Regno, M. G. Meo, and P. Russo, "Modelling and numerical simulation of pedestrian flow evacuation from a multi-storey historical building in the event of fire applying safety engineering tools," *Journal of Cultural Heritage*, vol. 41, pp. 188–199, 2020.

[39] R. Yakovchuk, Y. Ballo, A. Kuzyk, O. Kagitin, and V. Kovalchuk, "FDS modeling of the fire-preventing eaves effectiveness to prevent the fire spreading on facade of high-rise buildings," *Bulletin of Lviv State University of Life Safety*, vol. 23, pp. 39–45, 2021.

[40] J. Zhang, Y. Tao, X. Liu, and H. Zhao, "Fire simulation research on a bus based on Pyrosim," *Journal of Physics: Conference Series*, vol. 1678, no. 1, p. 012100, 2020.

[41] R. S. Gomez, T. R. Porto, H. L. Magalhães, A. C. Santos, V. H. Viana, K. C. Gomes, and A. G. Lima, "Thermo-Fluid Dynamics Analysis of fire smoke dispersion and control strategy in buildings," *Energies*, vol. 13, no. 22, p. 6000, 2020.

[42] M. Elhelw, A. El-Shobay, A. Attia, and W. M. El-Maghlany, "Advanced dynamic modeling study of fire and smoke of crude oil storage tanks," *Process Safety and Environmental Protection*, vol. 146, pp. 670–685, 2021.

[43] R. Yang, F. Khan, M. Yang, D. Kong, and C. Xu, "A numerical fire simulation approach for effectiveness analysis of fire safety measures in floating liquefied natural gas facilities," *Ocean Engineering*, vol. 157, pp. 219–233, 2018.

[44] L. Pugnet, D. Chong, T. Duff, and K. Tolhurst, 2013. "(PDF) Wildland–Urban Interface (WUI) fire modelling using ..." [Online]. Available: https://www.researchgate.net/publication/273699623_Wildland-urban_interface_WUI_fire_modelling_using_PHOENIX_Rapidfire_A_case_study_in_Cavaillon_France. [Accessed: 31-Jan-2022].

[45] A. Palacios, B. Rengel, J. Casal, E. Pastor, and E. Planas, "Computational fluid dynamics modelling of hydrocarbon fires in Open Environments: Literature Review," *The Canadian Journal of Chemical Engineering*, vol. 98, no. 11, pp. 2381–2396, 2020.

[46] A. Rahmani and M. Salem, "Simulation of fire in Super High-rise hospitals using Fire Dynamics Simulator (FDS)," *Electronic Journal of General Medicine*, vol. 17, no. 3, 2020.

[47] E. Kashi and M. Bahoosh, "Jet fire assessment in complex environments using computational fluid dynamics," *Brazilian Journal of Chemical Engineering*, vol. 37, no. 1, pp. 203–212, 2020.

[48] R. Kallada Janardhan and S. Hostikka, "Predictive computational fluid dynamics simulation of fire spread on Wood Cribs," *Fire Technology*, vol. 55, no. 6, pp. 2245–2268, 2019.

[49]S. Gu, H. Kim and Y. Song, "A Study on Fire Features of Double-Skin Facade Structure by Using Fire Simulation (FDS)", *Fire Science and Engineering*, vol. 28, no. 1, pp. 1-11, 2014. Available: 10.7731/kifse.2014.28.1.001.

[50]A. Rahmani and M. Salem, "Simulation of Fire in Super High-Rise Hospitals Using Fire Dynamics Simulator (FDS)", *Electronic Journal of General Medicine*, vol. 17, no. 3, p. em200, 2020. Available: 10.29333/ejgm/7848.

[51]Z. Huang, Y. Meng, R. Yang, Y. Gao, Z. Yinghua and S. Wang, "Numerical simulation of a cinema fire based on FDS", *International Journal of Simulation and Process Modelling*, vol. 13, no. 3, p. 200, 2018. Available: 10.1504/ijspm.2018.093093.

[52]S. Min and S. Kim, "Efficiency in Parallel Computing of FDS Model for Compartment Fire Simulation: Shared Memory System", *Fire Science and Engineering*, vol. 35, no. 2, pp. 16-22, 2021. Available: 10.7731/kifse.756398f1.

[53]K. YANAGIDA and S. NISHIKI, "Numerical simulation of the evacuation in a tunnel fire by FDS+Evac", *The Proceedings of Mechanical Engineering Congress, Japan*, vol. 2018, no. 0, p. S0540302, 2018. Available: 10.1299/jsmemecj.2018.s0540302.

[54]S. Šulc, V. Šmilauer and F. Wald, "COUPLED SIMULATION FOR FIRE-EXPOSED STRUCTURES USING CFD AND THERMO-MECHANICAL MODELS", *Acta Polytechnica CTU Proceedings*, vol. 13, p. 121, 2017. Available: 10.14311/app.2017.13.0121.

[55]S. Editor, "Planning a Resilient City: A Strategy of Green Space Planning by Using Numerical Simulation Method of GIS-CFD", *International Journal of Simulation: Systems, Science & Technology*, 2016. Available: 10.5013/ijssst.a.17.33.60.

[56]G. Boyer, "Fully coupled CFD simulation of the pyrolysis of non-charring polymers: A predictive approach", *Fire Safety Journal*, vol. 91, pp. 208-217, 2017. Available: 10.1016/j.firesaf.2017.03.070.

[57]F. Jia, E. Galea and M. Patel, "The Numerical Simulation of Enclosure Fires Using a Cfd Fire Field Model Coupled With a Pyrolysis Based Solid Fuel Combustion Submodel--a First Approximation", *Journal of Fire Protection Engineering*, vol. 9, no. 4, pp. 1-17, 1998. Available: 10.1177/104239159800900402.

[58]J. Floyd, "CFD Fire Simulation Using Mixture Fraction Combustion and Finite Volume Radiative Heat Transfer", *Journal of Fire Protection Engineering*, vol. 13, no. 1, pp. 11-36, 2003. Available: 10.1177/1042391503013001002.

[59]B. Baek, C. Oh and C. Hwang, "Evaluation of Design Fire Curves for Gas Fires in a Compartment Using CFAST", *Fire science and engineering*, vol. 32, no. 4, pp. 7-16, 2018. Available: 10.7731/kifse.2018.32.4.007.

[60]J. Williamson, C. Beyler and J. Floyd, "Validation of Numerical Simulations of Compartment Fires with Forced or Natural Ventilation Using the Fire and Smoke Simulator (FSSIM), CFAST and FDS", *Fire Safety Science*, vol. 10, pp. 1277-1288, 2011. Available: 10.3801/iafss.fss.10-1277.

[61]B. Baek, C. Oh and C. Lee, "Evaluation of Modified Design Fire Curves for Liquid Pool Fires Using the FDS and CFAST", *Fire science and engineering*, vol. 32, no. 2, pp. 7-16, 2018. Available: 10.7731/kifse.2018.32.2.007.

[62]J. Yang, S. Baek, C. Lee and D. Kim, "Examination on Numerical Simulation Using Reduced-scale Model of Theater Fire: Influences of Fire Curtain and Stage Natural Vent", *Fire Science and Engineering*, vol. 33, no. 5, pp. 37-47, 2019. Available: 10.7731/kifse.2019.33.5.037.

[63]R. Regueira and M. Guaita, "Numerical simulation of the fire behaviour of timber dovetail connections", *Fire Safety Journal*, vol. 96, pp. 1-12, 2018. Available: 10.1016/j.firesaf.2017.12.005.

[64]L. Xu, "Numerical Simulation Research on Kitchen Fire of Ancient Buildings Under Water Spray Effect", *SSRN Electronic Journal*, 2021. Available: 10.2139/ssrn.3967946.

[65]M. Xu and D. Peng, "PyroSim-Based Numerical Simulation of Fire Safety and Evacuation Behaviour of College Buildings", *International Journal of Safety and Security Engineering*, vol. 10, no. 2, pp. 293-299, 2020. Available: 10.18280/ijsse.100218.

[66]A. Elghazouli, B. Izzuddin and A. Richardson, "Numerical modelling of the structural fire behaviour of composite buildings", *Fire Safety Journal*, vol. 35, no. 4, pp. 279-297, 2000. Available: 10.1016/s0379-7112(00)00044-8.

[67]X. Duanmu, Z. Zhan and Y. Song, "Numerical Simulation and Thermophysical Feature Analysis of Fire Propagation Law in Large Urban Rail Transit Buildings", *International Journal of Heat and Technology*, vol. 39, no. 6, pp. 1966-1972, 2021. Available: 10.18280/ijht.390635.

[68]C. Zhao, S. Lo, J. Lu and Z. Fang, "A simulation approach for ranking of fire safety attributes of existing buildings", *Fire Safety Journal*, vol. 39, no. 7, pp. 557-579, 2004. Available: 10.1016/j.firesaf.2004.06.001.

[69]J. Hua, J. Wang and K. Kumar, "Development of a hybrid field and zone model for fire smoke propagation simulation in buildings", *Fire Safety Journal*, vol. 40, no. 2, pp. 99-119, 2005. Available: 10.1016/j.firesaf.2004.09.005.

[70]T. Ma and J. Quintiere, "Numerical simulation of axi-symmetric fire plumes: accuracy and limitations", *Fire Safety Journal*, vol. 38, no. 5, pp. 467-492, 2003. Available: 10.1016/s0379-7112(02)00082-6.

[71]Y. Cao, M. Zhang, Q. Cheng and S. Zhang, "Peculiarities of hazardous chemical fire in high-rise R&D buildings based on numerical simulation", *Journal of Physics: Conference Series*, vol. 1827, no. 1, p. 012043, 2021. Available: 10.1088/1742-6596/1827/1/012043.

[72]Gerzhova, Blanchet, Dagenais, Côté and Ménard, "Heat Transfer Behavior of Green Roof Systems Under Fire Condition: A Numerical Study", *Buildings*, vol. 9, no. 9, p. 206, 2019. Available: 10.3390/buildings9090206.

[73]G. Wallace, "A Numerical Fire Simulation-Model", *International Journal of Wildland Fire*, vol. 3, no. 2, p. 111, 1993. Available: 10.1071/wf9930111.

[74]W. Chih and J. Geremia, "Analog simulation of a fire safety probability model for high-rise buildings", *Fire Technology*, vol. 9, no. 3, pp. 176-181, 1973. Available: 10.1007/bf02624774.

[75]F. Liu and J. Wen, "The effect of turbulence modelling on the CFD simulation of buoyant diffusion flames", *Fire Safety Journal*, vol. 37, no. 2, pp. 125-150, 2002. Available: 10.1016/s0379-7112(01)00022-4.

[76]W. Chih and J. Geremia, "Analog simulation of a fire safety probability model for high-rise buildings", *Fire Technology*, vol. 9, no. 3, pp. 176-181, 1973. Available: 10.1007/bf02624774.

[77]J. Hua, J. Wang and K. Kumar, "Development of a hybrid field and zone model for fire smoke propagation simulation in buildings", *Fire Safety Journal*, vol. 40, no. 2, pp. 99-119, 2005. Available: 10.1016/j.firesaf.2004.09.005.

[78]F. Jia, M. Patel, E. Galea, A. Grandison and J. Ewer, "CFD fire simulation of the Swissair Flight 111 in-flight fire – Part II: Fire spread analysis", *The Aeronautical Journal*, vol. 110, no. 1107, pp. 303-314, 2006. Available: 10.1017/s0001924000013178.

[79]Е. Кирик, К. Литвинцев, А. Тумановский and А. Шебеко, "CFD software FDS for fire simulation and its application for fire risk assessment", *Pozharnaia bezopasnost`*, no. 299, pp. 14-27, 2020. Available: 10.37657/vniipo.2020.99.2.001.

[80]F. Jia, E. Galea and M. Patel, "The Numerical Simulation of Enclosure Fires Using a Cfd Fire Field Model Coupled With a Pyrolysis Based Solid Fuel Combustion Submodel--a First Approximation", *Journal of Fire Protection Engineering*, vol. 9, no. 4, pp. 1-17, 1998. Available: 10.1177/104239159800900402.

[81]R. Hasib, R. Kumar, Shashi and S. Kumar, "Simulation of an experimental compartment fire by CFD", *Building and Environment*, vol. 42, no. 9, pp. 3149-3160, 2007. Available: 10.1016/j.buildenv.2006.08.002.

[82]A. Davidy, "CFD Simulation and Mitigation with Boiling Liquid Expanding Vapor Explosion (BLEVE) Caused by Jet Fire", *ChemEngineering*, vol. 3, no. 1, p. 1, 2018. Available: 10.3390/chemengineering3010001.

[83]S. Hostikka, *Development of fire simulation models for radiative heat transfer and probabilistic risk assessment*. Espoo: VTT, 2008.

[84]D. Pesic, D. Zigar, M. Raos and I. Anghel, "Simulation of fire spread between residential buildings regarding safe separation distance", *Tehnicki vjesnik - Technical Gazette*, vol. 24, no. 4, 2017. Available: 10.17559/tv-20150923233514.

[85]M. Brasseur and O. Vassart, *Fire safety of industrial halls and low-rise buildings*. Luxembourg: Office for Official Publications of the European Communities, 2007.

[86]D. Alvord, *The fire emergency evacuation simulation for multifamily buildings*. Gaithersburg, Md: National Bureau of Standards, 1984.

[87]D. Alvord, *Status report on the escape and rescue model and the fire emergency evacuation simulation for multifamily buildings*. Gaithersburg, Md.: National Bureau of Standards, 1985.

[88]X. Lu and H. Guan, *Earthquake disaster simulation of civil infrastructures*. Singapore: Springer, 2021.

[89]F. Jia, *The simulation of fire growth and spread within enclosures using an integrated CFD fire spread model*. University of Greenwich, 1999.

[90]J. Björkman and O. Keski-Rahkonen, *Simulation of the Steckler room fire experiment by using SOFIE CFD-model*. Espoo: Technical Research Centre of Finland, 1996.