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KA OKVIRU ZA UPRAVLJANJE POŽARNOM BEZBEDNOŠĆU ZASNOVANOM NA DIGITALNOM BLIZANCU PAMETNE ZGRADE

Key words: digital twin; fire safety; AI tools

TOWARDS DIGITAL-TWIN-BASED FIRE SAFETY MANAGEMENT FRAMEWORK FOR SMART BUILDINGS

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Ovaj rad istražuje razvoj i integraciju tehnologije digitalnih blizanaca u upravljanju protivpožarnom zaštitom, naglašavajući njen potencijal za unapređenje praksi bezbednosti zgrada. Korišćenjem naprednih alata kao što su PyroSim i BIM, u kombinaciji sa podacima u realnom vremenu sa IoT senzora i prediktivnom analitikom koju pokreće veštačka inteligencija, digitalni blizanci stvaraju dinamične virtuelne prikaze fizičkih prostora. Takvi sistemi omogućavaju precizne simulacije požara, praćenje u realnom vremenu i optimizovane strategije evakuacije, osiguravajući pravovremene i efikasne odgovore na vanredne situacije. Metodologija uključuje I napredne tehnike obrade podataka, povratne petlje simulacija uživo i vizualizaciju poboljšanu AR-om za poboljšanje donošenja odluka i situacione svesti. Integracija takvih tehnologija pokazuje značajan pomak ka proaktivnim i otpornim okvirima protivpožarne zaštite, premošćujući jaz između tradicionalnih statičkih protokola i adaptivnih, podacima vođenih rešenja.

This work explores the development and integration of digital twin technology in fire safety management, emphasizing its potential to improve building safety practices. By utilizing advanced tools like PyroSim and BIM, combined with real-time data from IoT sensors and predictive analytics powered by artificial intelligence, digital twins create dynamic virtual representations of physical spaces. These systems enable accurate fire simulations, real-time monitoring, and optimized evacuation strategies, ensuring timely and effective responses to emergencies. The methodology also incorporates advanced data processing techniques, live simulation feedback loops, and AR-enhanced visualization to improve decision-making and situational awareness. The integration of such technologies demonstrates a significant shift towards proactive and resilient fire safety frameworks, bridging the gap between traditional static protocols and adaptive, data-driven solutions.

1. Introduction

The concept of digital twins has become important in recent years as an advanced tool for managing fire safety within increasingly complex and densely populated environments. As cities continue to grow, and buildings become larger and more intricate, traditional fire management strategies face limitations due to their static nature and inability to adapt quickly to unfolding situations. Researchers, including Zhang et al [1]., have shown how the integration of various advanced technologies into a cohesive digital twin framework can transform fire safety. By connecting Building Information Modelling (BIM), Internet of Things (IoT) networks, and dynamic simulation tools like the Fire Dynamics Simulator (FDS), this approach enables real-time monitoring, simulation, and decision-making that far surpass traditional methods.

The Fire-Evacuation Digital Twin (FEDT) framework proposed by Zhang et al. demonstrates how digital twin systems can improve fire management by simulating fire behaviour dynamically while optimizing evacuation strategies. This framework incorporates three-dimensional modelling, continuous data updates, and intelligent decision-making algorithms to manage fire emergencies in large infrastructures, such as airport terminals. The FEDT system integrates real-time data from sensors embedded within buildings, creating a virtual representation that reflects current fire conditions. In their studies, the application of FEDT led to a reduction in evacuation times by over 27%, as compared to traditional approaches.

BIM is an important part of the digital twin approach for fire safety. Siddiqui et al. [2] emphasize that BIM allows for the detailed documentation and analysis of building data throughout its lifecycle. By ensuring that essential fire safety information is integrated into the BIM model, stakeholders can access up-to-date and accurate data in the event of an emergency. This strategy is particularly valuable for identifying high risk areas, planning evacuation routes, and evaluating the effectiveness of fire safety designs.

The integration of artificial intelligence into digital twin systems significantly enhances their capabilities for managing fire safety. Zhang [3] introduced the Artificial Intelligent Digital Twin of Fire (AID-Fire), a system designed to forecast fire progression and critical events using machine learning algorithms. This system was developed by training convolutional neural networks on large datasets containing information on various fire scenarios. By analysing real-time sensor data, AID-Fire can predict the evolution of a fire, enabling faster and more informed responses. Laboratory experiments validated the system’s accuracy, showing it could predict fire events with minimal delay and errors below 15%. Furthermore, the system is capable of anticipating critical phenomena such as flashover and backdraft, which are typically challenging to predict using conventional methods. These capabilities allow for more effective firefighting and evacuation strategies, ultimately improving safety for building occupants.

Virtual reality (VR) and augmented reality (AR) technologies have further expanded the applications of digital twins in fire safety. Liu et al. [4] explored the use of VR to create realistic simulations of fire evacuation scenarios, allowing researchers to study human behaviour and test new tools in controlled environments. Their work demonstrated how VR simulations could be used to evaluate the performance of novel firefighting equipment, such as helmet-mounted heat sensors with integrated displays. These devices provide firefighters with enhanced situational awareness, enabling them to locate fire sources and navigate smoke-filled environments more effectively. Additionally, AR systems have the potential to overlay critical information, such as building layouts and fire progression data, onto the firefighter’s field of view, improving decision-making during emergencies. By combining VR and AR, digital twin systems can provide comprehensive training environments and real-time operational support.

Simulation tools like PyroSim play a very important role in digital twin frameworks. Shih and Tsai [5] developed a method that uses fire prediction models to create dynamic evacuation plans based on real-time sensor data. Their approach divides large buildings into smaller sections and computes evacuation paths for each section simultaneously, significantly reducing the time required to generate evacuation plans. This method also accounts for the dynamic nature of fire spread, ensuring that evacuees are directed away from hazardous areas. Their simulations demonstrated that this system was ten times faster than conventional approaches and resulted in higher survival rates during fire emergencies. This highlights how digital twins can be adapted to handle the unpredictability of real-world fire scenarios.

Case studies provide further evidence of the potential benefits of digital twin technology in fire safety. Lv et al. [6] conducted simulations of fire scenarios in Airbus A350-900 aircraft cabins, focusing on evacuation under different fire and tilt conditions. Their analysis revealed that factors such as seat layout and partition design significantly influenced passenger safety, leading to recommendations for optimizing cabin configurations. Similarly, Floyd and Madrzykowski [7] revisited a historical firefighter line-of-duty death using modern fire dynamics modelling tools. Their study evaluated how advancements in equipment standards and fire modelling techniques could have prevented the incident, emphasizing the need for continuous innovation in fire safety practices.

Despite the many advantages of digital twin systems, challenges remain that need to be addressed to fully realize their potential. One of the primary obstacles is the lack of standardization and interoperability among different systems. For example, the data formats used by BIM and fire simulation tools are not always compatible, making it difficult to integrate these systems into a unified framework. Siddiqui argue for the development of standardized data exchange protocols to address this issue. Another challenge is the reliability of IoT sensors, which can be compromised during fires. Developing more resilient sensors and communication networks is essential to ensure the effectiveness of real-time systems. Furthermore, the successful deployment of digital twin systems depends on their usability for end-users. For example, firefighters and building operators must be able to use AR and VR tools effectively during emergencies, which requires careful design to account for human cognitive and physical limitations.

By considering the keywords from the recent studies having similar subjects a Word Cloud can be developed, and it is presented in Figure 1.

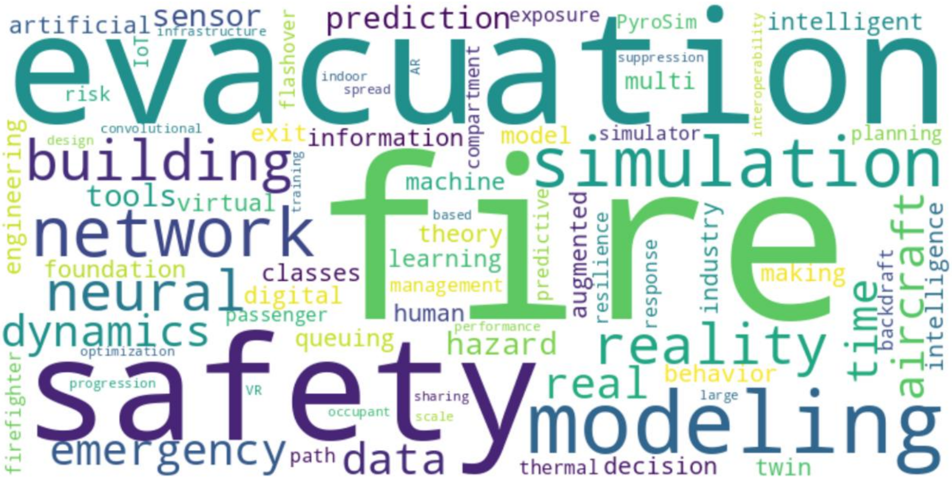

Figure 1. Word Cloud on digital-twin-based fire safety management framework for smart buildings

This paper proposes a simplified framework for designing a digital twin for fire safety by using a real building simulation and explores the advantages and the challenges involved in the process.

2. Methodology

The methodology for creating a robust fire safety management (FSM) framework leveraging digital twin technology integrates advanced simulation tools, real-time data processing, and predictive analytics to address the dynamic nature of fire emergencies.

This approach, presented in Figure 2, is designed to overcome the limitations of traditional fire safety practices by employing a comprehensive and interconnected system that ensures real-time responsiveness and predictive capability.

The framework begins with the digital modelling of the building environment using tools such as PyroSim and Building Information Modelling (BIM). PyroSim serves as the primary simulation tool for fire dynamics, allowing detailed visualizations of potential fire scenarios, including smoke spread, heat distribution, and evacuation dynamics. BIM complements this by providing an accurate and structured spatial representation of the building, ensuring that all critical architectural and structural details are incorporated into the simulations. This base step establishes a virtual replica of the building, serving as the backbone of the digital twin.

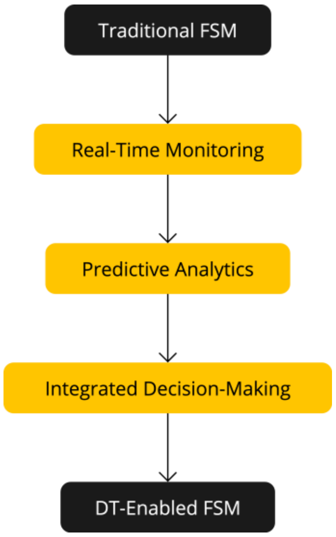

Figure 2. Fire safety management approach

Real-time data integration forms the second component of the methodology. IoT sensors strategically placed throughout the building monitor key parameters such as temperature, smoke concentration, and air quality. These sensors continuously feed data into the digital twin system, ensuring that the virtual model reflects the real-world state of the building at any given moment. This integration is achieved through data pipelines that convert sensor outputs into formats compatible with simulation tools like PyroSim. Pre-processing tools, often developed in Python, handle data formatting and ensure seamless communication between physical sensors and the virtual environment.

The dynamic aspect of this methodology is further enhanced through live data processing and real-time feedback loops. For instance, temperature spikes detected by sensors can trigger updates to the fire simulation model, allowing it to predict the fire's progression under changing conditions. Scripts can be employed to dynamically modify simulation parameters, adjusting factors such as heat release rates and smoke behaviour. This capability ensures that the digital twin adapts to the evolving nature of the fire, providing valuable insights into how the situation may unfold.

Predictive analytics powered by artificial intelligence (AI) represents the third element of the framework. AI models trained on historical fire data and simulations are integrated into the digital twin to forecast potential outcomes. These models can predict critical events such as flashover or the spread of flames, enabling proactive decision-making. For instance, neural networks may analyse sensor data to estimate the time available for safe evacuation or to identify areas of the building at the greatest risk. This predictive capacity significantly enhances the effectiveness of the FSM framework by providing actionable intelligence before critical thresholds are reached.

Visualization tools, including augmented reality (AR), are incorporated into the framework to improve situational awareness and decision-making. AR overlays real-time fire data onto the physical environment, providing first responders and building operators with a clear understanding of the situation. For example, AR devices can display optimal evacuation routes, highlight areas with high heat concentration, or indicate the location of trapped occupants. This level of visibility is critical for coordinating emergency responses effectively and ensuring occupant safety.

Another important component of the methodology involves evacuation optimization. The digital twin simulates various evacuation scenarios, accounting for factors such as population density, exit availability, and fire spread. These simulations inform the development of dynamic evacuation plans that adapt in real-time based on sensor inputs and predictive analytics. For instance, if a primary exit becomes inaccessible due to smoke or fire, the system can immediately recalibrate evacuation routes, directing occupants to alternate exits.

The framework also emphasizes the importance of post-event analysis and feedback. After a fire incident, data collected by the digital twin can be analysed to evaluate the effectiveness of the response and identify areas for improvement. This iterative process ensures that the FSM framework evolves and improves over time, incorporating lessons learned from real-world scenarios.

3. Case study

The methodology framework is further presented on a real case scenario. The procedure starts with employing real sensor data within digital twin-based fire safety frameworks focuses on integrating real-time information into dynamic simulations to provide a responsive and adaptive fire management system. This approach combines advanced simulation tools, sensor technologies, and computational methods to enhance situational awareness, predict fire progression, and optimize responses during emergencies. The building modelled in PyroSim is presented in Figure 3.

PyroSim is advanced fire modelling software that allows users to simulate fire dynamics, smoke movement, and heat distribution within complex building environments using the Fire Dynamics Simulator (FDS) as its core engine. It is very important for fire safety as it provides accurate visualizations, enabling the design of effective evacuation plans, risk assessments, and fire mitigation strategies in both real-time and pre-incident scenarios. Smoke extraction systems and sprinklers systems can be integrated into the model, and different fire scenarios can be explored by setting an object to virtually catch fire, for example a car. In order to do this, a graph presenting the Heat Release Rate (HRR) should be incorporated into the software. After the object catches fire, the program models how the fire evolves, the effect on temperature, pressure, visibility in that specific area.

The next step in this methodology involves pre-processing real-world sensor data for integration into fire simulation software like PyroSim. Sensor data, such as temperature readings, smoke concentration, and air quality, are recorded and exported into formats compatible with the Fire Dynamics Simulator (FDS). This step typically involves saving the data in structured file types like CSV or JSON. Pre-processing scripts are then used to convert this data into FDS-compatible entries, such as time-varying heat release rates or smoke concentration profiles. Python scripts, for example, can map sensor data into &TIME, &DEVC, or &CTRL entries, which allow the simulation to reflect realistic environmental conditions dynamically. This step ensures that simulations are not only accurate but also reflective of actual fire scenarios. In Figure 4 it is presented an example of such a script.

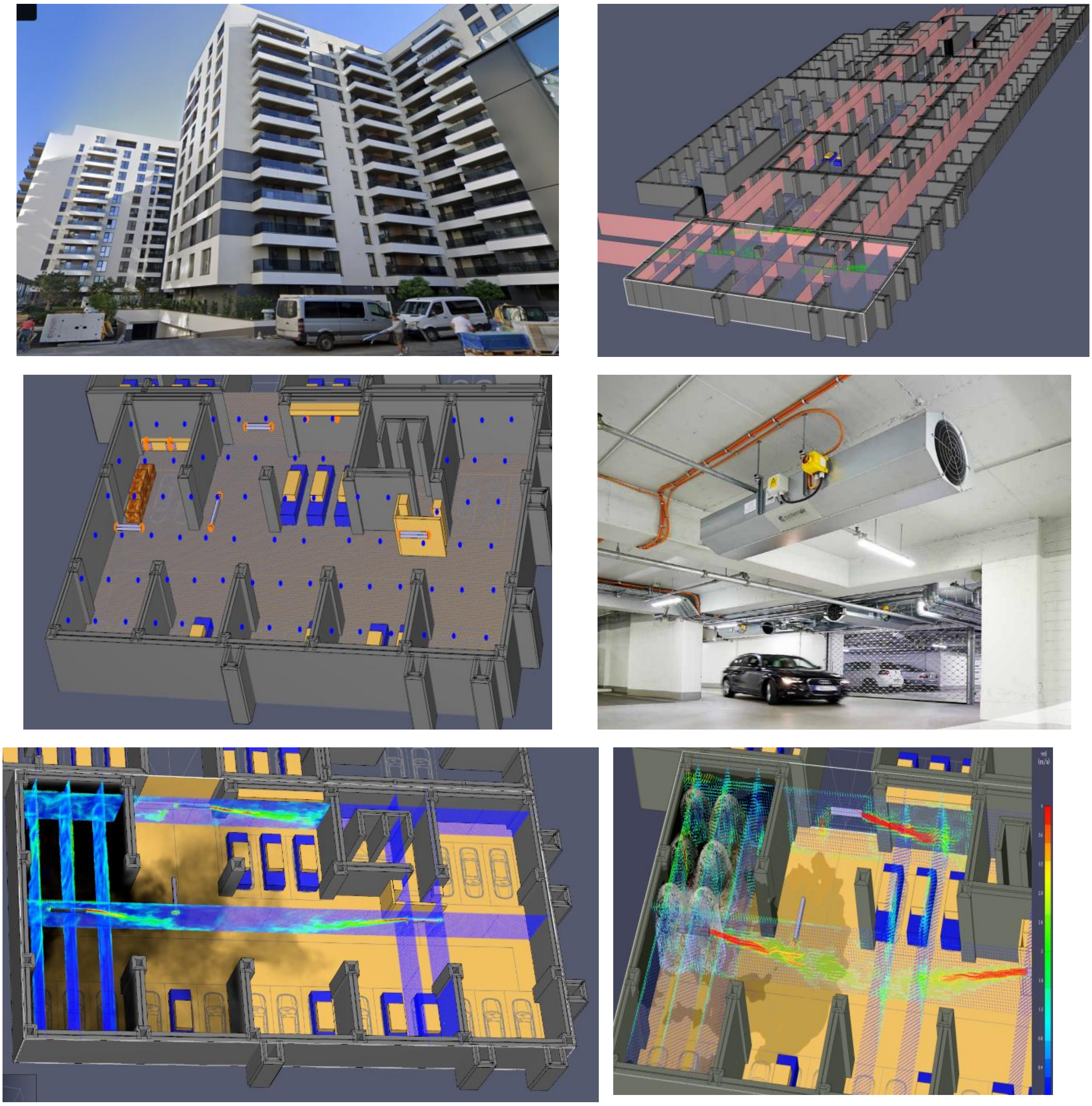

Figure 3. Modelled building– Different scenarios explored through Pyrosim

```
import requests
# Fetch data from a sensor API
response = requests.get("http://sensor-api.local/temperature")
temp_data = response.json()
# Write updated FDS control logic
with open("live_simulation.fds", "w") as fds_file:
fds_file.write(f"&DEVC ID='Sensor_1',
QUANTITY='TEMPERATURE', VALUE={temp_data['value']} /")
```

Figure 4. Script for importing data into PyroSim (example)

Incorporating live sensor data into simulations represents the next phase of the methodology. This involves setting up a system that continuously pulls real-time data from sensors during the simulation runtime. APIs and communication protocols like MQTT or HTTP facilitate this data exchange. Python scripts are often utilized to fetch this data in real-time, dynamically adjusting simulation parameters based on incoming information. For instance, if sensors detect an increase in temperature in a specific area, the simulation updates to reflect accelerated fire growth or altered heat release rates. This dynamic interaction between physical sensors and virtual simulations enhances the accuracy and responsiveness of the digital twin.

A more advanced application involves coupling live data with simulation updates in a real-time feedback loop. This approach enables the simulation to respond dynamically to ongoing changes in the environment as detected by the sensors. For example, fire spread rates and heat release parameters are adjusted during the simulation based on live inputs. This coupling requires external frameworks like MATLAB or Simulink, which can process sensor data and feed it back into the simulation engine. This methodology not only captures the immediate state of the environment but also anticipates changes, enabling proactive interventions.

Incorporating IoT-enabled automation into the system enhances its functionality. IoT sensors deployed across the building relay continuous streams of data to the digital twin, providing a comprehensive view of the environment. These devices not only capture static data but also track dynamic changes, such as rising temperatures or smoke movement. By integrating IoT data directly into simulations, the digital twin becomes a real-time reflection of the physical space, enabling timely and informed decision-making.

The methodology also includes provisions for using blockchain technology to ensure the integrity and reliability of sensor data. Blockchain can record data transactions in a tamper-proof manner, ensuring that the information fed into the simulation is authentic and has not been altered. This is particularly important in scenarios where data accuracy is critical for decision-making, such as during emergency evacuations.

Another key element is data visualization and result interpretation. Simulations are rendered in PyroSim or other visualization platforms to create detailed and accessible representations of fire dynamics and evacuation scenarios. The visualization aids decision-makers by illustrating smoke propagation, heat distribution, and potential evacuation bottlenecks in real-time. These outputs can also be displayed in augmented reality (AR) environments, offering an intuitive way for emergency responders to interpret and act on the data.

Finally, the methodology includes continuous evaluation and feedback to refine the system. After each simulation or real-world incident, the collected data and system performance are analysed to identify areas for improvement. This iterative process ensures that the digital twin evolves over time, incorporating lessons learned and adapting to new challenges.

4. Conclusions

The proposed methodology for implementing digital twin-based fire safety management systems offers a step-by-step approach to transforming traditional fire safety practices into dynamic, adaptive frameworks. The process begins with creating a detailed digital model of the building using PyroSim and BIM, capturing spatial and architectural details critical for fire simulation. Real-time data from IoT sensors are integrated to continuously update the digital twin, ensuring accurate reflection of evolving conditions. Pre-processed sensor data or live inputs dynamically adjust fire simulation parameters, enhancing the model’s responsiveness. Predictive analytics powered by AI enable forecasting of critical events such as flashover and fire spread, improving decision-making and response planning. The system incorporates AR for enhanced visualization, aiding in situational awareness and evacuation management. By putting together coupled simulations and advanced feedback mechanisms, the methodology ensures a seamless integration of real-world data and virtual modelling to create a robust and proactive fire safety framework. This approach highlights the transformative potential of digital twins in enhancing resilience and safety in modern buildings.

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