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Integrated System for Early Fire Detection and Evacuation Based on Arduino

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Abstract The research relevance is determined by the need to create reliable and adaptive fire protection systems capable of quick response to threats and provision of safe evacuation in real time. The study aimed to develop and test an integrated system for early fire detection and safe evacuation based on Arduino with an adaptive route control algorithm. The research methodology consisted of creating an integrated Arduino-based early fire detection and evacuation management system with MQ gas sensors, actuators, and a server data processor, where the Dijkstra algorithm provided dynamic route updates, and the effectiveness of the system was evaluated through testing in simulated scenarios. The study confirmed that calibrated MQ series sensors, combined with signal filtering, provide reliable detection of hazardous gas concentrations and reduce the probability of false alarms, forming a sufficient information base for early detection of fire risks. The adaptive evacuation algorithm effectively responds to dynamic changes in the situation by correcting the building graph and promptly re-planning routes without critical time losses. The warning system demonstrates high consistency with the analytical module: sound and light signals are activated in a timely manner and correctly reflect the current safe routes, reducing the risk of disorientation. Centralised server processing and data visualisation provide comprehensive monitoring in near real time, supporting event analysis and system scaling. Overall, the proposed approach improves response speed, evacuation reliability and the practical suitability of the system for use in real emergencies. The results of the study can be used by fire safety system developers, automation engineers, building and engineering system designers, managers of enterprises and institutions responsible for personnel safety, as well as for scientists researching the integration of IoT and optimisation algorithms in early emergency detection systems.

Keywords Gas Sensors, Graph Algorithms, Smart City, Building Safety, Critical Readings

AMS 2010 subject classifications 68M10, 68M11, 93C40

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1. Introduction

Fire is one of the most serious threats to human life and health, especially in the context of modern urbanisation and increasing building density. Traditional fire safety systems, despite their widespread use, often prove to be insufficiently effective in dynamically changing situations. This creates the need to develop more advanced solutions capable of responding quickly to emerging threats and ensuring safe evacuation.

In contemporary scientific discourse, research on early fire detection systems and IoT integration increasingly focuses on combining sensor networks, routing algorithms, and automated alert systems. For example, Akpan et al. [1] described in detail the architecture of a system in which sensor data is continuously collected and processed for the timely detection of potential fire hazards. The study demonstrated that the combination of gas and smoke

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sensors with automated actuators can significantly reduce emergency response times and improve evacuation efficiency. At the same time, O'Halloran et al. [2] analysed the application of graph theory to predict the spread of functional failures in systems at the conceptual design stage. The study demonstrated that graph models can be used for the assessment of critical nodes and paths of potential failure propagation, which is relevant for the construction of adaptive evacuation algorithms, where building nodes and connections between them are modelled as a graph. Another perspective was proposed by Wayahdi et al. [3] in a comparative analysis of the Greedy, A-Star, and Dijkstra algorithms for finding the shortest path. The study proved that the Dijkstra algorithm provides stable and optimal route determination in structured graph models, especially under conditions of dynamic changes in edge parameters that simulate real fire hazard conditions.

The problem of early fire detection and effective evacuation of people from buildings has become a topical issue due to the increasing number of emergencies. Suwarjono et al. [4] investigated the effectiveness of using microcontrollers to automate fire detection processes, emphasising their affordability and ease of integration with various sensors. In their work, they highlighted the importance of the timely response of systems to critical readings to prevent serious consequences. Solórzano et al. [5] emphasised the use of gas sensors for early detection of hazardous conditions, which significantly reduced the response time in the event of a fire. In their work, they examined different types of gas sensors and their sensitivity to specific threats such as carbon monoxide and smoke. Cheng et al. [6] proposed the use of graph-based algorithms to optimise evacuation routes during emergencies, which was used to simulate complex situations in real time. They analysed different approaches to build evacuation models that maximise safety and efficiency. Lewin et al. [7] emphasised the need for adaptive systems that could accommodate changes in the building infrastructure, such as the temporary blocking of exits. In their work, they proposed methods to allow systems to dynamically update the status of escape routes. Bochi et al. [8] focused on developing solutions to enable evacuation of occupants under time constraints, pointing out the importance of quick access to exit status information. They also considered the impact of crowd psychology on the evacuation process and possible ways to improve it.

Ding et al. [9] studied the impact of crowd density on the effectiveness of evacuation algorithms, identifying key factors affecting the speed and safety of exiting a building. In their work, they gave examples of situations in which high human density could lead to congestion and increased evacuation time. Deng et al. [10] proposed ways to dynamically recalculate evacuation routes based on the current situation in the building, allowing the system to adapt to changing conditions. They also described algorithms that could automatically realign routes when obstacles were encountered. Apanavičienė and Shahrabani [11] investigated the possibilities of integrating fire systems with other elements of a smart city to improve safety, emphasising the importance of data coordination between different systems. They also analysed how such integration could contribute to a more efficient use of resources in emergencies. Coughlan et al. [12] analysed the benefits of using machine learning to predict fire development and adjust system actions, thus minimising damage and risks to people. They looked at different algorithms that could improve prediction accuracy and speed up system response. Teguh et al. [13] examined the role of mobile applications in citizen coordination during a fire, focusing on their potential effectiveness for information dissemination. In their work, they proposed methods for interfacing mobile applications with major evacuation control systems. However, despite existing developments, there are gaps in research on the adaptation of systems to dynamic changes in buildings and the need for integration with other elements of a smart city, which requires further investigation.

The main gap in previous studies is the lack of a comprehensive approach to fire safety that would combine early threat detection, real-time optimisation of evacuation routes, and integration with smart city infrastructure. Most existing systems are based on static models of buildings and people's locations and do not incorporate dynamic changes in conditions, such as changes in crowd density, temporary blocking of exits, or repair work. In addition, they have limited use of analytical algorithms and machine learning to predict the development of emergencies and do not provide effective interaction with users through mobile applications or real-time interfaces. Objectives of the study were to investigate the application of microcontrollers and gas sensors to develop an early fire detection system; to consider the algorithms of optimisation of evacuation routes using graphs and their influence on safety in emergencies; to evaluate the prospects of integration of the developed system with the smart city infrastructure to improve the overall efficiency of evacuation.

2. Materials and Methods

2.1. System architecture

To develop an integrated early fire detection and evacuation system, an Arduino microcontroller was chosen as the central element, which served as the computing and coordinating core of the entire system. Arduino continuously collected data from connected gas sensors, processed the information according to the predefined evacuation algorithm, and communicated with the main server for further analysis and data visualisation. Thus, the microcontroller was an intermediate link between the physical sensors and the safety control software modules, integrating the hardware and software parts of the system into a single functional complex.

The sensor subsystem consisted of five MQ series gas sensors (MQ-2, MQ-3, MQ-4, MQ-5 and MQ-7), each of which was specifically designed to detect certain types of gases and combustion products, including carbon monoxide, methane and other flammable substances. The sensors were strategically located in various rooms and key points of the building, which ensured comprehensive control and timely detection of potential fire hazards throughout the facility. Analogue signals generated by the sensors were transmitted to the corresponding Arduino inputs, where they were continuously read and analysed to determine whether critical gas concentration thresholds had been exceeded. This approach ensured prompt real-time response to changes in readings, providing continuous monitoring of the condition of the premises.

The control subsystem was based on the use of Arduino Uno or Arduino Mega, which provided a sufficient number of inputs to connect all sensors and actuators, as well as the necessary computing power to execute the evacuation algorithm. The controller's interaction with the sensor elements included constant monitoring of indicators, assessment of their criticality, and transmission of data to the server for further processing and storage. In addition, the controller coordinated the operation of active system components, such as sirens and light indicators, ensuring timely notification of dangerous situations and directing people to safe evacuation routes.

The software subsystem was implemented on a server or personal computer, which served as a platform for running the main security management software. The server processed data received from Arduino, calculated optimal evacuation routes, and stored sensor readings for analytics and further modelling of emergency scenarios. To ensure effective visualisation of evacuation routes, specialised graphics software was used, which displayed the status of the system in real time and provided the operator with complete control over the process. Text files containing information on the characteristics of the building, current sensor readings, and the results of evacuation route calculations were used for structured data input and output, which guaranteed data integrity and ensured the possibility of its further use to optimise system algorithms. The data processing pipeline of the integrated system starts with MQ gas sensors, which continuously measure the concentrations of gases and combustion products and transmit analogue signals to Arduino (Fig. 1).

As shown in the figure, the controller converts them into digital format, applies noise filtering, and compares the values with thresholds to identify critical nodes. Based on this data, the weights of the building graph are updated, which is used by the Dijkstra algorithm to generate optimal evacuation routes, adapting them to current conditions. In case of a threat, Arduino activates sirens and light indicators to alert people, and at the same time, the data is sent to the server for storage, analysis, and centralised control. The final stage is the visualisation of routes and sensor status through a graphical interface, which provides effective monitoring and real-time decision-making.

2.2. Integration of hardware and software components

The process of integrating the hardware and software components of the early fire detection and evacuation system was based on a multi-level architecture of interaction between gas sensors, an Arduino microcontroller, and server software. At the first level of integration, the sensors were physically connected to the Arduino. Each sensor was powered and grounded, and its analogue output was connected to the corresponding inputs of the controller. This configuration ensured stable and continuous data collection, which enabled Arduino to assess gas levels in different areas of the building. Continuous reading and processing of sensor signals detected critical concentration exceedances and signalled potential hazards in a timely manner. This ensured the basic function of the system: early detection of threats and transmission of information for further analysis. At the second level of integration,

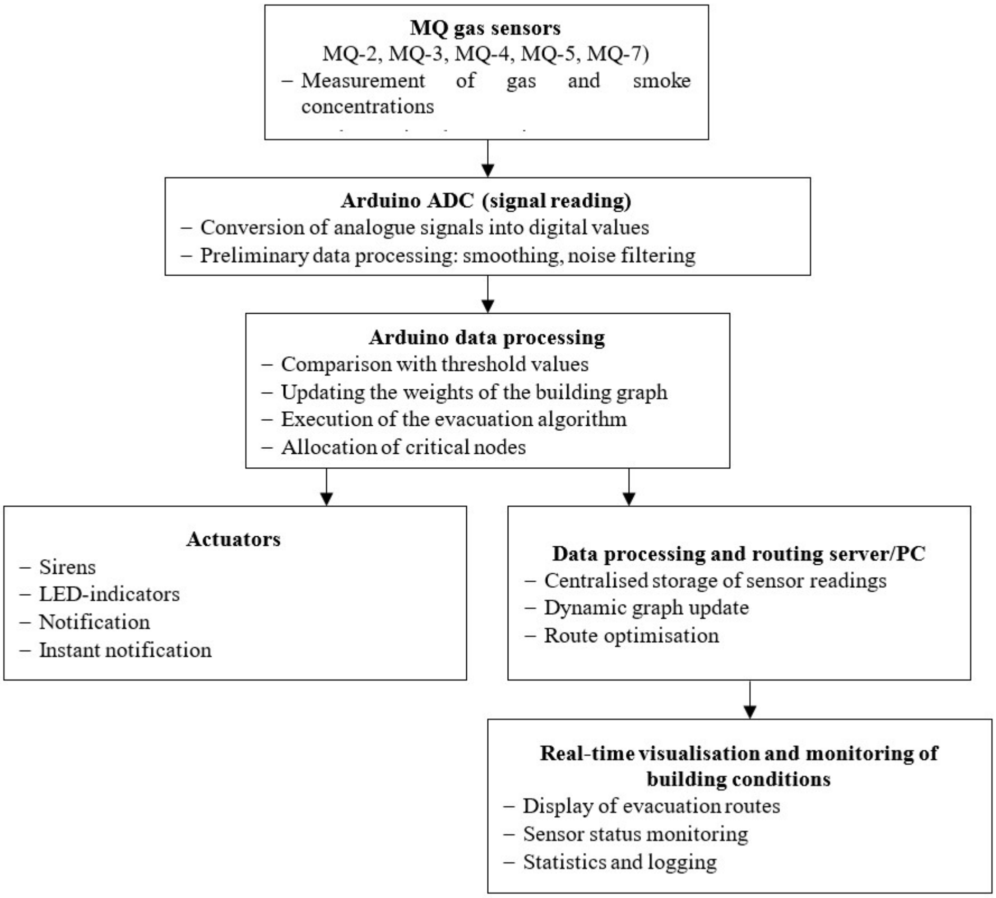

Figure 1. Integrated system data processing conveyor.

data was transferred from Arduino to the server platform. When gas thresholds were reached or exceeded, the microcontroller automatically transmitted the processed information to the server, where data was stored and analysed in real time. The server provided updates to evacuation routes, adapting them to current conditions, and provided operators with complete information on the status of premises and sensor activity. This two-way communication between hardware sensors and the server enabled the principle of rapid response and control necessary for high-level security systems.

At the software level, integration consisted of modular organisation of data processing algorithms and control of actuators such as sirens and light indicators. The software architecture provided separation of functions for data collection, performance analysis, activation of alarm devices, and updating of evacuation routes. This increased the flexibility of the system and ensured scalability in case of adding new sensors or control areas. Visualisation of evacuation routes and monitoring of the system status were conducted through a graphical interface, which provided the operator with a convenient tool for observing the entire building in real time and making operational decisions in emergencies.

2.3. Activation thresholds and calibration of MQ sensors

To ensure effective and reliable early detection of fire risks, five MQ series gas sensors were used in the developed system, namely MQ-2, MQ-3, MQ-4, MQ-5 and MQ-7. Each sensor had specific sensitivity to certain types of gases and combustion products, which was used for comprehensive monitoring of the air environment in the building's premises. In particular, the MQ-2 sensor was designed to detect smoke, flammable gases such as LPG, methane and propane. The MQ-3 was sensitive to ethanol and other alcohol vapours, while the MQ-4 specialised in detecting methane. The MQ-5 sensor monitored the concentration of LPG and natural gas, and the MQ-7 detected carbon monoxide (CO).

A substantial part in ensuring the accuracy of the system was the sensor calibration process. At the initial stage, the sensors were installed in a controlled environment with clean air and stabilised for 24 hours to determine their base resistance (Ro), which addressed individual differences and natural fluctuations in the characteristics of each element. After stabilisation, analogue signals were measured indoors, reflecting real operating conditions. Based on the data obtained, threshold values were set for each sensor in the Arduino software, which determined the critical limits for triggering an alarm. To improve the accuracy and stability of the indicators, noise filtering algorithms were used, among which the most effective were the moving average and exponential smoothing methods. This reduced the impact of short-term signal fluctuations and ensured a correct assessment of the danger, which is especially relevant for algorithms that automatically generate evacuation routes and activate alarm devices.

2.4. Algorithm for evacuation and updating graph weights

To ensure the effective organisation of evacuation routes in the event of a fire hazard, an evacuation algorithm based on graph theory methods was implemented in the developed system. The building was modelled in the software as a graph structure, where the vertices corresponded to specific rooms, staircases or exits, and the edges represented the physical paths connecting these nodes. The weight of each edge was determined based on the travel time or length of the path; therefore, the algorithm was able to evaluate the efficiency of routes in terms of speed and safety of movement. This approach formed dynamic evacuation routes incorporating changing conditions in the premises and ensures a prompt response to localised threats.

A distinctive feature of the algorithm was its ability to dynamically update the weights of the graph edges depending on the sensor readings. When the gas concentration at a specific node exceeded a certain threshold, all edges originating from that node were adjusted. A substantial aspect of this process was that the weight of the edges could be increased several times (for example, $Y = 5$), which reduced the priority of using this path by the algorithm. In cases of critical danger, the node could be completely excluded from the graph by setting the weight of the edges to infinity (∞), which guaranteed that this route would be avoided. This adaptability enabled Dijkstra's algorithm to select the safest evacuation routes, automatically bypassing high-risk nodes and reducing the probability of contact between people and dangerous areas. The process of implementing the algorithm in the software included continuous reading of data from all building sensors and evaluating their compliance with threshold values. After receiving the indicators for each node, the algorithm updated the graph weights and calculated the optimal routes from the current location of people to the nearest exits. Cyclical execution of this process updated evacuation routes in real time, critical for safety in rapidly changing fire conditions.

2.5. Testing and evaluating the effectiveness of the system

The developed integrated system for early fire detection and evacuation organisation underwent comprehensive testing to assess its functional reliability, efficiency and responsiveness in various emergency scenarios. Functional testing involved simulating conditions of increased gas concentration and smoke to verify the sensitivity of MQ sensors and the correctness of their operation. At the same time, the evacuation algorithm, based on graph theory, was tested in various scenarios, including real-time sensor readings. This approach not only verified the correct operation of the sensors but also evaluated the algorithm's ability to generate optimal routes, incorporating dynamically changing conditions and potentially dangerous nodes.

In addition, the performance of actuators and routing efficiency were evaluated. Sirens and light indicators were activated correctly when gas thresholds were exceeded, ensuring immediate notification of users about the existing danger. The light indicators functioned as intuitive navigators, indicating the direction of evacuation and quickly directing people to the nearest safe exits. This demonstrated the effectiveness of the integration of hardware and software subsystems in ensuring continuous management of the evacuation process. The parameter for evaluating the effectiveness of the system was the response time from the moment the sensor threshold was exceeded to the activation of the alarm and the formation of the evacuation route. Measurements showed that the system responded within 1–2 seconds, which meets modern requirements for early warning systems and can be used for the timely evacuation of people. At the same time, the functionality of the operator's graphical interface was evaluated, which monitored the status of all sensors, managed evacuation messages and displayed routes in real time. This interface increased the speed of decision-making and ensured centralised management of safety in the building.

During testing, certain limitations of the system were also identified, and recommendations for their elimination were proposed. To ensure stable operation with a large number of sensors, it is advisable to use an Arduino Mega microcontroller, which has a larger number of analogue inputs and higher computing power. For remote monitoring and real-time data transmission, it is recommended to integrate Wi-Fi or GSM modules, which can be used to monitor the condition of the building from any location. In addition, testing has highlighted the need for a stable power source, as the continuous operation of sensors and controllers is critically dependent on power supply, which is critical for high-level security systems.

3. Results

3.1. Results of calibration and threshold values of sensors, and testing of the evacuation algorithm and graph update

After conducting experiments, the MQ series sensors demonstrated high stability and accuracy in determining the concentrations of gases and combustion products. The MQ-2 sensor responded to smoke, LPG, methane, and propane at concentrations of 300–400 ppm, ensuring timely system activation in the event of increased gas levels. The MQ-3 detected ethanol and other alcohol vapours within the range of 200–300 ppm, providing a timely response to potential ignition sources associated with vapour-like liquids. The MQ-4 detected methane at a concentration of 1000 ppm, the MQ-5 responded to LPG and natural gas in the range of 200–300 ppm, and the MQ-7 showed an effective response at 100 ppm of carbon monoxide (CO), which is critical for preventing poisoning of people indoors.

All sensors provided stable analogue signals without significant fluctuations after filtering and smoothing of data. The threshold values were optimal for early detection of potentially dangerous situations, instantly signalling the threat. The study determined that the sensors demonstrate minimal error under constant environmental conditions, and their performance is reproducible in repeated tests, confirming their reliability for integration into an early response and evacuation system. The summarised results of the sensors' performance are presented in Table 1.

Table 1. Sensor performance results

Sensor	Detection	Trigger limit	Units
MQ-2	Smoke, LPG, methane, propane	300–400	ppm
MQ-3	Ethanol, alcohol vapours	200–300	ppm
MQ-4	Methane	1000	ppm
MQ-5	LPG, natural gas	200–300	ppm
MQ-7	Carbon monoxide (CO)	100	ppm

The table shows that the early fire detection system relies on a combination of sensors with different sensitivities to gases and combustion products. This provides comprehensive coverage of potentially hazardous substances in the room, ensuring differential response to different sources of threat. The selection of sensors with different response thresholds avoids false alarms while ensuring early warning when gas concentrations rise to dangerous levels. Thus, a multispectral approach to air monitoring: the system monitors several types of gases simultaneously, which increases the efficiency of the evacuation algorithm, as routes can be adapted depending on the specific source of the threat. This differentiated sensor configuration ensures system reliability and its ability to respond quickly to a variety of hazard scenarios. Thus, the MQ series sensors provide sufficient sensitivity to respond quickly to elevated gas concentrations and integrate effectively into the system to form safe evacuation routes and alert people to danger in a timely manner.

The results of testing the evacuation algorithm demonstrated its high efficiency in forming safe routes under conditions of dynamic changes in the fire situation. Experimental testing confirmed that the use of Dijkstra's algorithm in combination with an adaptive graph weight update mechanism ensures the correct and timely re-planning of evacuation routes in accordance with the current state of the environment. When the threshold values of gas sensors in specific nodes of the building were exceeded, the corresponding sections of the graph automatically lost priority, which led to their bypassing during the calculation of the shortest paths. In critical scenarios, when the danger level reached high values, the nodes were completely excluded from the graph, which created routes through potentially dangerous areas. To integrate the sensors into the system, the MQ sensors were connected to Arduino via a breadboard, each receiving power (VCC) and ground (GND) and transmitting analogue signals to the corresponding controller inputs (Fig. 2).

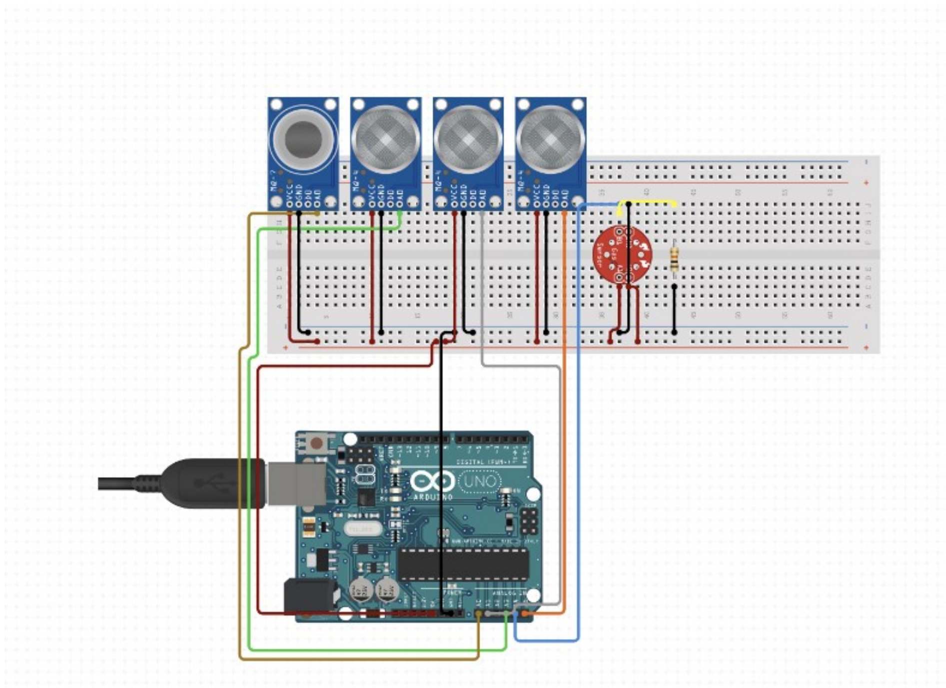

Figure 2. Diagram for connecting gas sensors to Arduino.

Analysis of the results showed that the algorithm demonstrates stable adaptability to changing conditions. In the absence of danger, evacuation routes corresponded to static optimisation with minimum travel time. After dangerous gas concentrations were detected, there was a dynamic increase in the weights of edges adjacent to problem nodes, which prompted a restructuring of routes with an emphasis on safety, even at the expense of increasing the total length or time of evacuation. Thus, the system implements a compromise between speed and safety, which is critical for real emergency conditions.

Experimental results also confirmed the high performance of the algorithm. The time required to recalculate routes after receiving new data from sensors remained consistently low and did not exceed a few seconds, even in scenarios with multiple active sensors. This indicates that the algorithm can be used in real time without the risk of delays that could negatively affect the evacuation process. The adaptability of the algorithm was also evident in its ability to respond correctly to cascading scenarios, when dangerous areas spread sequentially to several adjacent nodes of the graph. To summarise the test results, Table 2 shows the effect of updating the graph weights on the characteristics of evacuation routes.

Analysis of the table shows that the evacuation algorithm effectively adapts to different conditions. In normal mode, routes are formed in minimum time, without the need for correction. In the event of a local threat and critical nodes, the algorithm selects safe detour routes with low response times, demonstrating high adaptability.

Table 2. Generalised results of testing the evacuation algorithm

Scenario	Graph state	Route character	Adaptability	Reaction time
Normal mode	Statistical weight	Minimum time	Not required	Minimal
Local threat	Increased weight	Danger area bypass	High	Low
Critical area	Node offline	Alternative route	Very high	Low
Multiple threats	Dynamic weights	Combined route	Static	Stable

In a multiple-threat scenario, the system forms combined routes, maintaining stability and consistent response times, which confirms the reliability of the approach to updating graph weights and using the Dijkstra algorithm. In addition to quantitative indicators, a qualitative assessment of the algorithm's behaviour is also a substantial result. Visual analysis of the constructed routes confirmed their logical consistency with the spatial structure of the building and real traffic restrictions. The routes did not intersect with high-risk areas and correctly directed evacuation flows to the nearest safe exits, confirming the adequacy of the graph model used. To demonstrate the operation of the algorithm, Figure 3 illustrates the change in edge weights and route restructuring when the sensor is activated.

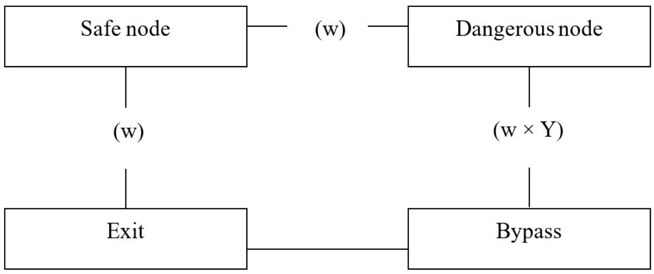

Figure 3. Graph update scheme.

The diagram shows that when the threshold value of the gas sensor in node X is exceeded, the weight of all edges originating from this node increases, or the node is completely excluded from the graph. This forces Dijkstra's algorithm to abandon a direct passage through the dangerous area and choose an alternative route with minimal risk. The visualisation demonstrates the adaptability of the algorithm: routes change in real time according to current sensor data, while maintaining optimality in terms of travel time and safety. The diagram highlights the importance of the interconnection between sensors, controllers and graph structures to ensure fast and safe evacuation. The obtained results concluded that the evacuation algorithm with dynamic graph weight updates is an effective decision support tool in early fire detection systems. Its ability to quickly adapt to a changing environment while maintaining an acceptable response time makes it suitable for use in real-world conditions in buildings of various types and complexity.

3.2. Assessment of actuators and warning systems

The results of the assessment of the actuators and the warning system confirmed their key role in ensuring effective and coordinated evacuation in the event of a fire hazard. The tests established that the system correctly implements the connection between the analytical part, which forms evacuation routes, and the physical means of informing people in the building. The activation of sirens and light indicators occurred simultaneously with the detection of dangerous gas concentrations and the launch of the evacuation algorithm, which ensured minimal delay between the moment the threat was detected and the start of the warning.

Analysis of time characteristics showed that audible signals were triggered almost instantly after the sensor thresholds were exceeded and served as the primary means of attracting attention. Light indicators integrated into the evacuation route structure were activated with a slight time delay due to the need to calculate the current safe route. This sequence of actions is functionally justified, as it warns of danger first and then provides clear visual cues regarding the direction of movement.

Another result of the testing was the verification of the compliance of visual and audio signals with the actual evacuation routes. Light indicators dynamically changed their status depending on the results of the algorithm, which prevented situations where the system could direct people through dangerous areas. In cases of local threats, the indicators redirected evacuation flows along alternative routes, while in scenarios with multiple danger zones, a combined warning scheme was formed with priority given to the safest exits. To summarise the results obtained, Table 3 shows the consistency of the actuators' operation with the logic of the evacuation algorithm.

Table 3. Results of the assessment of actuators and warning systems

Evaluation criterion	**Observed behaviour of the system**	**Functional compliance**
Siren activation	Instant reaction to threat	Full
Operation of light indicators	Dynamic patch change	Full
Algorithm synchronisation	Compliant in real time	High
Evacuation direction	Bypass of danger areas	Short
Signalisation stability	Without issues during testing	High

Analysis of the table shows that the actuator and warning system functions effectively and in accordance with the evacuation algorithm. Instant activation of sirens when threshold values are exceeded ensures that people are promptly warned of danger, while the dynamic operation of light indicators correctly directs movement to safe areas. High synchronisation with the Dijkstra algorithm ensures that evacuation routes are always updated in real time in accordance with changes in the schedule. The stability of the alarm system and the absence of failures in test scenarios confirm the reliability of the system under critical loads. Overall, the results demonstrate the full functional compliance of the actuators with safety requirements and their effective integration into the data processing pipeline.

In addition to quantitative indicators, the structural consistency of signals within the building was emphasised. The spatial layout of light indicators created a continuous visual chain from rooms to emergency exits, minimising the risk of people becoming disoriented in stressful conditions. Audible signals, in turn, served as a global danger indicator, independent of people's location, which increased the overall level of awareness. Overall, the results of the study confirm that the warning system is logically and functionally integrated with the evacuation algorithm. Its speed, signal coordination, and spatially correct routing create conditions for reducing the time it takes for users to make decisions and increasing the overall efficiency of the evacuation process in an emergency.

Centralised data processing and visualisation, system response time and evacuation efficiency. The results of the server part of the system's operation demonstrated its key role in ensuring comprehensive and coordinated management of early fire detection and evacuation processes. During experimental operation, the study established that centralised data collection from the Arduino microcontroller can provide a complete overview of the building's status in near real time. Data from gas sensors was sent to the server without loss, correctly identified by graph nodes and stored in a structured form, which ensured its further analysis and use for dynamic updating of evacuation routes.

Analysis of the data storage process demonstrated that the server architecture effectively supports both real-time monitoring and retrospective analysis of events. Logging sensor values, graph node states, and route calculation results creates a basis for identifying typical scenarios of dangerous situations and assessing system stability over time. This approach can be used not only to respond to threats, but also to form analytical conclusions about the spatial distribution of risks in the building. A significant result is the confirmation of the effectiveness of updating the building graph at the server level. When new data on changes in gas concentrations was received, the server synchronised correctly with the microcontroller and displayed the status of edge weights and node availability. This ensured consistency between local calculations on Arduino and the centralised building model, which is critical for multi-user scenarios or system scaling. The graph update time remained stable and did not cause delays in displaying current evacuation routes.

An assessment of the graphical interface showed that the visualisation of evacuation routes is informative for operators. The interface displayed the spatial structure of the building in the form of a graph with clear indication of hazardous areas, accessible paths and recommended routes. Dynamic changes in the colours and states of elements provided a rapid assessment of the level of risk in different parts of the building and real-time control of the evacuation process. The consistency between the visualised routes and the actual light signals in the building is notable, as it minimises the probability of cognitive dissonance between the system's recommendations and users' perceptions. The results obtained show that centralised data processing and visualisation not only improve the speed of response to emergencies, but also create an analytical basis for further improvement of the system. Server integration ensures the scalability of the solution, the ability to connect additional sensors and expand functionality without significant changes to the basic architecture, which is a substantial advantage of the proposed approach.

The results of the experimental assessment of the time characteristics of the integrated early fire detection and evacuation system demonstrated its ability to function in an operational response mode, which is critical for minimisation of risks to human life and health. During the tests, the complete time chain of the system's response was recorded, from the moment the gas sensor thresholds were exceeded to the activation of the actuators and the display of the updated evacuation routes. Analysis of these indicators evaluated both the internal speed of the computing components and the overall efficiency of the system in terms of supporting the evacuation process. The study established that the delay between the detection of a dangerous gas concentration and the formation of a control signal for the actuators is stable and predictable. Primary signal processing, including analogue-to-digital conversion, filtering, and comparison with threshold values, takes place with minimal time expenditure, after which the procedure for updating the graph weights and recalculating the evacuation routes is launched. Even in scenarios with multiple active sensors, the total processing time remained within limits that did not create critical delays for system users to make decisions.

Assessment of the evacuation efficiency in simulated scenarios was emphasised. The results showed that dynamic route updates significantly affect the total time required to leave the danger zone. Compared to static routes that do not take environmental changes into account, the adaptive approach made it possible to avoid traffic jams and potentially dangerous areas, even if this resulted in a slight increase in the length of the route. Thus, the system focuses not only on minimising travel time, but also on reducing risk, which is crucial in real fire conditions.

The assessment of evacuation efficiency also incorporated behavioural aspects, in particular the time required for people to orient themselves in space after receiving an alarm signal. The study established that combining audible alarms with clear visual indicators of the direction of movement significantly reduces the decision-making and movement initiation phase. This, in turn, has a positive effect on the overall evacuation time, especially in buildings with complex layouts. Overall, the results show that the proposed system ensures a timely response to fire hazards and effectively supports the evacuation process by minimising delays at critical stages. The combination of fast sensor data processing, an adaptive routing algorithm, and a coordinated warning system creates conditions for a significant reduction in the time people spend in the danger zone, confirming the practical value and applied significance of the developed approach.

3.3. Analysis of system limitations and potential

Analysis of the results of experimental operation of the integrated early fire detection and evacuation system revealed several technical limitations, which at the same time outline the directions for further development and scaling of the proposed solution. The study established that the functional capabilities of the system significantly depend on the hardware resources of the microcontroller, in particular, the amount of RAM, the number of analogue inputs and the bandwidth of data exchange channels. In basic configuration, the system demonstrates stable operation for a limited number of sensors and actuators, but with the increase in the size of the building or the density of the sensor network, there is a need to use more powerful controllers or a hierarchical architecture with multiple data collection nodes.

A separate aspect is the limitations associated with the characteristics of the MQ series gas sensors. Despite their availability and versatility, operational results have shown sensitivity to temperature and humidity fluctuations, as well as the need for periodic recalibration to maintain measurement accuracy in long-term operation. This limits the possibility of completely autonomous operation of the system without scheduled maintenance, especially in difficult microclimate conditions or industrial facilities. At the same time, these limitations are not critical to the system concept and can be compensated for by using additional types of sensors or correction algorithms.

The prospects for scaling the system are primarily related to the expansion of the sensor and actuator subsystems. The results of the study show that the system architecture is logically suitable for connecting additional temperature, smoke, flame, or human presence sensors, which will improve the accuracy of detecting dangerous situations and the adaptability of the evacuation algorithm. Similarly, the expansion of the set of actuators, in particular the integration of information boards or personalised warning devices, creates opportunities for more flexible management of evacuation flows.

A substantial area of development is the introduction of wireless communication channels. Experimental results show that the use of Wi-Fi or GSM modules can significantly improve system functionality through remote monitoring, backup alerts, and integration with external information systems. At the same time, the use of wireless technologies places additional demands on power consumption, communication channel protection and fault tolerance, which must be incorporated in the design of industrial or mission-critical systems.

Notably, the system is dependent on a stable power supply. Test results have confirmed that short-term power interruptions can lead to partial data loss or temporary actuator failure. This determines the need to use backup power sources, such as rechargeable batteries or uninterruptible power supplies, especially for facilities with increased reliability and safety requirements. Table 4 summarises the identified limitations and potential areas for development.

Table 4. Limitations and potential for development of the system

Aspect	**Identified limitations**	**Development potential**
Hardware platform	Limited controller resources	Use of higher-powered MCUs
Sensory subsystem	Sensitivity to the environment	Integration of additional sensors
Communications	Wired connection	Wi-Fi/GSM integration
Power supply	Network dependency	Backup power
Scalability	Local level	Divided architecture

Analysis of the table shows that the present configuration of the system limits its adaptability and scalability in complex or dynamic environments. The study determined that the existing architecture demonstrates limited flexibility in terms of integrating new components and rapidly expanding functionality. At the same time, the potential for development prioritises an increase in the autonomy and stability of the system, as well as expanding the capabilities of centralised monitoring and control, which creates prospects for a more comprehensive approach to building security and a dynamic response to threats. Thus, the results of the study concluded that, despite the existing technical limitations, the proposed system has significant potential for further development. Its modular architecture, adaptive evacuation algorithm, and the ability to integrate modern communication and energy solutions create the conditions for using the system both in small facilities and in large-scale infrastructure projects with increased security requirements.

4. Discussion

The results obtained showed high accuracy of the system when detecting dangerous gas concentrations and timely activation of the evacuation algorithm. Thanks to the application of graph methods, evacuation routes were optimised, which allowed for minimising the time for people to leave the building and reducing the risks to their lives and health. This approach proved its effectiveness both in modelling and in calculations based on real data. This problem has also been investigated by Ren et al. [14], where the results confirmed that the development of an intelligent fire safety system using Arduino aims to create more effective methods for early fire detection. Systems based on this microcontroller can integrate various sensors such as smoke, temperature, and motion sensors to monitor the environment in real time. The results presented by the authors correlate with proposed conclusions regarding the feasibility of using the Arduino platform as a basis for intelligent early fire detection systems. In both cases, the effectiveness of integrating heterogeneous sensors and applying real-time algorithmic data processing for the timely detection of fire-hazardous situations has been confirmed. The similarity of the results is evident in the high response speed of the system and its ability to function without constant operator intervention. At the same time, a comparison with the results of Jedhe et al. [15] revealed both conceptual similarities and significant differences. As in the conducted study, the authors confirmed the effectiveness of Arduino solutions in terms of fast system response and economic feasibility. The conclusion about the possibility of scaling the system and integrating it with external interfaces is also common. However, the results of Jedhe et al. focus mainly on remote monitoring and alerting functions, while the current system demonstrates another qualitative characteristic: the adaptability of evacuation routing based on dynamic updating of the building graph. The lack of a direct correlation between the evacuation efficiency indicators in this work and the authors' results is explained by the fact that in their study, evacuation is not modelled as an optimisation problem, but is considered only as a fact of danger alert.

When comparing the developed system with traditional fire safety systems, significant advantages were identified. Unlike standard methods, the Arduino-based system demonstrated a faster response to changes in the environment and flexibility in customisation. Data from the gas sensors was processed in real time, providing dynamic updates on building status and current evacuation routes. This is particularly important for modern multi-storey and architecturally complex facilities where standard systems may be less effective. He et al. [16] concluded that this ensures quick reaction to changing situations and adapt firefighting measures, which significantly reduces the risk of fire spread. In conceptual terms, the authors' conclusions correlate with the results of the study, particularly in terms of confirming the critical role of early fire detection and the need for real-time intelligent data processing. At the same time, He et al. viewed the system primarily as an analytical tool for threat detection, whereas in the presented study, the functional core of the system is shifted towards decision-making and evacuation management.

The results of Zhong et al. [17] demonstrate a significantly different, fundamentally oriented approach that emphasised the use of memristor reservoir computing for highly efficient time signal processing. According to the authors, systems using machine learning algorithms can learn from previous incidents, which improves prediction accuracy and response timeliness. From the perspective of theoretical computer science, their results significantly outperform classical algorithms in terms of speed and energy efficiency of stream data analysis. However, there is no direct correlation with the results of the study, and Zhong et al. rather outline a promising direction for the further development of the computing core of such systems.

At the same time, the study by Norkobil et al. [18] emphasised computer vision and the use of YOLOv6 deep neural networks to detect fires in a "smart city" environment. The authors' results demonstrate high accuracy and speed of detection of open flames and smoke based on video streams. Compared to the results obtained, there is only a partial correlation at the conceptual level of early threat detection. In turn, Tang et al. [19] concluded that adaptability to external influences and fire suppression system coordination are becoming key factors in the modern approach to safety. Modern systems can automatically adapt to changes in the environment, such as changes in weather or building density, ensuring more efficient functioning in different environments. In addition, integration with other smart city systems, such as traffic monitoring and citizen alerts, ensures consistency across all services and maximises the chances of successful emergency management. These findings are consistent with the findings of this study, with the thesis that integrating fire suppression into the smart city infrastructure significantly improves safety. The analysis shows that adaptive technologies that can consider various external factors improve efficiency of resource management and minimise response time to threats. Thus, the implementation of such systems not only improves the responsiveness of actions but also creates a safer urban environment for residents, which meets modern requirements for the quality of life in megacities.

Despite the successes achieved, some limitations have been identified in the study. The main drawback is the static nature of some data used in the system, such as the building layout and the distribution of people at the time of running the evacuation algorithm. In real life, such parameters may change, which requires the development of additional mechanisms to take them into account dynamically. In the future, it is planned to integrate sensors that will be able to monitor changes in real time and adapt routes according to the current situation. Lovreglio et al. [20] also conducted a study, the results of which confirmed that the limitations and challenges for the future development of fire suppression systems are related to the need to ensure reliable operation in the face of a constantly changing environment and an increasing number of potential threats. Difficulties arise from the need to integrate multiple sensors and devices that must communicate effectively and function in real time. The authors' findings demonstrate that even technically advanced systems cannot guarantee optimal evacuation without adequate training of people. Therefore, the conclusions of Lovreglio et al. confirmed the feasibility of further expanding the modern system by integrating training or simulation modules.

Huang et al. [21] also found that the need for dynamic real-time data logging is critical to ensure the effectiveness of the fire suppression system. Without continuous monitoring and updating of environmental conditions and potential threats, the system will not be able to adequately respond to changes and minimise the effects of emergencies. Compared to the results obtained, there is a partial correlation in terms of the time characteristics of the system's response, but the fundamental difference lies in the nature of the input signals. The presented results showed a stable and rapid response at the pre-smoke stage of a fire, when the concentrations of gases and combustion products already exceed the thresholds, but visual signs have not yet formed. In contrast, the approach by Huang et al. demonstrated higher efficiency at the stage of visible smoke or flames.

By collating the data from the research, key trends can be identified that indicate the need for fire suppression systems to adapt to the current environment. The results show that traditional methods can no longer fully meet the demands of rapid response and efficiency in urban metropolitan environments. Thus, the integration of modern technologies and dynamic real-time data recording is becoming an integral part of the successful development of fire safety systems, allowing not only to prevent fires, but also to minimise their consequences for life and property [22].

Prospects for further system development include the use of machine learning techniques to predict possible evacuation scenarios and automatically correct routes based on accumulated data. This can increase the accuracy of evacuation models and improve overall safety. Integration of the system with mobile applications that will notify users of safe routes and provide instructions in case of emergency also seems promising. This would create a unified information space where all participants would have access to up-to-date information.

Rohilla et al. [23] concluded that the prospect of using machine learning in firefighting systems opens new horizons for improving their efficiency and reliability. Machine learning algorithms can analyse large amounts of data collected from sensors and surveillance cameras, identifying hidden patterns and anomalies that may indicate fire risk. The conclusions of Rohilla et al. indirectly confirm the promise of integrating the modern system with automated fire extinguishing equipment as the next stage of development. Hsiao and Hsieh [24] identified that integration with mobile applications is an important step in improving the safety of fire suppression systems. Such applications can provide users with operational information on the status of systems, as well as remote control and monitoring capabilities. This not only improves communication between first responders and citizens but also facilitates a faster response to emergencies, ultimately improving safety in urban environments. The results obtained by Hsiao and Hsieh largely correlate with current conclusions regarding the feasibility of multi-level architecture and centralised visualisation of building status. At the same time, the study recorded a slightly shorter response time at the local level, which can be explained using peripheral data processing directly on the Arduino microcontroller.

In conclusion, the study has shown that intelligent fire safety systems based on Arduino and MQ sensors have significant potential to increase the level of protection for people in urban environments. The developed system successfully solves the problems of early fire detection and evacuation optimisation; however, for its further improvement, it is necessary to pay attention to adaptation to dynamic conditions and wider integration with smart city infrastructure.

5. Conclusions

The study demonstrated that calibrated MQ series sensors provide stable and reproducible detection of hazardous gas concentrations, and the use of signal filtering methods significantly increases reliability and reduces the probability of false alarms. The study determined that a combination of sensors with different specific sensitivities provides a comprehensive picture of the air environment, sufficient for the timely detection of fire risks in rooms.

Analysis of the evacuation algorithm's performance demonstrated its ability to effectively adapt to dynamic changes in the fire situation by correcting graph weights and excluding hazardous nodes. The study determined that the algorithm provides rapid route re-planning without a significant increase in computation time, confirming its applicability in real-time and its use as a decision support tool in early fire detection and evacuation systems.

The assessment of the actuators and the warning system confirmed their decisive role in ensuring timely and coordinated evacuation. The tests established a stable and accurate connection between the analytical module that generates routes and the physical means of notification: sirens and light indicators were activated almost immediately after dangerous gas concentrations were detected, which minimised the interval between the detection of the threat and the start of the alarm. The time characteristics of the system's operation confirmed the appropriate sequence of alarms: audible signals served as the primary universal alert, while light indicators were activated after the actual routes were calculated and provided spatially oriented movement cues. This approach helped reduce the risk of disorientation and made evacuation actions more intuitive for users.

Analysis of signal consistency with the evacuation algorithm logic showed that visual indicators correctly reflected route changes and did not direct people through dangerous areas. In more complex scenarios, the system supported the redistribution of evacuation flows, maintaining the priority of safe exits. The high stability of the actuators and the absence of failures during testing demonstrate the reliability of the integration of the warning system into the general data processing pipeline and its suitability for use in real emergency conditions. Centralised data processing and visualisation confirmed their key role in ensuring coordinated management of early fire detection and evacuation processes. During experimental operation, the study established that centralised data collection from the Arduino microcontroller provides a comprehensive view of the building's status in near real time. Data from gas sensors was received without loss, correctly linked to graph nodes and stored in a structured form, which created the basis for operational analysis and dynamic updating of evacuation routes.

The server architecture effectively supported both real-time monitoring and retrospective analysis of events thanks to systematic logging of sensor values, node statuses, and route calculation results. This made it possible not only to respond quickly to threats but also to generate analytical summaries of the spatial distribution of risks in the building. The graph was updated at the server level in a stable manner and in coordination with local calculations, which ensured the relevance of routes even when several sensors were activated simultaneously and created the conditions for scaling the system. The visualisation in the graphical interface proved to be informative and convenient for operators. The representation of the building as a graph with clear indication of dangerous areas, accessible paths and recommended routes can be used for quick assessment of the situation and control of the evacuation process. The consistency between the visualised routes and the actual light indicators in the building reduced the risk of misinterpreting the system's recommendations and increased confidence in its prompts.

The assessment of time characteristics showed that the system can operate in a rapid response mode. The delay between the detection of a dangerous gas concentration and the activation of actuators was stable and predictable, and the total processing time remained acceptable even in complex scenarios with several active danger zones. This ensured timely route updates and did not cause critical delays for users.

The effectiveness of evacuation in simulated scenarios confirmed the advantages of an adaptive approach over static routes. Dynamic route adjustments made it possible to avoid dangerous areas and traffic jams, focusing not only on minimising travel time but also on reducing risk. The combination of audible alerts with visual indicators reduced the time required for orientation after the alarm sounded and had a positive effect on the overall speed of evacuation. The limitations of the study include the use of the limited hardware resources of the Arduino microcontroller, the sensitivity of sensors to changes in the environment, the need for a stable power supply, and the local scalability of the system. Prospects for development include the use of more powerful controllers, the integration of additional sensors and actuators, the use of Wi-Fi/GSM modules for remote monitoring, the introduction of backup power supplies and a distributed architecture for scaling the system to large facilities.

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