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Analysis of the Importance of Electronic Components in Automated Smoke Protection Systems for Modern High-Rise Buildings

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Abstract

This study presents an analysis of the reliability of electronic components in Automated Smoke Protection Systems (ASPS) for high-rise buildings, with a focus on smoke extraction and pressurization subsystems. By using probabilistic modeling, the research assesses the significance of critical components, including the Network Information Module (NIM) and microprocessor controllers, developed by the author. The methodology includes fault tree analysis to identify failure scenarios and their probabilities. Results indicate that the assessment for the ASPS's failure probability is 5.689×10^{-3}, with the NIM identified as a critical component. The study emphasizes the importance of probabilistic safety assessments for enhancing the reliability of municipal automation systems and ensuring dweller safety during fires. The authors provide recommendations for improving system design and incorporating real-world reliability data.

Keywords: Smart Home, Safety, Automated Systems, Controller, Software Module, Probability, Model.

1. Introduction

With the introduction and development of the "smart home" concept [1], the issues of dweller comfort and safety have gained particular significance. The integration of modern information technologies and automated control systems significantly enhances resource efficiency, ensures comfortable living conditions, and strengthens building safety [2].

One of the critical components of smart home safety is Automated Fire Protection Systems (AFPS). These systems comprise a complex of sensors, controllers, actuators, and software modules that enable early fire detection, timely notification of dwellers and relevant services, and automatic localization and minimization of fire spread. A range of international and national standards [3-9] regulates the requirements for these safety systems.

The Automated Smoke Protection System (ASPS) is a key subsystem of the AFPS, responsible for the rapid and effective removal of smoke from premises and evacuation routes. The reliability of this system is critical, as its failure-free operation directly impacts human lives, health, and the extent of material losses during a fire. The ASPS is a complex system designed to ensure dweller safety and minimize smoke-related damage during a fire. It operates as a unified functional mechanism, with all subsystems interconnected and performing distinct but complementary tasks. The main subsystems include Smoke Extraction Subsystems (SES), Pressurization Subsystems (PS), Smoke Extraction Compensation Subsystems (SECS), and Automation Systems. The failure of a single critical component within a subsystem renders the system non-functional. Full operation of the ASPS requires a fire signal from the Fire Alarm System (FAS) and the activation of a fire scenario, which accounts for the fire zone, valve assignments, fans, smoke shafts, and other relevant components. In some cases, ASPS activation occurs after dual confirmation (e.g., manual activation and two FAS sensors). The system also includes control of the internal fire water supply automation.

Thus, by design, the primary purpose of the ASPS is to ensure the operation of engineering equipment involved in fire response, both in automatic mode and with manual control (remote or local). Monitoring the status of subsystem equipment and signaling failures is also a function of the ASPS [10, 11]. The FAS, which includes dozens of sensors of various types distributed throughout the building, serves as the technical means for fire detection to trigger the ASPS. Control of the actuators for the internal fire water supply equipment is performed in automatic mode (via fire hydrant position sensors) and remotely (via buttons installed in fire hose cabinets). The ASPS employs Local Control Panels (LCP) and the Central Smoke Protection Control Panel (CSPCP), developed with the author's contribution at the Institute of Mathematical Machines and Systems Problems of the National Academy of Sciences of Ukraine [11]. The core component of the CSPCP is a microprocessor controller, programmed to implement algorithms for operating engineering equipment during a fire. These algorithms enable the controller to receive signals from the FAS, fire hydrant position sensors, and control commands from buttons installed in fire hose cabinets and in the 24/7 staffed control room, issuing control commands to actuators. The management and monitoring of all systems in the residential complex are performed from a fire control post located in one of the residential complex buildings (Building No. 1), using the "SCADA System for Existing Equipment Dispatching" software, which was also modified by the author [10, 11]. Data exchange is facilitated via the RS-485 interface using fire-resistant cabling [10].

Technicians carry out regular preventive maintenance checks on fire-related equipment to verify the operational control functions of the smoke protection system and engineering equipment. They perform these checks from the CSPCP control panel using the "ASPS Start" and "ASPS Stop" buttons.

1.1. Objective of the Article

The primary purpose of the article is to analyze the importance of automation system components, developed or enhanced by the author, using probabilistic modeling of the ASPS operation for its primary function of smoke extraction during a fire.

2. Equipment and Operation Algorithm

2.1. Description of the Automation System

We developed the fire protection automation system based on the technical specifications outlined in DBN V.2.5-56:2014 [5]. We designed it to manage ventilation systems that ensure forced smoke extraction from the floor (zone) of the building where a fire occurs.

Additionally, we aimed to create an air overpressure in elevator shafts and stairwells to prevent the spread of smoke within the building and facilitate a safe evacuation [5, 6].

Thus, the ASPS controls pumps, valves, dampers, fans, and other equipment as specified in the developed project documentation and modern high-rise building safety concepts. The control function is the primary function of the system, as illustrated in Fig. 1. Additionally, the system informs maintenance personnel about the equipment's status, and it sends notifications of emergencies to the City's Operational Dispatch Service and the Fire Station Control Post. Thus, the ASPS has a critical information function, providing notifications during automatic, remote, or local activation about:

- Detection of the fire zone (signaled on the CSPCP control panel);
- Opening of smoke extraction and pressurization valves in the fire zone;
- Activation of relevant smoke extraction fans;
- Activation of all Pressurization Subsystems;
- Equipment status signaling following regulatory documents and standards;
- Status of fire alarm buttons located in fire hose cabinets on each floor;
- Fire signals from the FAS for the respective floor (generated when two or more sensors are triggered simultaneously);
- Activation of smoke extraction valves installed in each smoke extraction zone;
- Activation of pressurization valves installed in elevator lobbies;
- Activation of smoke extraction fans;
- Activation of the Pressurization Subsystem fans.

Project specifications dictate the electronic architecture of the ASPS, which typically follows the structural scheme illustrated in Fig. 2:

- At the lower level, near the technological equipment, Local Control Panels (LCPs) for fans and Automation Panels (APs) for controlling valves, dampers, trasoms, and for wireless signal transmission, Floor-level Beam Forming Units (FBUs) are installed.
- At the upper level, in the control room or fire control post, the Central Smoke Protection Control Panel (CSPCP), based on the ELECON-11 control cabinet, connects all APs and FBUs (if used at the site) via a technological communication line (RS-485 interface).

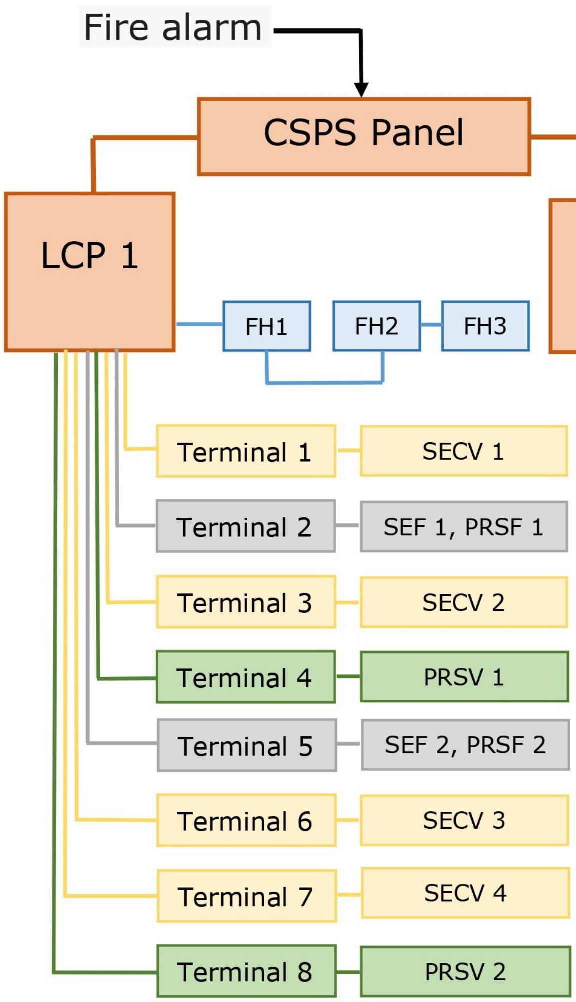

Figure 1. Schematic Diagram (Architecture) of the Automation System for a Single Floor

CSPCP – Central Smoke Protection Control Panel, LCP – Local Control Panel, FH – Fire Hose Cabinet, SEF – Smoke Extraction Fan, SECV – Smoke Extraction Compensation Valve, PRSF – Pressurization Subsystem Fan, PRSV – Pressurization Subsystem Valve.

The system can include multiple CSPCPs integrated into a single system via a Technological Local Network (TLN) [11].

• Local panels (ASPS components) – LCP, AP, and FBU – allow operators to control their respective units "on-site" when they switch the control panels to "Local" mode. This mode is used only during commissioning or in case of CSPCP failure. The ELECON-11 control cabinet (Fig. 2) ensures control of actuators in automatic and remote modes. Additionally, the CSPCP performs:

- Monitoring the correct operation of all equipment – smoke extraction valves, local control panels, and fan electric drives;

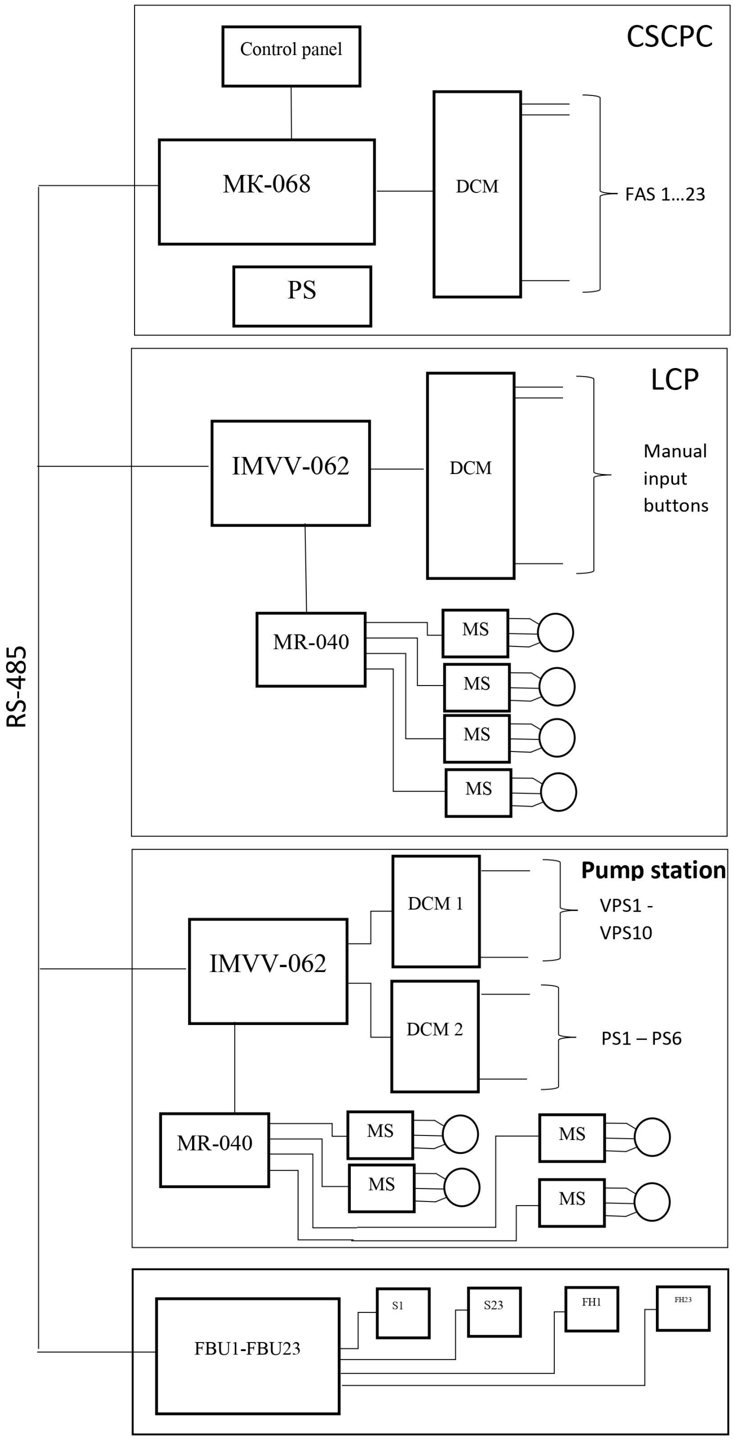

Figure 2. Structural Electrical (Functional) Diagram of the ASPS

PS – power supply, DCM – Dry Contact Module, MK-068 – controller module, IMVV-062 – Network Input-Output Module, MS – Magnetic Starter, VPS –Valve Position Sensor, PS – Pressure sensor, S – smoke extraction valves, FBU – Floor-Level Beam Forming Unit, FH – Fire Hose Cabinet.

- Monitoring fan operation following DBN [5, 6, 9] (activation of magnetic starters, pressure differential monitoring);
- Monitoring the status of all switches, buttons, limit switches, and circuits for remote control readiness of smoke extraction valves and fans;
- Signaling the operational status and any equipment failures on the CSPCP control panel's mnemonic display in all modes;
- Testing (functional verification) of equipment operability by issuing control commands from the CSPCP control panel (remote test mode), fire hose cabinet buttons, or smoke extraction valve buttons (local test mode).

2.2. Brief Description of Main Electronic Modules

2.2.1. General Description

We developed a series of Process Control Microcontrollers (PCM), which serve as the primary technical implementation of the described algorithms for managing engineering systems in buildings and industrial facilities [10, 11].

The controller module is the primary unit, containing a processor with embedded software that executes all logical control functions for mechanisms connected to the control cabinet according to their operational algorithms. The MK-068 controller module is one of the authors' latest developments [10, 11]. The controller connects all peripheral input/output modules. An internal RS-485 line links the control panel to the module IMVV-062 within the cabinet. An external RS-485 line connects units located near equipment (FBU, LCP panels, etc.). Figure 3 illustrates the functional composition of a typical CSPCP.

2.2.2. IMVV-062 Controller Module

This module extends the input/output capabilities of the primary MK-068 controller. You can install it in a remote LCP panel for local signal input/output or in the CSPCP to enhance the primary controller's capabilities. The IMVV-062 module connects to the primary controller via the RS-485 network. Up to four MCK-048 input modules and four MR-040 or MT-049 output modules can be connected to the IMVV-062.

2.2.3. Network Information Module (NIM)

The system's tools are grounded in the architecture of network information modules, with development towards the ecosystem of microprocessor modules.

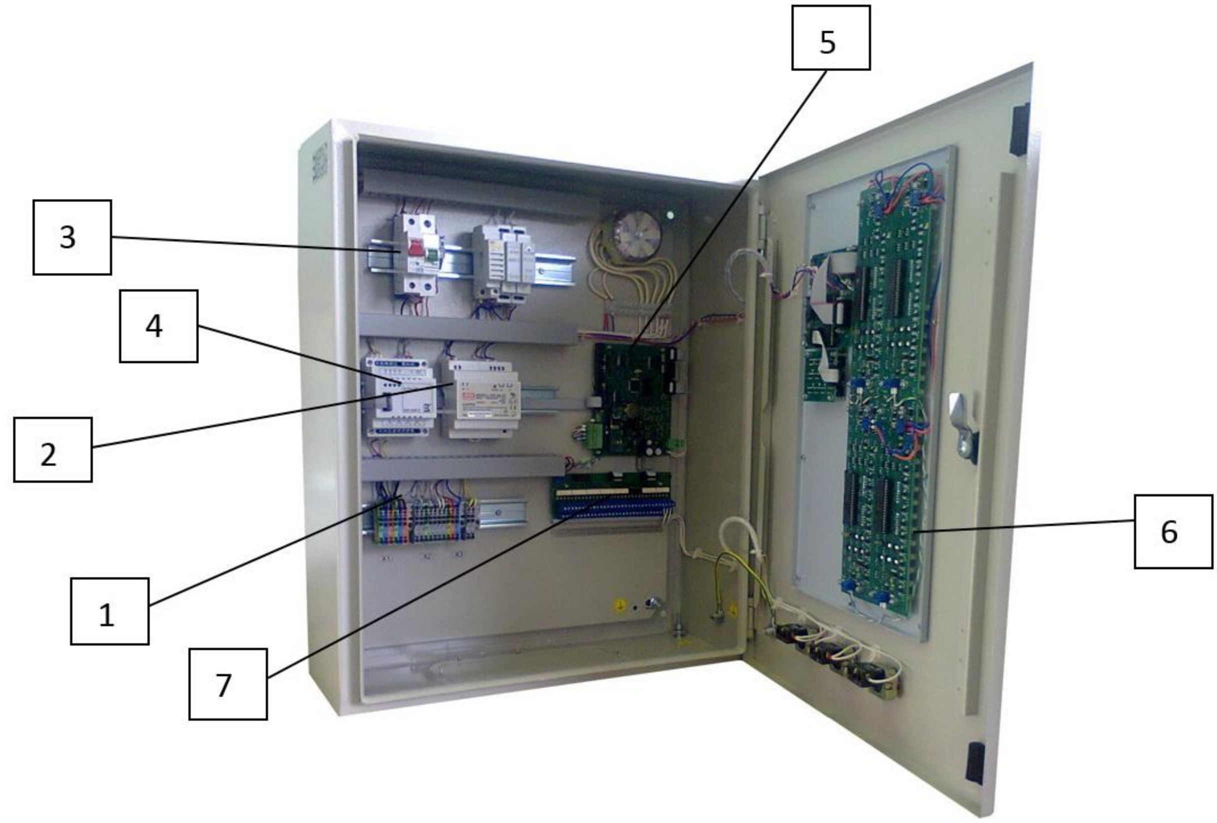

Figure 3. Functional Composition of a Typical CSPCP

1) Terminal block for external connections. 2) 24 V power supply unit. 3) Automatic circuit breaker for cabinet power. 4) Relay (thyristor) module for outputting signals. 5) Controller module. 6) Mnemonic display and control panel. 7) Module for receiving "dry contact" input signals.

Features of network information modules:

1. **Data Transmission.** The primary function of the NIM is to process and transmit information between system components, e.g., receiving sensor data, processing it, and sending it to a server or other devices for further processing.

2. **Network Connectivity.** The NIM supports various network types, including wired (e.g., Ethernet) and wireless (e.g., Wi-Fi, Bluetooth, ZigBee, LoRa), enabling real-time data exchange and system flexibility.

3. **Interfaces.** The module supports various interfaces for device and network connectivity, including USB, GPIO (for external sensors or actuators), Serial (RS-232, RS-485), I2C, SPI, and others, allowing the connection of diverse devices and sensors.

Thus, the NIM can be connected from any point in the ASPS to restore its operation in case of a controller failure.

2.3. Automation System Operation Algorithm

The activation of the fire protection system can be automatic (via FAS fire detectors), remote (via button posts in fire hose cabinets), or local (from the CSPCP).

Upon receiving a signal from the FAS or a button in a fire hose cabinet, the automation system forms a beam, issuing commands to open relevant smoke extraction valves and activate the corresponding exhaust and Pressurization Subsystems. Other smoke extraction valves in these systems are blocked until firefighting operations are complete. After firefighting, personnel deactivate all involved ventilation systems, manually close the smoke extraction valves, and reset the formed beam to return it to standby mode for signals from the fire alarm system (FAS) or fire hose cabinet buttons.

We propose to use the so-called "Information Point of Presence" interface [10, 11] by implementing the Network Information Module (NIM) to ensure the communication and data transfer between various network components. Thus, the operator could see and control the equipment status for the ASPS automation on mnemonic diagrams and a liquid crystal display on the CSPCP and LCPs control panels (Fig. 2).

This project uses an ELECON microprocessor controller, developed by the ELECON Scientific and Technical Society at the Institute of Mathematical Machines and Systems Problems of the National Academy of Sciences of Ukraine, as an automation tool that provides the equipment operation program described above, as well as operating and alarm signals.

The core component of the microcontroller is a single-chip computer, programmed to implement the necessary algorithms for operating pressurization and smoke extraction ventilation systems. Based on these algorithms, the controller receives FAS signals and commands from buttons in fire hose cabinets, issuing control commands to actuator mechanisms for pressurization fans, smoke extraction fans, and valves. The controller also provides visual and digital status indications on the mnemonic display and generates external operational and emergency signals.

3. Development of the ASPS Probabilistic Model

3.1. General description of the method

Researchers have applied probabilistic safety analysis to assess the safety of high-risk facilities, such as nuclear power plants, since the second half of the last century [12-29]. This approach justified the safety of nuclear energy, demonstrating that operational risks are significantly lower than household risks and enabling nuclear engineers to improve safety parameters by identifying project weaknesses and replacing less reliable equipment as needed. Computer codes developed in the USA and Sweden are typically used for these purposes [12-14, 29]. Since the early 2000s, researchers have extended these methods to other potentially hazardous facilities [15-28]. Mathematical probabilistic models enable the identification of the most critical combinations of basic events that lead to undesirable outcomes, the assessment of event significance, and the development of enterprise safety policies, risk reduction measures, and integrated safety assessments based on systematic model analysis. You can apply this methodology to analyze the systemic safety of high-rise buildings. While specific rules (methodology) exist for this analysis [12-14, 18, 20, 21, 28, 29], we use the method without a detailed description.

3.2. System Composition of a Typical Project and Monitored Parameters

Modern typical project documentation specifies control of the following engineering equipment during a fire [9, 15]:

- Smoke extraction fans (activation);
- Pressurization fans (activation);
- Smoke extraction valves (opening);
- Pressurization valves (opening);
- Smoke extraction compensation valves (opening);
- Automatic opening of the bypass line valve at the water meter node;
- General ventilation (deactivation);
- Internal fire water supply pumps (activation);
- Elevator operation in "Fire" mode.

Monitored Parameters:

- Integrity of remote start circuits;
- Readiness of smoke extraction and pressurization fans;
- Activation of smoke extraction and pressurization fans;
- Opening of smoke extraction, pressurization, and compensation valves;

- Deactivation of automatic mode;
- Opening of fire hose cabinets;
- Fire hydrant positions.

We included in the probabilistic modeling of the system only those elements of the ASPS that ensure the primary function – smoke removal in the event of a fire. According to the Probabilistic Safety Assessment (PSA) methodology, these include the listed above electromechanical components and electronic automation system components, with the possibility of recovering from potential failures during startup. This capability exists for nearly all components and subsystems, as reflected in the qualitative ASPS analysis (see Section 4.1 below).

The operator can control the ASPS equipment in any of the three modes: automatic, remote, or local:

- **Automatic Mode**: Triggered by the FAS upon activation of two automatic smoke detectors in the same room;
- **Remote Mode**: Via control buttons in fire hose cabinets or LCPs. Operators carry out the remote control separately for each floor of the building from the fire control post using a PC with the appropriate software installed;
- **Local Mode**: Via control buttons located directly on the equipment.

The operators have all the required information on an indication panel in the 24/7 staffed control room (Fig. 3) to ensure fire safety, control, signaling, and coordination of all services responsible for fire suppression, information on the readiness and activation of smoke protection systems and fire-related engineering equipment, following the DBN V.2.5-56:2014 [5]. Operational personnel can restore equipment functionality (address failures) in many cases (see Section 4.1 below) [10]. To achieve overpressure in elevator lobbies, operators open the pressurization valves on the fire-affected floor and the adjacent floors, following the guidelines of DSTU-N B V.2.2-38:2013 [4].

The CSPCP processes signals indicating the readiness and activation of fire-related engineering equipment and displays them on the indication panel (control panel) at the front (Fig. 3). Following the DBN V.2.2-15:2019 [6], activation signals for smoke extraction and Pressurization Subsystems must be transmitted to the City's Centralized Dispatch Panel using relay contacts and/or MR-040 electronic modules.

To gain the modeling objective (article’s goal), consider the system’s functional diagram (Fig. 2). Each CSPCP contains MK-068 microcontrollers, modified by the author [10, 11], and the following electronic modules:

- IMVV-062 Controller Module;
- MCK-048 Dry Contact Module;
- MT-049 Thyristor Module or MR-040DC Relay Module.

The Autonomous Power Supply Unit (APSU) is also located in the CSPCP and functionally linked to all modules. Each LCP contains an IMVV-062 controller module.

3.3. Model for probabilistic safety assessment

According to the Probabilistic Safety Analysis algorithm [18, 20, 25-29] and ASPS's composition described above, the main modeling assumptions are:

1. The failure of any ASPS subsystem results in system failure.
2. Any unit may fail during automatic startup due to automation system (ASPS) component failures or mechanical issues (e.g., jamming).
3. Recovery of unit functionality during mechanical failures in a fire is impossible.
4. The operator can eliminate automation failure by manually restarting from the CSPCP or LCP or by using a NIM controller. Additionally, the operator can use the NIM device to intervene in the ASPS from any location.
5. MK-068 controller failure is considered without its latest modifications (i.e., without mutual processor control), as described in the author’s recent publications [10, 11], since many sites use single-processor controllers.
6. We did not model the cable network failure due to its low probability, given its fire-resistant design.
7. Smoke extraction and pressurization shafts, as passive system components, are not included in the model.

Thus, returning to the article's principal objective, the ASPS components included in the probabilistic model are listed in Table 1. The probability parameters in Table 1 are the failure rates of components or personnel: failure frequency per calendar year for online components, probability of failure on demand for components running on demand, and probability of human error for personnel errors. We created a probabilistic model in the form of a Fault Tree (FT) (Fig. 4). The undesirable event is the failure of the Automated Smoke Protection System on the 22nd floor during a fire, denoted as ASPS event at the top of the FT in Fig. 4. We give the descriptions of intermediate states from Fig. 4 in Table 2.

We used in Table 1 numerical failure probability values for technical system components based on expert data, with human operator error probability assessed considering sufficient operator competence and high stress levels during a fire (OP-F event), using the methodology [24-28]. The NIM-F event in Table 1 is a combination of the NIM component failure ($P_{NIM\_component} = 10^{-5}$) and the operator error event without stress factor (connection before the fire) ($P_{Operator\_Error} = 10^{-2}$).

We marked in Fig. 4 the opposite event to event A (probability P_A) with a forward slash, such as /A (probability $P_{/A}$): $P_A = 1 – P_{/A}$.

For example, the intermediate state event CSPCP-fail means the failure of the CSPCP with a probability $P_{CSPCP\text{-}fail}$. Therefore, the event /CSPCP-fail implies fault-free operation of the CSPCP with a probability $P_{/CSPCP\text{-}fail} = 1 – P_{CSPCP\text{-}fail}$. The values of $P_{/CSPCP\text{-}fail}$ and $P_{CSPCP\text{-}fail}$ are calculated and used inside the FT model.

Table 1. Basic Events

Identifier	**Description of the Event**	**Probability parameter**
BG-F	Failure of the 24 V autonomous power supply unit (APSU)	3.000E-003
BUTTON-F	Failure of the manual start button	3.000E-003
E-Contact-F	Failure of the contact	3.000E-003
FAS-F	Fire Alarm System failure	3.000E-004
IMVV-F	IMVV-062 module failure	1.000E-005
MCK-F	MCK-048 controller failure	5.000E-005
MK-F	MK-068 controller failure	1.000E-006
MR-F	MR-040 module failure	2.000E-005
MS-F	Motor Starters failure	5.000E-004

NIM-F	Network Information Module failure, including human errors	1.000E-003
OP-F	Operator error to eliminate automation failure by manually restarting from the CSPCP, LCP, or by using a NIM controller under fire conditions	2.000E-002
POWS-main	Power supply failure	1.000E-002
POWS-restore	Power supply restore failure	8.000E-002
PRS-MF	Pressurization Subsystem Fan mechanical failure	7.000E-004
PRSV-F	Pressurization Subsystem Valve failure	5.000E-004
SECV-1-F	Smoke Extraction Compensation Valve No. 1 failure	3.000E-004
SECV-2-F	Smoke Extraction Compensation Valve No. 2 failure	3.000E-004
SECV-3-F	Smoke Extraction Compensation Valve No. 3 failure	3.000E-004
SECV-4-F	Smoke Extraction Compensation Valve No. 4 failure	3.000E-004
SECV-5-F	Smoke Extraction Compensation Valve No. 5 failure	3.000E-004
SEF-MF	Smoke Extraction Subsystem Fan mechanical failure	8.000E-004
SEV-F	Smoke Extraction Valve failure	2.000E-004

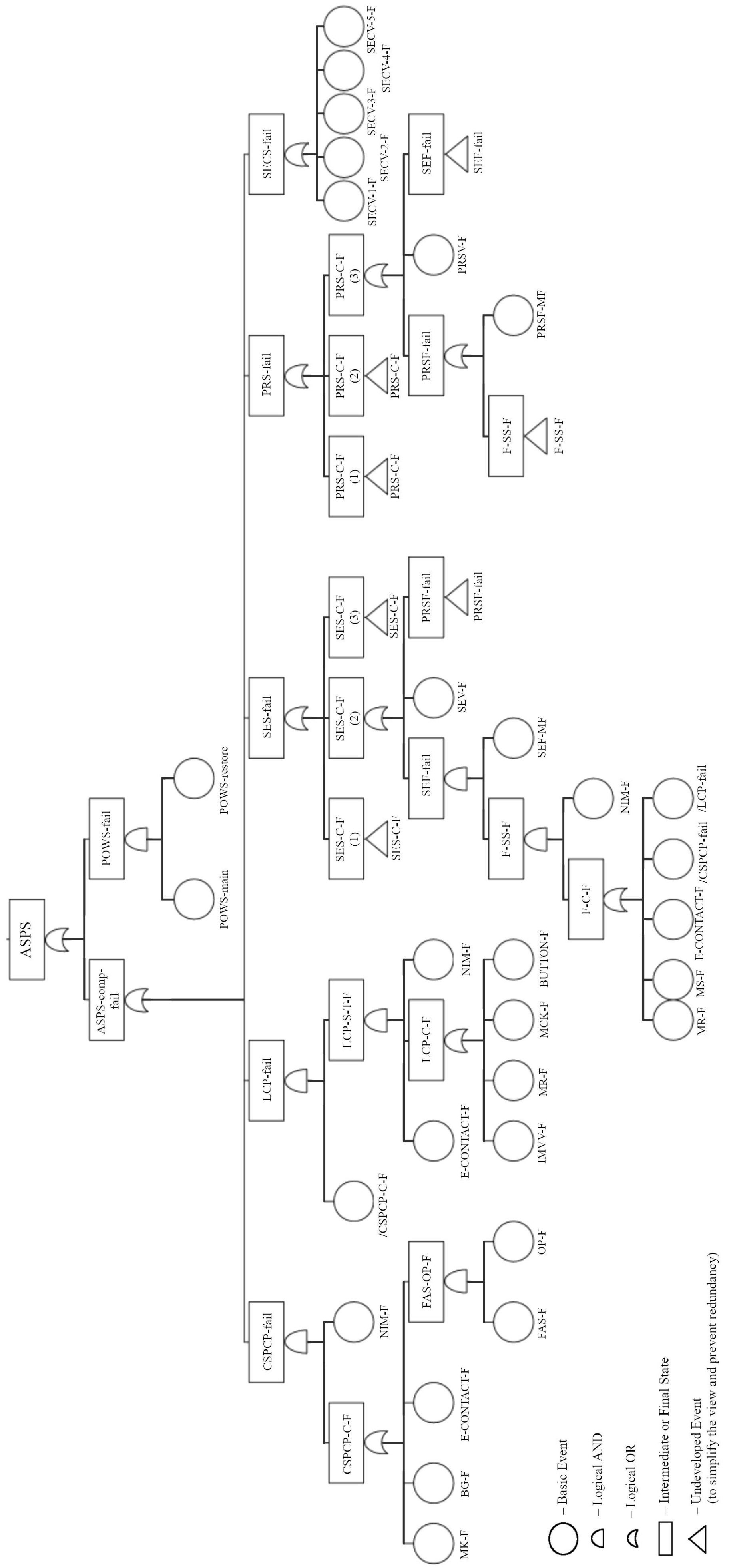

Figure 4. Fault Tree of the ASPS

Table 2. Description of the intermediate states

Identifier	**Description of the State**
ASPS	ASPS failure (the undesirable event, the final state of the FT)
ASPS-comp-fail	ASPS's component failure
POWS-fail	Power supply failure with impossibility to restore
CSPCP-fail	CSPCP failure
LCP-fail	LCP failure
SES-fail	Smoke Extraction Subsystem failure
PRS-fail	Pressurization Subsystem failure
SECS-fail	Smoke Extraction Compensation Subsystem failure
CSPCP-C-F	CSPCP's component failure
LCP-S-T-F	LCP signal transfer failure
SES-C-F	Smoke Extraction Subsystem component failure
PRS-C-F	Pressurization Subsystem component failure
FAS-OP-F	FAS failure and operator error to eliminate automation failure by manually restarting from the CSPCP, LCP, or by using a NIM controller under fire conditions
LCP-C-F	LCP component failure
SEF-fail	Smoke Extraction Subsystem Fan failure
PRSF-fail	Pressurization Subsystem Fan failure
F-SS-F	Fan Start Signal failure
F-C-F	Fan component failure

The fault logic shown in Fig. 4 is straightforward at the subsystem level:

Automated Smoke Protection System (ASPS)

```
|
├─ Smoke Extraction Subsystem (SES-fail event)
| ├─ Smoke Extraction Fan
| ├─ Smoke Extraction Valve
| └─ Automation System
|
├─ Pressurization Subsystem (PRS-fail event)
| ├─ Pressurization Fan
| ├─ Pressurization Valve
| └─ Automation System
|
├─ Smoke Extraction Compensation Subsystem (SECS-fail event)
| ├─ Smoke Extraction Compensation Valve
| └─ Automation System
|
└─ Control System
  ├─ Central Smoke Protection Control Panel (CSPCP-fail event)
  | ├─ Automation System
  | └─ Operator's actions
  └─ Floor-Level Smoke Protection Panels (LCP-fail event)
    ├─ Automation System
    └─ Operator's actions
```

4. Probabilistic safety modeling and results

4.1. Qualitative analysis of safety

We carried out the qualitative analysis of ASPS failure modes based on [21]. Table 3 presents the qualitative analysis of the ASPS failure modes as a whole at the subsystem level. Table 4 presents the results of the qualitative analysis of the ASPS failure modes at the component level for a particular subsystem, the Smoke Extraction Subsystem, as one of the subsystems of ASPS.

Table 3. Qualitative Analysis of ASPS Components at the Subsystem Level

Component	Function	Failure	Cause (or Basic Event)	Consequence	Detection/Diagnosis	Possibility of Recovery
Smoke Extraction Subsystem	Smoke extraction from the floor	1) Fan failure to activate 2) Valve failure to open	1) Lack of power supply (230 V) 2) ASPS failure 3) Mechanical failure (valve jamming) 4) Line disconnection at the terminal	The smoke extraction is impossible, posing a danger to dwellers	The Automation System does not detect pressure / CSPCP control panel, NIM	Non-recoverable during a fire due to mechanical causes; recoverable in other cases
Pressurization Subsystem	Displacement of smoke from the pressurization zone (elevator lobby or stairwell)	1) Fan failure to activate 2) Valve failure to open	1) Lack of power supply (230 V) 2) Mechanical failure (valve jamming) 3) Line disconnection at the terminal	Smoke spreads to the evacuation zones	The Automation System does not detect pressure / CSPCP control panel, NIM	Non-recoverable during a fire due to mechanical causes; recoverable in other cases
Smoke Extraction Compensation Subsystem (SECS)	Pressure equalization after the operation of the Smoke Extraction Subsystem	1) Fan failure to activate or valve failure to open	1) Lack of power supply (230 V) 2) Mechanical failure (valve jamming) 3) Line disconnection at the terminal	Creation of a hazardous overpressure zone	The Automation System does not detect pressure / CSPCP control panel, NIM	Non-recoverable during a fire due to mechanical causes; recoverable in other cases
Central Smoke Protection Control Subsystem (CSPCP)	Control and monitoring of the entire Smoke Extraction Subsystem	No signal received or unprocessed signal by the CSPCP or LCP panel	1) Controller failure 2) Lack of power supply, 3) Contact failure	The system or a specific floor (or section) does not respond to a fire until the operator remotely controls it	No response to signals /test activations	Recoverable by the operator
Fire Alarm System (FAS)	System activation upon fire detection	No signal	1) Lack of power supply 2) Sensor failure	SES does not activate automatically	No signal	Non-recoverable

"Information Point of Presence". NIM	The Network Information Module (NIM) ensures communication and data transfer between various network components	No control redundancy in case of CSPCP or LCP failure	Module failure	The entire system or a specific floor (or section) does not respond to a fire, with no possibility of remote recovery	Testing in emergency mode, /CSPCP control panel, duty operator	Non-recoverable

Table 4. Qualitative Analysis of ASPS at the Component Level of the Smoke Extraction Subsystem

Component	**Function**	**Failure**	**Cause**	**Consequence**	**Detection/Diagnosis**	**Possibility of Recovery**
Fan	Creating airflow in the shaft for smoke extraction	1) The fan fails to start, 2) The fan fails to operate for the required duration	Loss of power supply, motor failure	The lack of smoke extraction increases the danger to dwellers.	PIT does not detect pressure changes	Non-recoverable during a fire due to mechanical causes; recoverable in other cases
Valve	Opens the pathway to the shaft for smoke extraction from the premises	1) Valve fails to open (jamming) 2) Mechanism failure	Loss of power supply, jamming, contamination, mechanism failure, terminal fault	Smoke cannot exit	PIT does not detect pressure changes / visual inspection	Non-recoverable during a fire due to mechanical causes; recoverable in other cases
Pressure Indicator Transmitter (PIT)	Monitors the presence and variation of pressure in the shaft	1) Pressure Indicator Transmitter (PIT) failure	Sensor failure, damage to the data transmission line	Inability to detect pressure changes, loss of monitoring	Does not transmit signal / measure pressure	Non-recoverable during a fire, not modeled
LCP Panel	Processes signals from the Fire Alarm System (FAS) or Fire Hose Cabinet (FH), controlling the Smoke Extraction Subsystem, Pressurization Subsystem, and Smoke Extraction Compensation Subsystem	1) No signal received 2) Unprocessed signal by CSPCP, LCP Panel, or FH	Controller failure, loss of power supply, or lack of contact at the terminal	The floor control system, or a particular floor, does not respond to a fire	No response to signals / test activations	Recoverable
Cabling Infrastructure	Ensures the transmission of power and control signals	1) Cable break or short circuit	Mechanical damage, overheating	Loss of communication between components	Failure to execute commands	Fire-resistant cables. Non-recoverable during a fire, not modeled

4.2. Assessment of failure probability parameters and importance of the ASPS components

We carried out the modeling and calculations using the SAPHIRE code [29], with the fault tree shown in Fig. 4 and probability parameters from . The calculation used a simplified first-type approach based on point estimates of reliability (failure probabilities) for ASPS components included in the model. Thus, the obtained results are the evaluative calculation aligned with the stated objective and no more. We confirm the feasibility and value of probabilistic safety analysis in this domain. The calculation results yield minimal cut sets – combinations of events leading to ASPS failure (Table 5) – and a table of system component importance based on the Fussell-Vesely parameter [13, 28] (Table 6). The rounded numbers in Table 5 may cause the sum of Cut Set Contributions to exceed the rounded Accumulated Total.

Table 5. Minimal Cut Sets of the ASPS (Mincut Upper Bound: 5.689E-003)

Cut No.	Accumulated Total (%, rounded)	Cut Set Contribution (%, rounded)	Frequency per Calendar Year	Cut Sets
1	17.6	17.6	9.995E-004	/IMVV-F, /BUTTON-F, /MCK-F, NIM-F, /MR-F
2	35.1	17.6	9.990E-004	/E-Contact-F, NIM-F
3	49.2	14.1	8.000E-004	POWS-main, POWS-restore
4	61.5	12.3	7.000E-004	PRSF-MF
5	70.3	8.8	5.000E-004	PRSV-F
6	75.6	5.3	3.000E-004	SECV-1-F
7	80.9	5.3	3.000E-004	SECV-2-F
8	86.2	5.3	3.000E-004	SECV-3-F
9	91.4	5.3	3.000E-004	SECV-4-F
10	96.7	5.3	3.000E-004	SECV-5-F
11	100.0	3.5	2.000E-004	SEV-F

Cut No.	Accumulated Total (%, rounded)	Cut Set Contribution (%, rounded)	Frequency per Calendar Year	Cut Sets
12	100.0	0.1	3.000E-006	BG-F, NIM-F
13	100.0	0.0	1.000E-006	E-Contact-F, NIM-F
14	100.0	0.0	5.000E-007	NIM-F, MS-F
15	100.0	0.0	2.000E-008	NIM-F, MR-F
16	100.0	0.0	6.000E-009	NIM-F, OP-F, FAS-F
17	100.0	0.0	1.000E-009	NIM-F, MK-F

There are other, less important events and cut sets, but we do not include those less important results in Tables 5 and 6.

Table 6. Results for Fussell-Vesely Importance assessment

Event Name	Probability parameter	Fussel-Vesely Importance
NIM-F	1.000E-003	3.506E-001
POWS-main	1.000E-002	1.399E-001
POWS-restore	8.000E-002	1.399E-001
PRSF-MF	7.000E-004	1.224E-001
PRSV-F	5.000E-004	8.744E-002
SECV-1-F	3.000E-004	5.245E-002
SECV-2-F	3.000E-004	5.245E-002
SECV-3-F	3.000E-004	5.245E-002
SECV-4-F	3.000E-004	5.245E-002
SECV-5-F	3.000E-004	5.245E-002
SEV-F	2.000E-004	3.496E-002
BG-F	3.000E-003	5.244E-004
MS-F	5.000E-004	8.739E-005
FAS-F	3.000E-004	1.049E-006

Event Name	Probability parameter	Fussel-Vesely Importance
OP-F	2.000E-002	1.049E-006
MK-F	1.000E-006	1.748E-007

The ASPS failure probability is 5.689×10^{-3}, a satisfactory result for complex technical systems. The most critical risk is the first event combination with NIM failure: when all other components except the NIM function correctly (/IMVV-F, /BUTTON-F, /MCK-F, NIM-F, /MR-F; and /E-Contact-F, NIM-F).

The obtained results on the contributions of cut sets indicate the high importance of related components for ASPS operation, as confirmed by Table 6. There are 17 ASPS failure scenarios, but as shown in Table 5, the probabilities of other scenarios differ significantly (by orders of magnitude). The last minimal cut set (NIM-F, MK-F) is nearly improbable, even without considering the latest dual-processor controller variant, which ensures controller operability through mutual processor failure control [10, 11]. Power supply availability is also critical for ASPS failure risk, as indicated by the third minimal cut set (Table 5), aligning with operational experience.

The most critical system component is the NIM electronic module (NIM-F event). Probabilistic analysis revealed that the importance of safety system components for reducing dweller risk in high-rise buildings varies by nine orders of magnitude. The results of the calculations lead us to the conclusion that it is essential to carry out verification calculations for high-rise buildings, enabling residents to be aware of the risk of potential fires upon settlement. For future research, we consider it essential to account for real equipment reliability data, backup power supply availability, fire department equipment, and other factors.

5. Conclusions

1. The electronic ASPS components, including those developed by the authors, are highly significant in preventing the failure of critical high-rise building systems during a fire. System enhancements through hardware and logical unification enable a wide range of automation systems in the municipal sector.

2. The "Information Point of Presence" interface, proposed by the authors for municipal automation systems, significantly enhances safety during emergencies, enabling system-wide control from CSPCP and LCPs or even the Internet.

3. The enhanced Network Information Module (NIM) ensures seamless communication and data transfer between network components, enabling the integration and control of various devices (sensors, actuators, cameras) via the network, thereby maintaining high ASPS reliability.

4. The Process Control Microcontroller (PCM) series, first developed by the authors, serves as the primary technical implementation of the described algorithms for managing engineering systems in buildings and industrial facilities, demonstrating high reliability.

5. Probabilistic modeling is highly valuable for analyzing the operability of safety systems in the municipal sector, optimizing the design of distributed control systems with complex network topologies, and improving reliability metrics. It is necessary to carry out similar probabilistic safety analyses for all modern high-rise building projects, based on real-world data on equipment reliability. In the contemporary world, individuals purchasing an apartment in a high-rise building should be aware of the risks associated with potential fires.

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