EFFICIENCY INCREASE FOR ELECTRICAL FIRE DETECTION AND ALARM SYSTEMS THROUGH IMPLEMENTATION OF FUZZY EXPERT SYSTEMS

Ionuț-Lucian HOMEAG[1], Radu PÂRLOG-CRISTIAN[2], Mircea COVRIG[3]

Securitatea la incendiu reprezintă un element fundamental în contextul cerințelor şi exigențelor actuale. Ca o consecință imediată a acestui fapt apare necesitatea de îmbunătățire a securității la incendiu a construcțiilor şi ocupanților prin implementarea sistemelor electrice de detectare şi alarmare la incendiu. Detecția incendiului depinde în mare măsură de modul cum se efectuează procesarea semnalelor primite de la senzori şi luarea deciziei de alarmare. Folosirea detectoarelor multisenzor oferă mai multe informații despre condițiile existențe în spațiul supravegheat şi permite o detecție precisă, limitând alarmele false. În acest articol se propune un algoritm de detecție a incendiilor bazat pe sisteme expert fuzzy ce înglobează experiența factorului uman şi concluziile rezultate în urma desfăşurării unor teste experimentale la scară reală.

Fire safety represents a milestone in the context of nowadays requirements. As an immediate follow up comes the necessity of improving the fire safety by introducing and installing fire detection and alarm systems. Fire detection generally depends on how the signals from sensors are processed and the alarm decision is taken. The use of multisensor fire detectors gives more information about the environmental conditions and allows an accurate detection with fewer false alarms. This paper presents a fire detection algorithm proposal, based on fuzzy expert systems which include the human experience and whose design is based on experimental data following real scale fire tests.

Keywords: intelligent Building Management System, automatic fire detection, electrical fire detection and alarm systems, artificial intelligence, expert systems, membership functions, fuzzy sets, detection algorithms

[1] Eng., General Inspectorate for Emergency Situations, Bucharest, Romania, e-mail: homeag.ionut@gmail.com

[2] Prof., Faculty of Electrical Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: raduparlogcristian@yahoo.com

[3] Prof., Faculty of Electrical Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: m_covrig08@yahoo.com

1. Introduction

Modern buildings raise multiple safety and security issues that needs to be addressed (fire, authorized access, control of environmental conditions, emergency evacuation). Compliance with safety and security requirements is acquired by implementing systems and components, more or less complex, ultimately said intelligent control.

Electrical fire detection and alarm systems are among the critical components and encompass complex equipment and electrical components.

For such systems, the hardware component is supported by a dedicated software component which gives a intelligent behaviour of the entire building management system. The practical use of electrical fire detection and alarm systems is greatly wide, having special application in large and complex buildings where it is part of an intelligent control as introduced by the new concept of Building Management System (BMS) [1].

BMS or *Building Management System* refers to intelligent control which represents ultimately a chain of interconnected systems for monitoring and control of a large variety of equipment and building functions, having a certain level of efficiency.

Systems interconnection can be done taking into account the various integration levels, starting with basic functions like fire protection, anti-theft, lighting, heating, ventilation, etc., going to a superior integration level among systems according their functions and particularities, and in the end we may consider the global integration.

In the last decade there has been a tendency for standardization of different solutions for ensuring users safety and security. Among the most recent solutions for increasing efficiency of electrical fire detection and alarm systems is the use of fuzzy expert systems due to their flexibility, easy functioning and the possibility of naturally integrating human experience for decision making.

2. Electrical fire detection and alarm systems (EFDAS)

The general architecture of an electrical fire detection and alarm system is shown in Fig.1. The main components are [3]:

- control and indicating equipment (ECS);
- automatic fire detectors;
- manual call points;
- electrical connection circuitry;
- auxiliary equipment – rechargeable batteries, repeaters, sounders, optical alarm indicators.

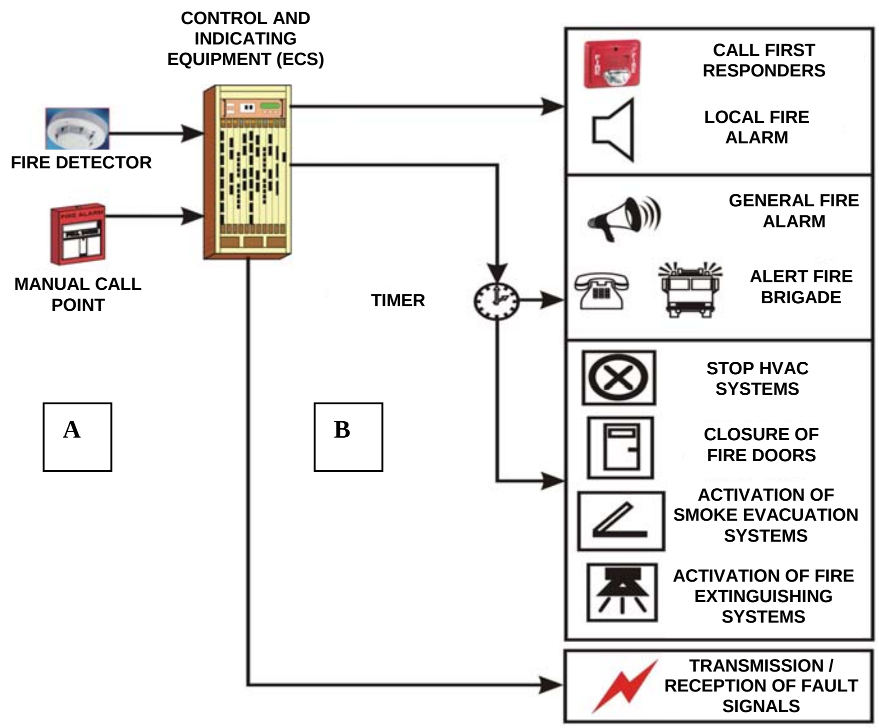

Fig.1. The general architecture of an electrical fire detection and alarm system [3]

The system is structured on two main levels:

- A: detection level which comprises the field equipment such as fire detectors, manual calls, repeaters;
- B: decision making and intervention management level which comprises the control and indicating equipment with its output functions designed for a proper intervention.

The fire detectors are installed and selected, in principle, according to the nature of fire danger, the required speed of detection and the need for limitation of false alarms. They are connected to the control and indicating equipment and provide continuous surveillance of the protected spaces.

The control and indicating equipment is providing power to the network and is processing the signals from the fire detectors. Depending on the incoming signals it can trigger a set of intervention measures, previously configures in the implemented software.

Regardless the producer or the protected objective, the control and indicating equipment is ensuring the following main functions [4]:

- Reception and processing of the incoming signals from the fire detectors, manual call points or any other devices (e.g. input/output units), to determine whether these signals correspond to a fire alarm condition and to indicate any such fire alarm condition audibly and visually;
- Regular check and control of system operating status, connectivity between devices (auto-control function), including the rescan of an individual detector that has signalled a momentary alarm indication. This ability helps to cut false alarms due to single transient events;
- Power the network (main power, auxiliary power).

In a fire alarm situation, the control and indicating equipment may trigger a local alarm and activate a searching procedure for verifying the fire conditions by the local service. If the fire alarm signal persists after a given timeframe, the general fire alarm will de triggered. This includes the internal fire alarm (acoustic and optic) and on a case by case basis a fire alarm signal will be sent to the fire brigade.

In a fire alarm condition, the system may also trigger special intervention actions like closing the fire resistant doors, opening the smoke evacuation hatches, cutting the power in certain areas of the objective and starting the fire extinguishing systems (water spray, carbon dioxide, nitrogen, etc.).

The signals that are dealt with in such systems are of electrical nature by precedence, thus justifying the name of electrical fire detection and alarm systems (using the acronym EFDAS).

Actual approaches focus on the efficiency of the fire detection process (i.e. timely detection of physical and chemical parameters associated to the fire) and the detection algorithm (i.e. the way in which signals from the fire sensors are processed and the fire alarm decision is triggered).

Different generations of EFDAS can be characterized by:

- the nature of electrical signals coming from sensors, the digital form being the most used in modern systems;
- digital signals allows the implementation of various software for decision making, drift compensation, detector verification, detector sensitivity adjustment, communication with the user or with an upper management level;
- fire detector electrical signals can distinguish between different fire alarm conditions according to the operational procedures such as:
    - Pre-alert (early warning signal) – identification of suitable conditions for fire development which implies a local, on the ground verification of the protected environment;
    - Fire alarm signal – persistence of fire conditions and transgression of user safety levels.

3. Implementation of fuzzy expert systems in EFDAS

Expert systems are applications designed for enabling certain expert competences to a non-expert. Expert systems try to emulate the human expert reasoning and for this are considered to be part of artificial intelligence field [5]. Artificial intelligence offers excellent premises for using fuzzy sets and fuzzy reasoning because most of the time the knowledge belongs to human experts, being by precedence fuzzy, ambiguous or imprecise [6].

An expert system can provide solutions to problems that do not accept a deterministic solution and its reasoning is based on the existing knowledge stored in a data base (rule base) in combination with a specific inference mechanism.

The response analysis of electrical fire detection and alarm systems implies in many situations imprecise and fuzzy data which can have serious consequences on the response time and unacceptably high rates of false alarms. Very often the analyzed signals from the protected environment returns imprecise data ("highly possible...") or without certain validity ("in 90% of cases...."). The use of fuzzy data like "*medium smoke density*" or "*high temperature*" are very similar with human perception of fire effects, thus being excellent inputs for a fire detection algorithm of an EFDAS using fuzzy expert systems.

Fuzzy sets and fuzzy logic are used to heuristically quantify the meaning of linguistic variables, linguistic values and linguistic rules that are specified by the expert. The concept of a fuzzy set is introduced by first defining a *membership function*.

Let X_i denote a universe of discourse and $\tilde{A}_i^j \in \tilde{A}_i$ denote a specific linguistic value for the linguistic variable $\tilde{x}_i$. The function $f(x_i)$ associated with $\tilde{A}_i^j$ that maps the universe X_i to [0,1] is called a *membership function*. This membership function describes the certainty that an element of X_i, denoted x_i, with a linguistic description $\tilde{x}_i$, may be classified as $\tilde{A}_i^j$. Membership functions are subjectively specified in an ad-hoc (heuristic) manner from experience or intuition [7].

It is important not to mix up the term ***certainty*** with ***probability***. A membership function does not represent a *probability density function*. There is nothing stochastic about the fuzzy system and membership functions are not restricted to obey the laws of probability. In fuzzy logic, the term certainty means ***degree of truth***.

For instance, let X_i = [0,100 °C], $\tilde{x}_i$ = *temperature,* $\tilde{A}_i^j$ = *medium*, then $f(x_i)$ may be a Gaussian curve (Fig. 2) that peaks at 1 at x_i = 50 °C and is near 0 when x_i < 50 °C or x_i > 50 °C. Then if x_i = 50 °C, $f(x_i)$ = 1, so it is absolutely certain that x_i is *medium*. If x_i = 10 °C then $f(x_i)$ is very near zero, which means that it is very certain that x_i is not *medium*. This approach is clearly different from a standard Gaussian probability density function. Recall that it is possible that a Gaussian probability function reach a maximum value at a value other than 1. The standard Gaussian membership function always has its peak value at 1.

Clearly, many other choices for the shape of the membership function are possible (e.g. triangular, trapezoidal, sigmoid,...) and each of these will provide a different meaning for the linguistic values that they quantify.

Then a *fuzzy set* denoted A_i^j is defined as:

$$A_i^j = \{(x_i, f_{A_i^j}(x_i)), x_i \in X_i\} \tag{1}$$

A more in depth mathematics of fuzzy sets, fuzzy logic and fuzzy expert systems are presented in [8] and [9].

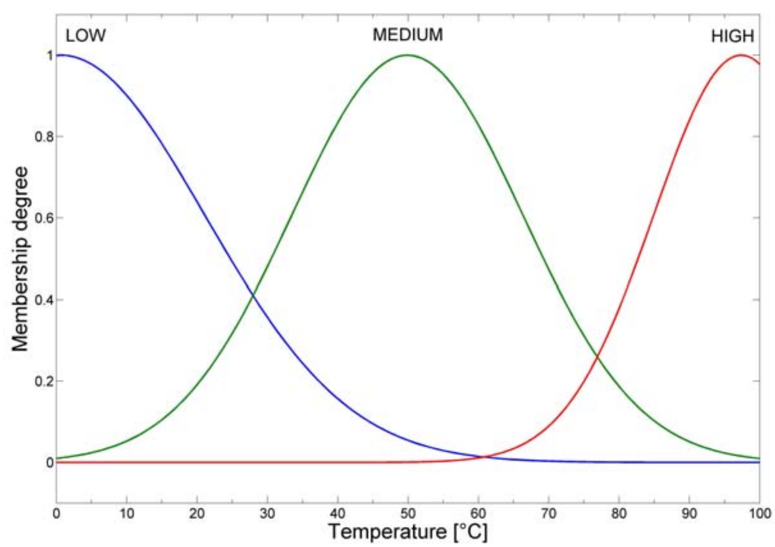

Fig.2. Membership function for the linguistic value *medium* of the linguistic variable *temperature*

One of the major issues for an EFDAS is the optimal adjustment of its standardized components to a diverse and sometimes contradictory environment in terms of fire detection requirements. Using fuzzy systems has the advantage of not operating with strict and crisp alarm thresholds, thus by using linguistic variables, values and rules the user can set and assign different priorities to phenomenon observed during fires without affecting the input variables mapping and the way fuzzy sets are defined on the discourse universes.

For instance, the use of multisensor fire detectors such as optical/thermal/chemical (OTC) in complex fire applications (office time, restaurant, kitchen, industrial hall, etc.) raise the issue of how to best inference the electrical signals coming from the three sensors in order to take an accurate alarm decision. Without a flexible system, that would imply installing specialised single point detectors and multisensor on certain applications, which is not at all an economic approach from both angles: operational and ensuring fire safety.

Using the expert fuzzy systems solved in an elegant way the two contradictory requirements: (1) operating in special applications and (2) the use of standardized electrical components, thus adding value to specialized software and customized for special applications.

Anticipating this need and opportunity, through authors' research, a fuzzy expert system has been developed in order to be implemented as a detection algorithm for electrical fire detection and alarm systems, whose main components will be presented in the following sections.

4. Fuzzy fire detection and alarm expert system

Fuzzy expert systems (FES) offer the flexibility of operating standard electrical components from an EFDAS without making adjustments to the fire detectors. Applying such techniques implies the implementation of response functions in which the pre-alert and fire alarm thresholds are adjusted accordingly to the fire conditions from the protected environment and in concordance with the fire risk.

In Fig.3 is depicted the architecture of an EFDAS, having as central element a fuzzy expert system (FES). The conclusions drawn by the authors after conducting various real scale fire detection tests revealed that the main parameters for triggering a pre-alert or a fire alarm status are the following: **smoke density** (S_a), **smoke density variation** (S_d), **temperature** (T_a), **differential temperature** (T_d) and **concentration of carbon monoxide** (CO). These five input variables will be used in the design process of a fuzzy expert system which will serve as the fire detection algorithm for a multisensor fire detector type optical/thermic/chemical (OTC).

Input variables temperature (Ta), smoke density (Sa) and concentration of carbon monoxide (CO) are entering directly into the fuzzification block of the fuzzy expert system, thus resulting the linguistic variables $\{\widetilde{T}_a, \widetilde{S}_a, \widetilde{C}_{CO}\}$, each of them having three linguistic values {*low, medium, high*}.

It is well known that false alarms may occur due to sudden variation of one or more fire parameters as a consequence of some interferences or disturbances in the protected environment. The authors considered that by applying some attenuation / dumping filters will provide stability to transient phenomenon and resilience to generating false alarms.

Consequently, the inputs differential temperature (T_d) and smoke density variation (S_d) will pass firstly through an attenuation filter to eliminate sudden variations, which normally are responsible for false alarms.

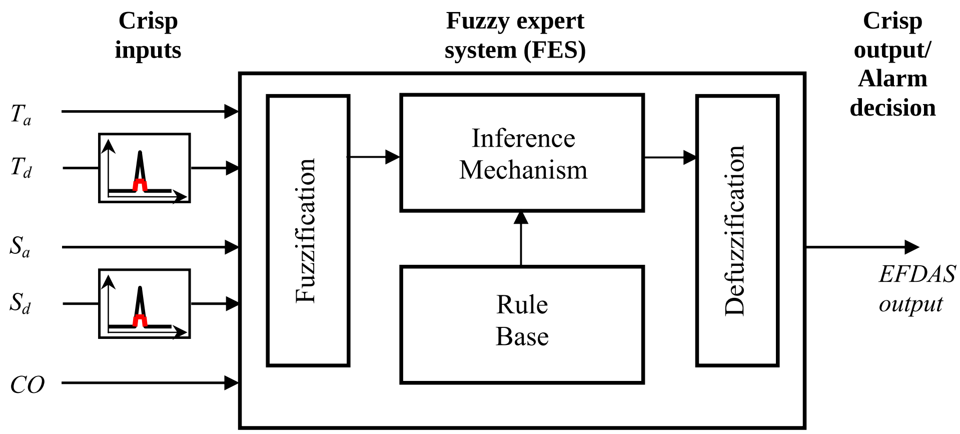

Fig.3. The general architecture of the fuzzy expert system

The attenuation filter is controlled by a parameter τ generated by a fuzzy controller which set the timeframe, in seconds, for applying the attenuation over the original signal from the sensors. The architecture of the attenuation filer is depicted in Fig.4.

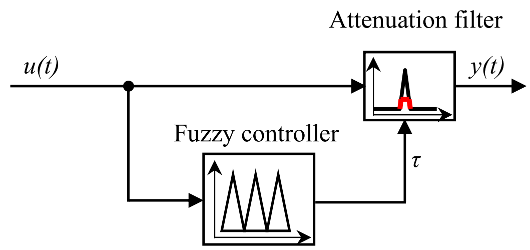

Fig.4. The architecture of the attenuation filter

The output $y(t)$ is given by the following equation:

$$y(t) = \begin{cases} 0, & t < t + \tau \\ u(t+\tau), & t = t + \tau \end{cases} \tag{2}$$

where $u(t)$ – input signal (T_d or S_d) at the time moment t

y(t) – output attenuated signal (T_d or S_d)

τ – attenuation time duration [s]

Basically the attenuation filter will operate in a sequential manner:

1. Firstly, will cut to zero the input signal amplitude *u(t);*

2. After the timeframe given by τ will let pass the signal unspoiled at the moment $t+\tau$;

3. Return to step 1.

After the attenuation filter the variables T_d and S_d are entering into the fuzzification block of the fuzzy expert system, thus resulting the linguistic variables $\{\widetilde{T}_d, \widetilde{S}_d\}$, each of them having three linguistic values {*low, medium, high*}.

The FES output represents the EFDAS decision to trigger the fire alarm or not, which is basically an electrical signal whose characteristics express the status of EFDAS.

In Fig.5 is depicted the fire detectors response under a fire situation given by a wooden smouldering fire (wood pyrolysis). Depending on the fire safety scenario which should take into account the fire behaviour, occupants' reactions, the fire brigade summoning time, this can imply having a shorter timeframe between the pre-alert (AP) and the fire alarm (AI) than the one performed naturally by the fire detector.

The fire detection response in concordance with the fire safety scenario (ideal response) is depicted with the green line. Such implementation based on fuzzy techniques can solve the issue in a very simple way by re-adjusting few parameters using the user interface.

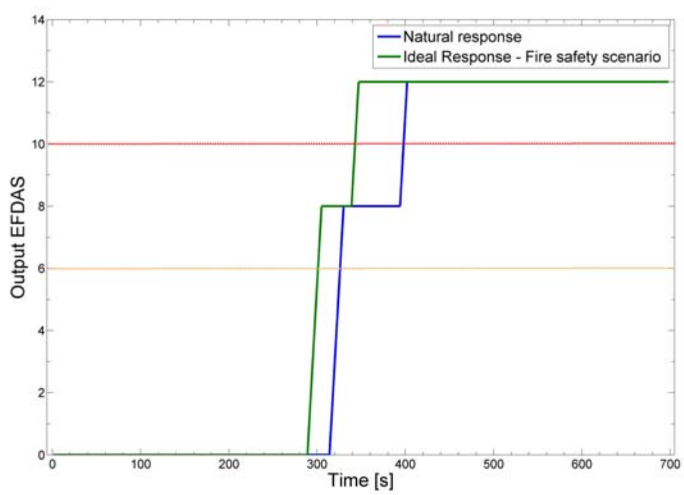

Fig. 5. Fire detection response: natural (blue) and in concordance with the fire safety scenario (green)

Taking this into consideration, the authors propose a fire detection algorithm whose design implied the completion of the following steps:

- selection of most relevant input variables – we used the five input variables mentioned above as being the most relevant for determining the fire conditions;
- Design of the attenuation filters driven by dedicated fuzzy controllers;
- Selection of most suitable type of membership functions for input / output variables and calculation of specific parameters – we used a combination of membership function types: triangle, trapeze, gauss and difference sigmoid;
- Elaborate the rule base – starting from the requirement of ensuring the fire safety and efficiency of active fire safety measures the rule base is composed of 9 fundamental rules:

(1) **IF** $\tilde{S}_a$ is *Low* **and** $\tilde{S}_d$ is *Low* **and** $\tilde{T}_a$ is *Low* **and** $\tilde{T}_d$ is *Low* **and** $\tilde{C}_{CO}$ is *Low* **THEN** $\tilde{y}$ is *NU*.

(2) **IF** $\tilde{S}_a$ is *Medium* **and** $\tilde{T}_a$ is *Medium* **and** $\tilde{C}_{CO}$ is *Medium* **THEN** $\tilde{y}$ is *AP*.

(3) **IF** $\tilde{S}_a$ is *High* **or** $\tilde{T}_a$ is *High* **or** $\tilde{C}_{CO}$ is *High* **THEN** $\tilde{y}$ is *AI*.

(4) **IF** $\tilde{S}_a$ is *Low* **and** $\tilde{S}_d$ is *High* **THEN** $\tilde{y}$ is *AP*.

(5) **IF** $\tilde{S}_a$ is *Low* **and** $\tilde{S}_d$ is *Low* **and** $\tilde{T}_a$ is *Medium* **and** $\tilde{C}_{CO}$ is *High* **THEN** $\tilde{y}$ is *AI*.

(6) **IF** $\tilde{T}_a$ is *Medium* **and** $\tilde{T}_d$ is *High* **THEN** $\tilde{y}$ is *AI*.

(7) **IF** $\tilde{S}_a$ is *Medium* **and** $\tilde{S}_d$ is *High* **THEN** $\tilde{y}$ is *AI*.

(8) **IF** $\tilde{S}_a$ is *Medium* **and** $\tilde{S}_d$ is *Low* **and** $\tilde{T}_a$ is *Medium* **and** $\tilde{T}_d$ is *Low* **and** $\tilde{C}_{CO}$ is *Low* **THEN** $\tilde{y}$ is *NU*.

(9) **IF** $\tilde{S}_a$ is *Low* **and** $\tilde{S}_d$ is *Low* **and** $\tilde{T}_a$ is *Low* **and** $\tilde{T}_d$ is *High* **and** $\tilde{C}_{CO}$ is *Low* **THEN** $\tilde{y}$ is *NU*.

5. Experimental validation of the proposed algorithm

For establishing a reliable data base the authors performed a set of 20 real-scale fire detection tests following various fire scenarios with different compact / liquid fuels. The result was a data base with more than 280,000 data representing values of fire parameters such as temperature, smoke density, concentration of carbon monoxide and their variation in time (gradient). For measurement and monitoring it was used professional equipment, as well as a modern analogue –

addressable EFDAS. Point type fire detectors were installed, having the following sensor combination:

- D1(OTC) – multisensor optical/thermic/chemical
- D5(OT) – multisensor optical/thermic
- D3, D4, D6 (O) – optical smoke detector
- D2 (T) – heat detector

The temperature was monitored by using four thermocouples type K, with the measurement universe -100 ÷ 1300 °C and an adequate monitoring and recording system (*DataLogger*).

The tests were run in a dedicated space from a real building (S+P+2) under construction. The enclosure's dimensions were 506x430x305 cm (LxWxH) having a vertical opening 220x90cm and a central beam with 23cm height and 35cm depth. Fig.6 presents a drawing of the test enclosure on which is depicted the lay-out of the used equipment.

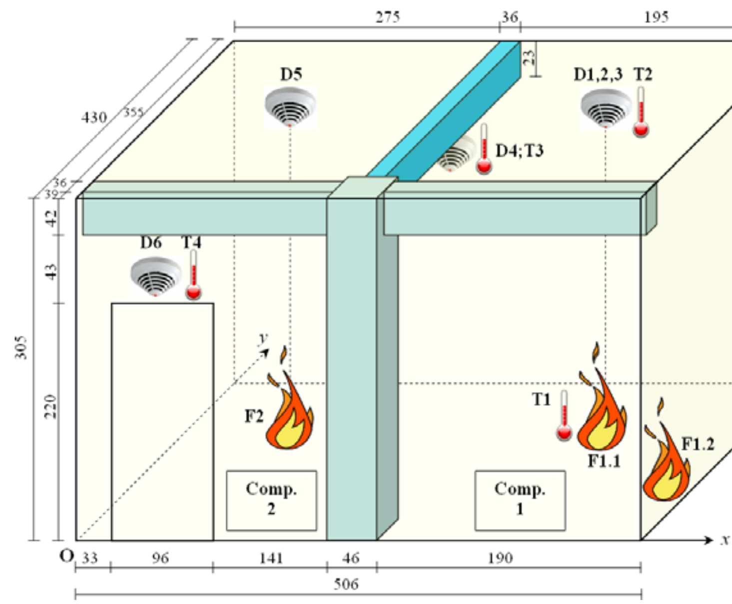

Fig. 6. Sketch of the test enclosure, the exact geometry and the lay-out of the fire detection and monitoring equipment

The central beam separates the enclosure into two fire compartments and will play a crucial role in the transport of smoke and hot gases from one compartment to the other.

The tests were run with various combustible materials, following the specifications of the standard test fires TF1 – TF5: burning flame beech wood, smouldering beech wood, cotton fire, polyurethane fire and liquid fire (mix of diesel and gasoline). Throughout the tests, the fuel quantity was modified, as well as the burning place in the enclosure and the sensitivity of fire detectors.

Using the fuzzy toolbox and Simulink tool from Matlab, the functioning of the fire detectors was simulated by running the proposed detection algorithm with the values of the input parameters obtained from the experimental tests.

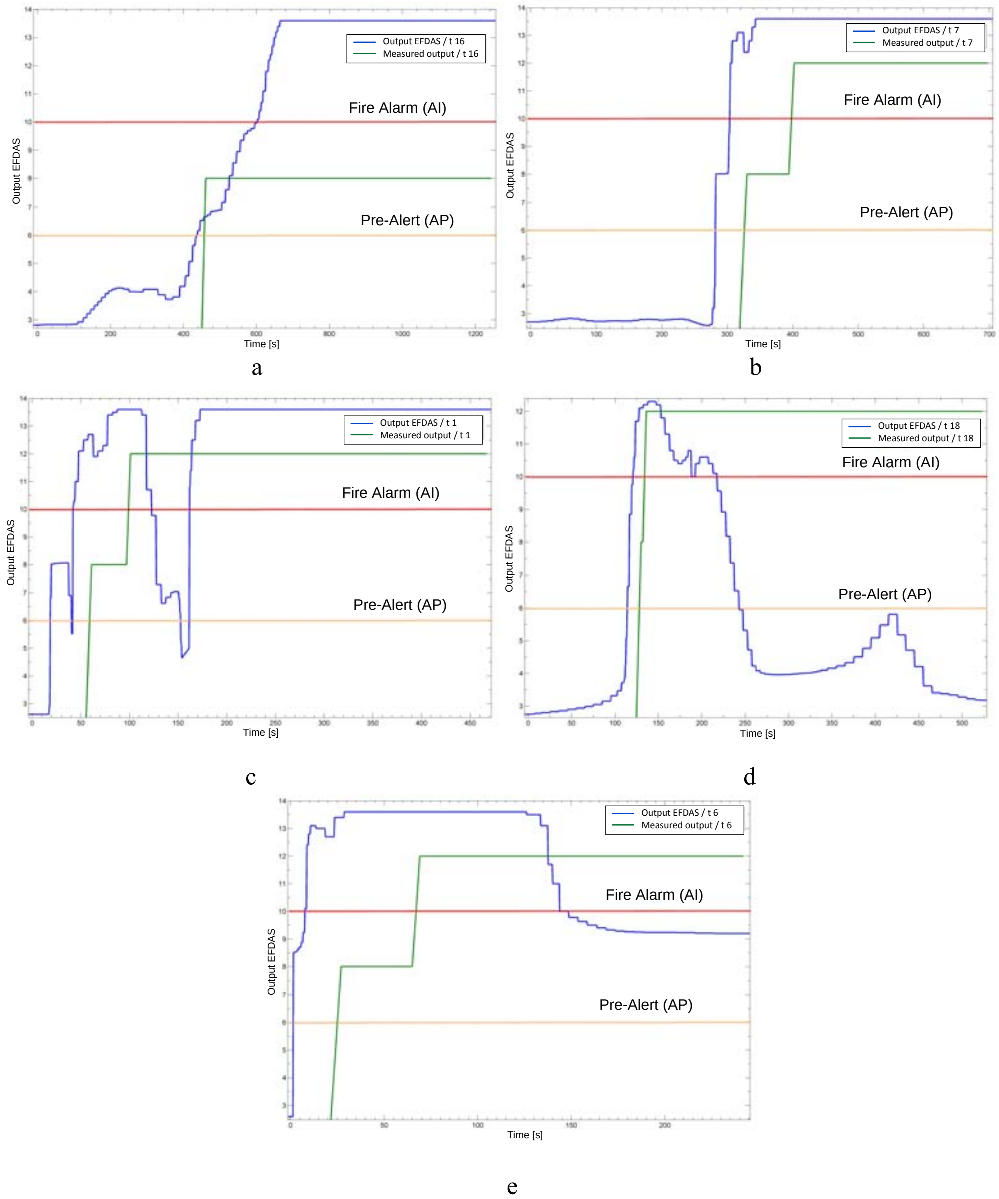

Fig.7. Output EFDAS: a) beech wood flaming fire; b) beech wood smouldering fire; c) cotton smouldering fire; d) polyurethane fire; e) liquid fire (mix of diesel and gasoline)

In Fig.7 are depicted the results for each category of tests, according to the burning nature – blue line shows the EFDAS output as given by the proposed algorithm and the green line represents the behaviour of the tested system (the output values as measured during the tests).

It was noticed that for all fire types the fire detection is faster for both pre-alert (AP) and fire alarm (AI) thresholds. At the same time the system maintains a good resilience towards false alarm production.

The biggest difference between the calculated response time and the one measured during the tests peaked at 94 seconds (s) in the case of the smouldering beech wood test (Fig.7.b), which represents a substantial reduction of the detection time and a major increase of the evacuation time for occupants.

Equally, in the case of liquid fires due to the fire dynamics and massive smoke production, with an increased rate of optical density, the proposed algorithm turns the system into pre-alert status followed shortly by the fire alarm (Fig.7.e). The difference between the calculated response time and the measured time is 26s for pre-alert and 59 s for the fire alarm.

A special case was the beech wood flaming fire (Fig.7.a) in which the tested system didn't triggered the fire alarm but only raising twice the pre-alert level even though the fire detectors were configured at maximum sensitivity. By using the proposed algorithm the fire was accurately detected and the fire alarm was triggered at 602 s, mainly as a consequence of high carbon monoxide concentration.

The results are centralized in Table 1 and graphically depicted in Fig. 8 and 9, according to the fire alarm category (pre-alert or fire alarm). For a quantitative comparison, on the same graph are depicted the response time values measured during the fire test for a multisensor fire detector, type optical/thermic/chemical (OTC).

Table 1

Response time values: calculated (EFDAS) and measured (experimental fire tests)

Test category	**Combustible material**	**Response time *EFDAS* [s]**		**Response time measured [s]**	
		AP	AI	AP	AI
t 1	Cotton smouldering fire	19	42	59	99
t 6	Liquid fire (mix of diesel and gasoline)	2	8	28	67
t 7	Beech wood smouldering fire	282	304	326	398
t 16	Beech wood flaming fire	437	602	457	N/A
t 18	Polyurethane fire	115	121	128	134

* N/A – not applicable (fire detector didn't reach that state)

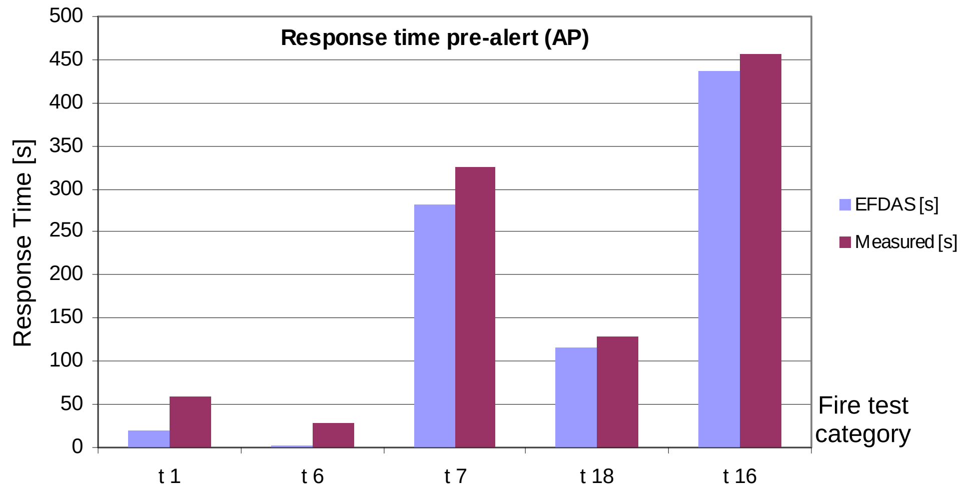

Fig. 8. Comparison response time values to pre-alert threshold (AP)

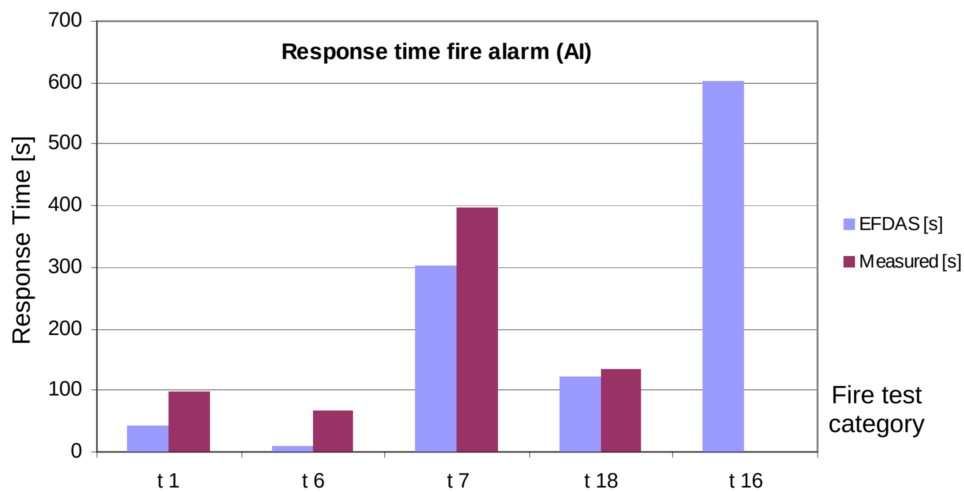

Fig. 9. Comparison response time values to fire alarm threshold (AI)

The proposed fuzzy expert system allows easy adjustment of the detection algorithm in order to be used for other applications as well. For instance, by convenient adjustment of membership functions parameters for input variables, cutting-off the attenuation filters for S_d and T_d, deletion from the rule base of the last two rules (8) and (9), as well as reducing the weight of the rule (4) to 50%, a new fire detection algorithm will be obtained which can be used for an EFDAS configured for a higher level of sensitivity, to be applied in protected objectives where human activity is limited and the environment is more stable without temperature variation, limited dust circulation, etc.

6. Conclusions

Electrical fire detection and alarm systems (EFDAS) based on classical fire detectors response, presents several limitations for certain applications due to the necessity of using fire detector which are not standardized for the time being.

Fuzzy expert systems due to their specific flexibility proved to be very useful for fire detection.

The fuzzy expert system proposed in this paper showed a faster fire detection capability and a better resilience to transient phenomenon responsible for false alarms production.

The use of several types of membership functions for each variable involved in the inference process allow the optimization of an EFDAS for a specific application without involving specialized components.

It is to be emphasized that an EFDAS based on fuzzy expert systems, in order to be highly reliable, require access to data bases with experimental data as accurate as possible and in accordance with the real environmental conditions.

REFERENCES

[1] *Pârlog-Cristian, R., Homeag, I.* Aspecte privind gestiunea tehnică a clădirilor moderne, Electricianul nr. 8/2003

[2] *Homeag, I.,* Considerații privind utilizarea sistemelor de detectare şi alarmare la incendiu în zone rezidențiale. A IX-a Conferință Internațională de Apărare Împotriva Incendiilor şi Catastrofelor, 25-26 septembrie 2008, Băile Felix, România

[3] *Homeag, I.* Referat doctorat: Sisteme expert pentru stingerea automată a incendiilor, Facultatea de Inginerie Electrică, UPB, Bucureşti 2009, p.7-17

[4] *Şerban M.* Sisteme de detecție şi alarmă la incendiu, Editura Ministerului Administrației şi Internelor, Bucureşti, 2009, ISBN 978-973-745-013-5

[5] *Siler, W., Buckley, J.* Fuzzy expert systems and fuzzy reasoning. USA, 2005, ISBN 0-471-38859-9, p.2-3

[6] *Caluianu, S.* Inteligență Artificială în instalații / Logica fuzzy şi teoria posibilităților, Matrix Rom Buc 2000, ISBN 973-685-10-6, p.8-9

[7] *Passino, K., Yurkovich, S.* Fuzzy control, 1998, ISBN 0-201-18074-X, p.249-250.

[8] *Klir G. J., Yuan B.* Fuzzy Sets and Fuzzy Logic: Theory and Applications. Prentice-Hall, Englewood Cliffs, NJ, 1995.

[9] *Sivanandam S. N., Sumathi S., Deepa S. N.* Introduction to Fuzzy Logic using MATLAB, 2007, ISBN-10 3-540-35780-7 Springer Berlin Heidelberg New York