Розроблена математична модель і методика для визначення оптимальної кількості засобів протипожежної системи захисту складів в закритих приміщеннях, на підставі яких можливо визначати заходи для покращення цієї системи з урахуванням допустимого для складу значення імовірності її відмови. Суть розробленої методики полягає у визначенні необхідної кількості засобів протипожежного захисту відповідно до норм, визначенні ймовірності відмови протипожежного захисту та визначенні оптимальної кількості засобів протипожежного захисту, щоб забезпечити значення іморівності відмов у допустимих межах. За критерії оптимізації обрано прямі збитки від пожежі і витрати пожежно-рятувальних підрозділів на її гасіння. Функцією мети даної моделі є зниження імовірності відмови протипожежної системи об'єкта до значення меншого або рівного допустимому. Вхідними даними при використанні математичної моделі є розрахункова кількість засобів протипожежного захисту згідно норм та стандартів.

Розроблена методика дозволяє прогнозувати значення імовірності відмови протипожежної системи для реалізації пожежної безпеки об'єктів захисту та її наслідків для людей і матеріальних цінностей. Також результатом застосування методики є оптимальна кількість протипожежних засобів на об'єкті, що забезпечить допустиме значення імовірності відмов. Дана методика застосована на прикладі існуючого логістичного складу, на якому змонтовані системи протипожежного захисту. Результати моделювання показали, що на об'єкті необхідно збільшити кількість пожежних сповіщувачів до 70 штук, протидимних пристроїв – до 3-ох штук, вертикальних завіс – до 4-ох, обладнати аераційними ліхтарями в кількості 4 шт, та збільшити кількість евакуаційних виходів – до 10

Ключові слова: протипожежна система захисту, збитки від пожежі, витрати на протипожежний захист, імовірність відмови систем

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ENGINEERING METHOD FOR DETERMINING RATIONAL FIRE PROTECTION PARAMETERS OF WAREHOUSES

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1. Introduction

One of the main tasks that is associated with fire safety for any objects is the development of effective systems and the introduction of all necessary means for fire protection of these objects. In order for the fire protection system of the facilities to be fully equipped, it is necessary that it includes all the necessary systems and devices that would make it possible to perform:

1) the fire alarm was received by the control and reception device (CRD) of the fire alarm from the fire detectors and the fire detectors, smoke protection systems, evacuation doors and automatic fire extinguishing systems (if any) were turned on instantly, and the alert was sent to the control center of the traffic control system;

2) instant determination of the onset of fire by combined fire detectors and signal transmission to the control panel;

3) instant fire warning at the facility using sound fire detectors;

4) instant inclusion of smoke protection systems (smoke and heat removal system with opening mechanism)

5) automatic opening of evacuating doors;

6) instant inclusion of an automatic fire extinguishing system for objects.

At the present stage, when installing fire protection systems (FPS) at the facility, a problem arises that they do not take into account for the facility, in order to reduce the cost of purchasing fire protection systems, the allowable service area for each device in the system. This approach leads to a decrease in the functionality of the fire protection system of the facility by 40...65 %. In turn, in case of fire at the facility, in this case, losses from the fire increase 2...3 times [1].

Fire statistics indicate that the number of fires in warehouse buildings in Ukraine annually exceeds 130 [2]. In most cases, warehouses are burned to the ground for a large amount of fuel load and the failure of fire protection systems to ensure their fire safety. Over the course of 5 years, a significant number of fires occurred in the USA, namely 1210 in warehouses, which resulted in losses of 155 million USD [3]. In 38 % of fires in warehouses, they were equipped with fire protection systems, however, they could not fully fulfill their task due to malfunctions and failure [4].

According to [5], fire protection systems (FPS) of facilities should include:

1) fire alarm systems;
2) fire alarm transmission systems;
3) evacuation control systems (regarding the fire warning system and evacuation direction indicators)
4) automatic fire extinguishing systems;
5) smoke removal systems;
6) autonomous fire extinguishing systems;
7) FPS dispatching systems;
8) oxygen reduction systems. Engineering systems and technological equipment that are not included in the FPS, but the FPSs are functionally connected: lightning protection; fire lifts; fire crane sets; fire doors, valves, gates, curtains (screens), etc.

For the premises of warehouses, fire alarms are used in the form of fire detectors (smoke, flame, heat and combined) and the warning system is said. When organizing such an alarm system, various information methods are taken into account [6], namely:

– informing those who provide assistance;
– warning of those present;
– control of the fire automatics system.

The control system should exhibit a fire, include fire warning equipment and automatic fire protection facilities facilitate the evacuation of people, call the units of the fire safety department to eliminate the fire (Fig. 1) [7].

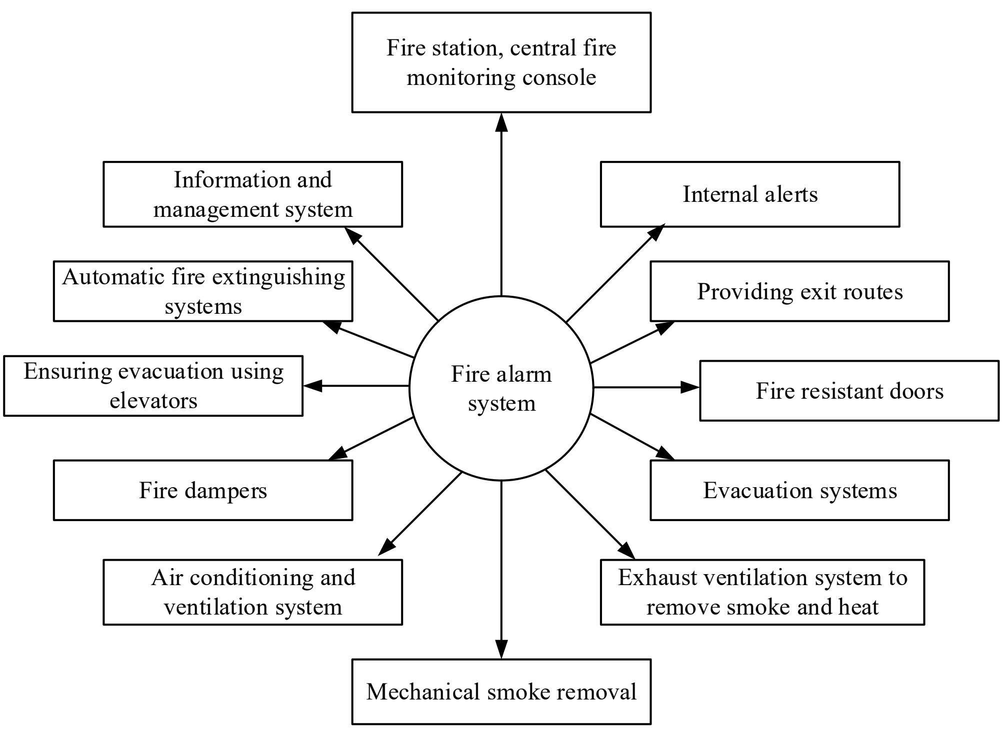

Fig. 1. Fire alarm system (FAS) for fire protection of an object [8]

According to the results of the analysis of the reports of the firefighting and fire-rescue department of the CES of Ukraine [8], it was concluded that at a larger number of facilities the recommendations are not fully used and this leads to significant losses from the consequences of fires. This also applies to smoke protection systems. For example, at most enterprises, it is believed that instead of a smoke protection system, a supply and exhaust ventilation system can be used, but this approach to solving this problem is erroneous. This is explained by the fact that already for 10 minutes of fire in the zone of the fire source, the optical density of the smoke will be more than 1.2 Np/m, and visibility less than 1.5 m [9].

In view of the foregoing, studies on methods for determining for any object (warehouses located in enclosed spaces) the optimal number of devices of the fire protection system that would make it possible to stably obtain the probability of a fire system failure within no more than $5\cdot10^{-5}...5\cdot10^{-4}$ [10].

2. Literature review and problem statement

The assessment of individual fire risk includes determining the probability of failure-free operation of fire protection systems. The issue of uncertainty in the assessment in determining fire risk has been investigated in many scientific papers. So, in [11], the authors present the results of the study of the probabilistic method for eliminating the negative effects in a fire due to the uncertainty that are missed when assessing the fire hazard. In the study, the probability of occurrence and the expected number of fire cases are estimated taking into account some uncertainties using fuzzy sets. It is shown that this technique can be applied to various types of objects. However, the issue of ensuring the reliability of the systems under study remains unresolved. This problem was partially covered in [12], where it was proposed to carry out two-stage protection of objects. The first stage of protection protects the object from threats, prevents the influence of hazards on the object, the second – reduces the negative impact in case of damage to the object due to these hazards (Fig. 2). In addition, in this work, the reliability of protection systems and the probability of their failures are investigated. However, the work did not solve the ways of troubleshooting and improving the reliability of these systems.

An option to eliminate the corresponding problems is to consider each element of the fire protection systems separately. It is this approach that is applied in [13–16], in which the reliability of elements of automatic fire extinguishing sprinkler systems, elements of power supply systems for fire protection systems, elements of an alarm transmission system, heat and smoke detectors, etc. were studied. To reduce the failure rate of fire protection systems, the authors [14] propose to ensure the reliability of electric networks and power supply systems that ensure the operation of these systems. In [15], the authors propose the installation of monitoring devices for fire protection systems in various rooms. In [16], it is proposed to back up heat and smoke detectors with manual fire detectors, which will reduce the failure rate.

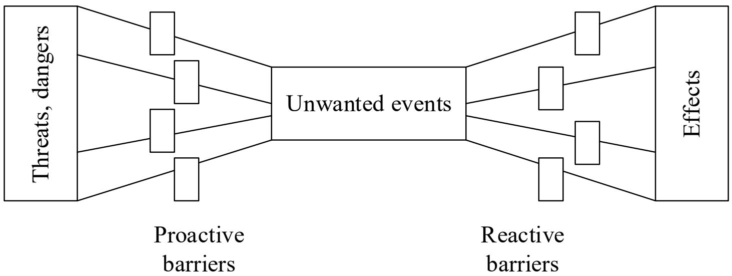

Fig. 2. Butterfly diagram of two-stage protection [11]

However, in these works another factor is not considered that affects the reliability of the protection systems, namely, the human factor. By eliminating the negative consequences of the negligence of people who exploit the object of protection (live or work on it), adoption is made in addition to technical decisions in the design of organizational. It is this approach that is proposed in [17]. However, the work does not resolve the issue of ensuring the reliability of fire protection systems, taking into account all factors.

Analyzing the latest research in the field of ensuring the reliability of fire protection systems, it should be noted that there is no integrated approach that would ensure the reliability of all fire protection systems, without exception. In particular, no methods have been developed to determine the required number of fire protection equipment that would ensure the failure rate within acceptable limits. In addition to the above analysis of the current state in the field of fire protection of objects, it can be added that the most important drawback is the lack of a methodology for adopting the optimal amount of funds for a particular object to ensure its fire safety.

All this allows to argue that it is advisable to conduct a study on the development of a methodology for determining the optimal amount of funds to ensure the failure-free operation of fire protection systems of facilities, including closed storage facilities. When developing methods, it should be taken into account that in the event of failure of elements of fire protection systems due to the human factor, failure of power supply elements, the influence of external factors, etc., timely detection and successful fire extinguishing of objects should be ensured.

3. The aim and objectives of research

The aim of research is development of a methodology for determining the optimal amount of firefighting equipment to provide instant warning of a fire in the closed premises of warehouses with the possibility of using this technique at the engineering level.

To achieve the aim, the following objectives are set:

– determine the required amount of firefighting equipment in an indoor facility to provide instant warning of a fire;

– determine the probability of failure of the firefighting system;

– develop a mathematical model to determine the optimal amount of fire protection

– verify the application of the engineering method of optimizing firefighting means on the example of a real object.

4. Methodology for determining the optimal amount of firefighting equipment in enclosed warehouses

The fire protection system of enclosed spaces of various facilities should be fully equipped and include:

1) fire alarm control panel
2) combined fire detectors;
3) sound fire alarms;
4) normally closed smoke exhaust valves;
5) dense vertical curtains of non-combustible materials, to create smoke tanks
6) evacuating doors with a system for their automatic opening.

Providing an acceptable value for the probability of failure of the fire-fighting system of an object within no more than $5\cdot10^{-5}...5\cdot10^{-4}$, there is also the likelihood of prompt evacuation of people from the fire zone, the value of which should be at least 0.95 ... 1, 0, with an instant operational call of the fire and rescue units (FRU), which will allow the FRU to significantly begin the fire elimination for a significantly shorter free-burning time. This approach to ensuring the acceptable value of the probability of failure of the fire system of the facility makes it possible to significantly reduce losses from the fire and prevent death.

4. 1. Methods for determining the required amount of firefighting equipment at the facility

The required amount of firefighting equipment in enclosed warehouses is subject to determination to provide instant warning of a fire. To do this, it is necessary to use the recommendations of state building codes [5].

The fire alarm control panel is installed in a special room of the administrative department of the warehouse. To ensure trouble-free operation of the control panel, they are installed in the amount of two (one is working, and the second is standby). The operating time (continuous operation) of the control panel for failure according to DSTU EN 54-2:2003 is 10 years, that is, its reliability is very high. To ensure reliable operation of the control panel, let's take their number $N_{c\text{-}r.d}=2$.

Combined fire detectors are installed on the ceiling of the warehouse and administrative premises. At the same time, it is assumed that one fire detector can serve an area of no more than $S_{f.d}=49$ m^2 [5]. In this case, their total number $N_{f.d}$ can be determined by the dependence

$$N_{f.d}=\frac{S_w+S_a}{S_{f.d}}, \tag{1}$$

where S_w – the warehouse area, m^2; S_a. – the total area of the premises of the administrative department of the warehouse, m^2.

Fire alarms are installed to inform the warehouse workers about a fire. Their number $N_{f.a}$ is determined provided that the area served by one detector $S_{f.a}=72$ m^2 [5]. Then

$$N_{f.a}=\frac{S_w+S_a}{S_{f.a}}. \tag{2}$$

Smoke protection system (smoke and heat removal system with opening mechanism). The required number of smoke control devices $N_{c.d}$ for the warehouse can be determined by the dependence

$$N_{c.d}=\frac{S_w}{S_{c.d}}, \quad (3)$$

where $S_{c.d}$=900 m^2 – the area of the warehouse served by one smoke receiving device [5].

Dense vertical curtains of non-combustible materials, which are lowered from the ceiling to the floor, but not lower than 2.5 m from the floor, forming smoke tanks under the ceiling. The total required number of curtain systems $N_{c.s}$ can be determined by the dependence

$$N_{c.s}=\frac{S_w}{S_{c.s}}, \quad (4)$$

where $S_{c.s}$=1,600 m^2 – the area of the warehouse served by one curtain system [5].

Doors with automatic opening system. The total required number of evacuation doors $N_{e.d}$ for the warehouse can be determined by the dependence

$$N_{e.d}=\frac{P}{l}, \quad (5)$$

where P – warehouse perimeter, m; l – distance between emergency exits, m [18]

$$l=1.5\sqrt{P}. \quad (6)$$

The above dependencies allow to determine the required number of fire protection equipment in accordance with the standards. At the same time, to ensure the reliable operation of all systems, it is proposed to use 2 control panels that will ensure the operation of all systems even if one of them fails.

4. 2. Methods for determining the probability of failure of fire protection systems

To determine the probability of failure of the fire protection system of the composition, one can use the concept of the total probability of failure of the fire protection system of the I_{FPS}, which will be equal to the product of the probabilities of failure of each component of the FPS. In this case

$$I_{FPS}=\left(1-\frac{N_{c\text{-}r.d.a}}{N_{c\text{-}r.d}}\right)\left(1-\frac{N_{f.d.a}}{N_{f.d}}\right)\left(1-\frac{N_{f.a.a}}{N_{f.a}}\right)\times$$
$$\times\left(1-\frac{N_{c.d.a}}{N_{c.d}}\right)\left(1-\frac{N_{c.d.a}}{N_{c.d}}\right)\left(1-\frac{N_{e.d.a}}{N_{e.d}}\right), \quad (7)$$

where $N_{c\text{-}r.d}$, $N_{f.d.a}$, $N_{f.a.a}$, $N_{c.d.a}$, $N_{c.s.a}$, $N_{e.d.a}$ – the actual number of appropriate fire protection equipment at the facility, which work in the established mode; if the ratio of the actual amount of any fire protection agent $N_{i.a}$ to the desired amount N_i is equal to one or more than one

$$\left(\frac{N_{\text{ia}}}{N_a}\geq 1\right),$$

then in this case this ratio must be taken within 0.995...0.999.

The permissible value of the probability of failure of the fire system [I_{FPS}] for any objects, including warehouses located in enclosed spaces, should not exceed the maximum value of fire risk [10], namely

$$[I_{FPS}]\leq 5\cdot 10^{-5}...5\cdot 10^{-4}. \quad (8)$$

The calculated dependence (7) allows to determine the overall probability of a fire protection system failure established in accordance with norms and standards, and compare it with an acceptable one. If this value does not equal the permissible value, it is necessary to proceed to the next step, namely, determining the optimal number of fire protection means will provide an appropriate level of reliability of all systems.

4. 3. Mathematical model for determining the optimal amount of firefighting equipment in enclosed warehouses

The basis for the development of a mathematical model can be taken dependence (7). Then:

– goal function

$$I_{FPS}\Rightarrow \min\leq [I_{FPS}]; \quad (9)$$

– by criterion

$$B=L_o+B_f\Rightarrow \min; \quad (10)$$

– by restrictions

$$a_1\leq N_{f.d.i}\leq b_1; \quad (11)$$

$$a_2\leq N_{f.a.i}\leq b_2; \quad (12)$$

$$a_3\leq N_{c.d.i}\leq b_3; \quad (13)$$

$$a_4\leq N_{c.s.i}\leq b_4; \quad (14)$$

$$a_5\leq N_{e.d.i}\leq b_5; \quad (15)$$

$$p\geq [p], \quad (16)$$

where a_1, a_2, ... a_5 – the minimum allowable amount of a certain type of fire protection; b_1, b_2, ... b_5 – the maximum allowable amount of a certain type of fire protection; B – total fire losses, rubles; $L_o=C_oS_F$ – losses of the facility from the fire, UAH; C_o – the average cost of one square meter of the area of the object, c.u./m^2 S_F – fire area, m^2; $B_f=C_f\tau_{p.f.u}$ – expenses of fire and rescue units to eliminate the fire, c.u.; C_f – the average cost of one minute of work of the FRU in the process of eliminating the fire, c.u./min; $\tau_{p.f.u}$ – the predicted time of the FRU during fire extinguishing, min; p – the probability of the studied and first points falling into the region of admissible values ($p=k/N$, where k – the number of calculation cycles at which the generated values fell into the region of admissible values; N – the total number of calculation cycles) [p] – the admissible probability value , the value of which depends on the number of experiments to determine the optimal value.

The minimum values of the constraints a_1, a_2, a_3, a_4, a_5 must be taken in accordance with their true value. If any of the fire protection system means is absent, then in this case the corresponding value a_i=0. The maximum values of the constraints b_1, b_2, ... b_5 should be taken in accordance with the values obtained with dependences (1)...(5).

Let's use the Monte Carlo method to solve the optimization problem. The range of permissible values is limited by conditions (11)...(15), surrounded by a 5-dimensional parallelepiped, in which the study is conducted. The solution to this problem is possible using a personal computer by generating pseudo-random numbers μ_{ji} in the interval 0 ... 1. To go from pseudo-random numbers μ_{ji} to the value of the number of means of elements of fire protection systems, it is necessary to use a dependence, an example of which for $N_{f.d.i}$ will

$$N_{f.d.i} = a_1 + \mu_{1i}\left(b_1 - a_1\right),$$

where μ_{1i} – pseudo-random number for determining the factor $N_{f.d.i}$ and at a certain i-th calculation cycle.

When calculating at each cycle of the program, the I_{FPS} value is calculated according to dependence (7) and the criteria F_o and B_f, which are compared with the values of the previous cycle. This cycle will be repeated as many times until condition (16) is satisfied. The results of the calculation will be the following parameters: FPS; $\tau_{f.b}$ –duration of free burning, min; S_F – fire area before and after the introduction of firefighting equipment; V_f – the speed of fire rescue units to the place of call, km/h; τ_t – trip duration to the place of call, min; τ_{loc}– fire localization duration, min; τ_e – fire extinguishing time, min; τ_r – fire response time, min; p – the probability of getting the studied and the first point in the range of feasible solutions; types of necessary firefighting equipment, their cost and quantity, and the total additional costs of their purchase, UAH.

Thus, the methodology for determining the optimal amount of fire protection means consists in sequentially performing the following operations:

– determination of the required amount of firefighting equipment,

– determination of the probability of failure of the firefighting system with the existing level of fire protection

– determination of the optimal amount of fire protection by solving the optimization problem using the Monte Carlo method.

For the effective implementation of the developed engineering methodology for determining the rational parameters of the fire protection of storage facilities according to criterion (10) based on the dependencies (1)–(8), the algorithm shown in Fig. 3.

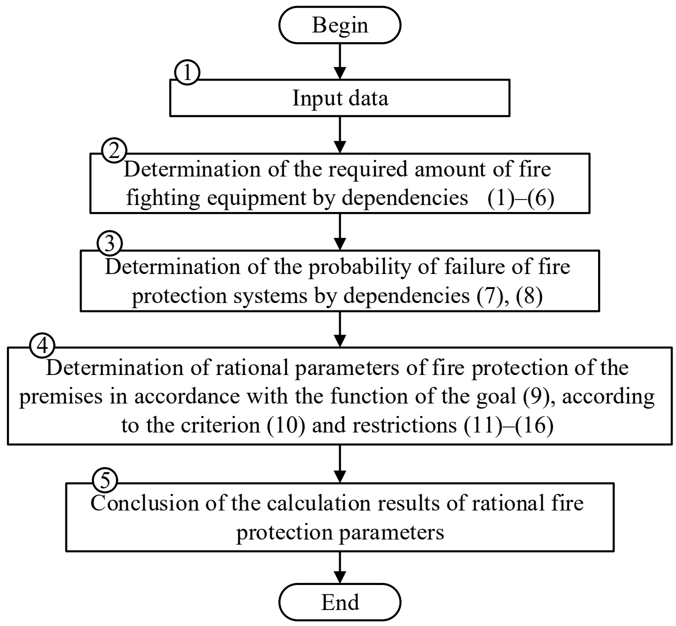

Fig. 3. The algorithm for determining the rational parameters of the fire protection of storage facilities according to the criterion (10)

According to the above algorithm, a program was written in C# for working in the Windows environment to determine the rational parameters of the fire protection of warehouses. The working window of the program is shown in Fig. 4.

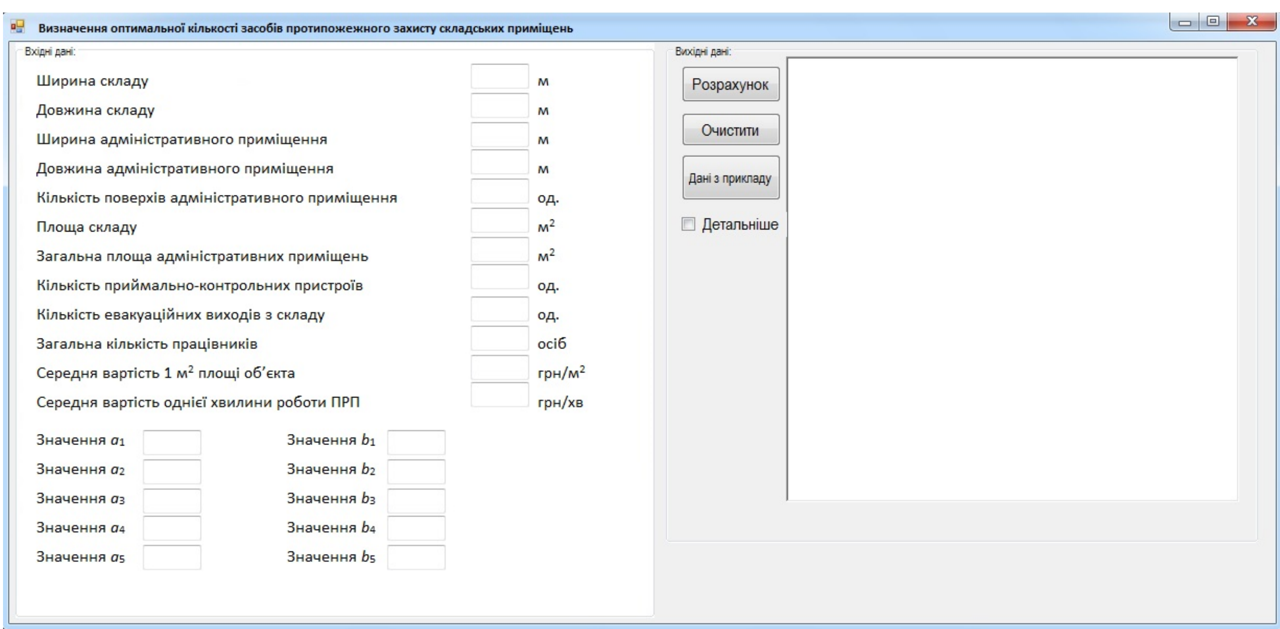

Fig. 4. The working window of the program to ensure the optimal amount of fire protection for storage facilities

4. 4. Application of the engineering method for optimizing firefighting equipment by the example of the logistic composition

Example. Conduct an audit of the logistics warehouse, which is located indoors (Fig. 5), to determine the existing value of the total probability of failure of the fire protection system of the I_{FPS} and, if necessary, in order to ensure its acceptable value, select the necessary firefighting equipment.

Fig. 5. Logistic warehouse of Nova Poshta LLC in Soroky Lvivski village in Pustomyty district of Lviv region (Ukraine)

The plan diagram of the logistic composition is shown in Fig. 6.

Input data: warehouse width – 36 m; warehouse length – 162 m; administrative building width – 36 m; office building length – 18 m; two-story office building; warehouse area S_w=5832 m^2; area of administrative premises, taking into account two floors S_a=1166 m^2; the total perimeter of the warehouse building P=432 m; $N_{c\text{-}rda}$=1 – reception and control device is installed in the administrative room in the guard room, where staff is on duty around the clock (the signal is not transmitted to the dispatch service of the traffic control system); a_5=0 in the warehouse, ordinary doors are used to evacuate personnel from the administrative premises in the amount of 2; a_1=194 pcs.; a_2=0; a_3=0; a_4=0; on the roof of the working area of the warehouse there are no aeration lights, it does not make it possible to use the curtain system; b_1=(5832+1166)/49=143 pcs; b_2=(5832+1166)/72=97 pcs; b_3=5832/900=7 pcs; b_4=5832/1600=4 pcs; $b_5=432/1{,}5;\ \sqrt{432}=14$; in one shift the total number of employees 142 employees.

Fig. 7 shows the main distribution address pipeline, and in Fig. 8 – auxiliary lateral distribution conveyor.

Fig. 7. The main distribution address conveyor of the logistics warehouse of Nova Poshta LLC in Soroky Lvivski village in Pustomyty district of Lviv region (Ukraine)

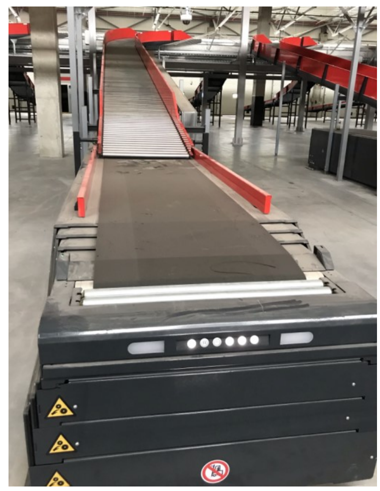

Fig. 8. Auxiliary lateral distribution conveyor of the logistics warehouse of Nova Poshta LLC in Soroky Lvivski village in Pustomyty district of Lviv region (Ukraine)

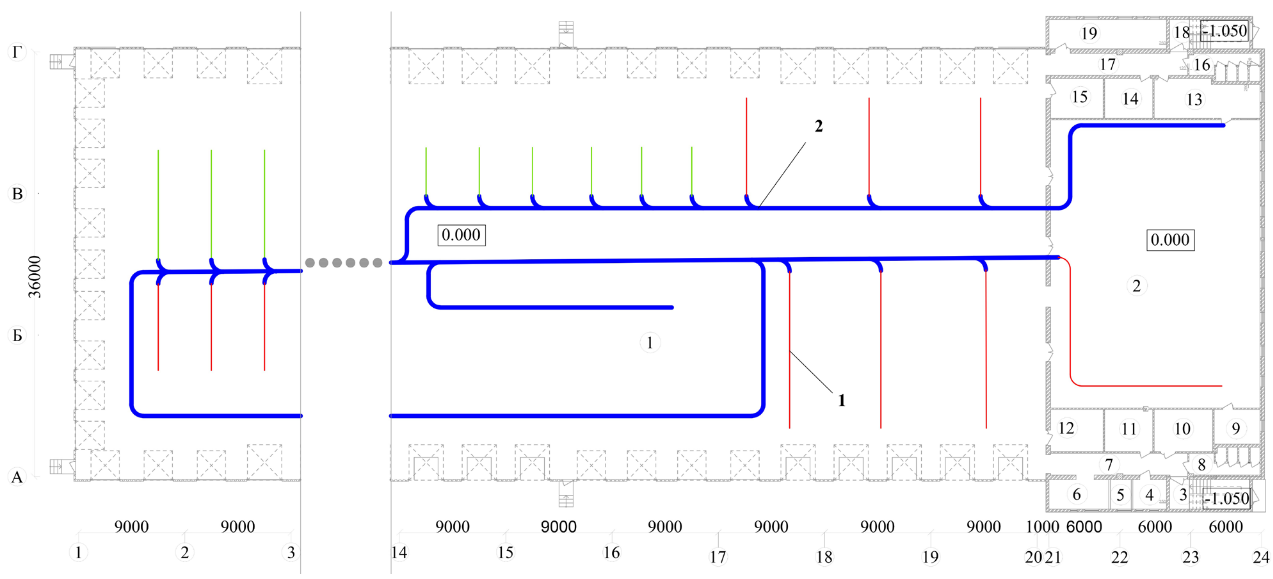

Fig. 6. The layout of the logistics warehouse: 1 — the main distribution address conveyor; 2 — auxiliary side distribution conveyors

Based on the initial data, let's determine the value of the probability of failure of the fire-fighting system of the composition using dependence (7)

$$I_{FPS}=\left(1-\frac{1}{2}\right)\left(1-\frac{194}{143}\right)\left(1-\frac{0}{97}\right)\times$$
$$\times\left(1-\frac{0}{7}\right)\left(1-\frac{0}{4}\right)\left(1-\frac{0}{14}\right)=$$
$$=0.5\cdot 0.001\cdot 1\cdot 1\cdot 1\cdot 1=5\cdot 10^{-4}.$$

The obtained I_{FPS} corresponds to the maximum permissible value $[I_{FPS}]$, which may not provide full fire protection of the warehouse, especially at the stage of evacuation of workers in case of fire.

Using the recommendations of [19], let's determine the value of the probability of personnel evacuation $P_{p.e}$ under existing conditions relative to the existing firefighting warehouse system at a critical fire time τ_c=4.3 min, evacuation time τ_e=1.44 min and time duration $\tau_{p.e}$=2 min from the start of the fire to the start of the evacuation

$$P_{p.e}=\frac{0{,}8\tau_c-\tau_e}{\tau_{p.e}}=\frac{0{,}8\cdot 4{,}3-1{,}44}{2}=1.$$

The results of the analysis of the probability of personnel evacuation shows that the evacuation process was successful, but at the limit. Therefore, it is necessary to consider the possibility of improving the fire protection system of the composition. To do this, it is possible to use the results of determining, based on the proposed mathematical model, the optimal number of elements of fire protection systems in closed storage rooms. For example, considered:

– goal function

$$I_{FPS}\Rightarrow \min\leq[5\cdot 10^{-5}]; \quad (17)$$

– by criterion

$$B=L_o+B_f\Rightarrow \min; \quad (18)$$

– by restrictions

$$143\leq N_{\text{f.d.}i}\leq 194; \quad (19)$$

$$0\leq N_{\text{f.a.i}}\leq 97; \quad (20)$$

$$0\leq N_{\text{c.d.i}}\leq 7; \quad (21)$$

$$0\leq N_{\text{c.s.i}}\leq 4; \quad (22)$$

$$0\leq N_{\text{e.d.i}}\leq 14; \quad (23)$$

$$p\geq[0.95]. \quad (24)$$

The result of the analysis of the calculations to determine firefighting means shows:

1) probability of failure of the fire-fighting system of the composition without re-equipment with fire-fighting equipment is I_{FPS}=5·10^{-4};

2) it is recommended that the number of fire detectors be installed in a building of 70 pieces;

3) amount of smoke control devices is recommended to be installed in the amount of 3 pcs.;

4) it is recommended to install dense vertical curtains in the amount of 4 pcs.;

5) on the roof of the working area of the composition, it is necessary to install aeration lights in an amount of 4 pcs. to remove smoke in case of fire from the volume of vertical curtains into the environment;

6) along the perimeter of the warehouse it is necessary to equip 10 swing doors with automatic opening systems from the signal of the fire alarm control panel

7) after these activities, the probability of failure of the fire-fighting system of the composition will decrease to 1.8·10^{-8}, which provides fire protection of the composition.

$$I_{FPS}=\left(1-\frac{1}{2}\right)\left(1-\frac{194}{143}\right)\left(1-\frac{70}{97}\right)\times$$
$$\times\left(1-\frac{3}{7}\right)\left(1-\frac{4}{4}\right)\left(1-\frac{10}{14}\right)=$$
$$=0.5\cdot 0.001\cdot 0.222\cdot 0.5714\times$$
$$\times 0.001\cdot 0.857=1.8\cdot 10^{-8};$$

8) under such conditions, the fire area in case of its occurrence will be no more than 90 m^2, and the localization duration will not exceed 27 minutes, the extinguishing time – 14 minutes, the duration of the final fire elimination – 10.25 minutes;

9) the total time of FRU employment will not exceed 67.65 minutes;

5. Discussion of the results of the study providing warehouse buildings with fire protection

The developed method for determining the required number of fire protection equipment according to the standards shows that for reliable operation of fire protection systems it is necessary to install 2 reception and control devices at the facility in order to ensure the operation of all systems in case of failure of one of them. The calculated dependences (1)–(6) allow to determine the minimum number of fire protection equipment depending on the geometric parameters of the object and the number of employees.

The developed method for determining the probability of failure of fire protection systems as applied to a real object with existing means has shown that the probability of failure of the fire system, calculated by formula (7), corresponds to the maximum allowable value of 5·10^{-4}, which may not fully provide fire composition protection. For such facilities, it is necessary to increase the number of fire protection equipment. Therefore, a developed mathematical model allows to do this.

The obtained mathematical model allows to determine the optimal number of elements of fire protection systems at the facility with the aim of timely detection, rapid evacuation of people, localization of the fire by automatic fire extinguishing systems, successful firefighting by fire and rescue units. This goal is achieved by increasing the reliability of each of these elements in the complex. But the existing methods for ensuring the reliability of fire protection systems are aimed only at improving the failure-free operation of a particular system.

Existing methods for determining the required number of elements of fire protection systems are based on the implementation of norms and standards. In particular, the resumption of the operation of individual elements of fire protection systems at facilities is carried out by replacing them in the event of a malfunction. However, if a malfunction occurs during a fire, such an approach is not possible. The obtained method allows fire protection systems to perform their functions even in the event of the exit of one or more elements from work by creating a stock of these elements at the facility.

The main limitations inherent in this study are that the paper considers 5 basic firefighting equipment for protecting objects from fires. However, the amount of these funds can be expanded in accordance with the purpose of the object and its characteristics.

The second limitation is that the use of this method is possible at industrial facilities located in enclosed spaces. In the future, the development of this mathematical model will allow it to be used for other types of objects. At the same time, it is necessary to develop a package of application programs that would make it possible to quickly enter the geometry of the object and automatically search for solutions.

When applying this method for objects with a developed system of premises, it is necessary to take into account a number of additional factors affecting the determination of the required amount of firefighting equipment.

6. Conclusions

1. To determine the required amount of firefighting equipment in the enclosed space of the facility, the existing methods are applied taking into account state norms and standards that can prevent the occurrence of a fire and quickly eliminate it in case of occurrence. According to the results of the study, dependencies are obtained for calculating the required number of fire protection equipment in accordance with standards and norms.

2. To determine the probability of failure of the firefighting system, a methodology has been applied to determine the total probability, which will be equal to the product of the probabilities of failure of each FPS component. Calculations using this technique show that for a real object (logistic warehouse) the probability of failure does not correspond to the permissible value.

3. A mathematical model has been developed that allows to determine the optimal amount of firefighting equipment in the premises of warehouses located in enclosed spaces.

4. The developed engineering method for determining the optimal amount of firefighting equipment for warehouses located in enclosed spaces, taking into account the probability of failure of the fire system of the facility, was tested in practice. The calculation results show that at the facility it is necessary to increase the number of fire detectors up to 70 pieces, smoke control devices – up to 3 pieces, vertical curtains – up to 4, equip aeration lamps in the amount of 4 pieces, and increase the number of evacuation exits – up to 10.

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