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Mathematical model of the optimization of fire extinguishing time length in the woodworking enterprises` workshops

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Abstract. On the grounds of an analysis of the existing criteria of decision making during the fire extinguishing organization process the differential criteria is recommended for solving the optimization mathematical models. The mathematical model of the optimization of fire extinguishing time length in the woodworking enterprises` workshops is developed; it is based on the determination of a fire area during the time of its unobstructed development, the amount of the devices for the fire extinguishing agent supply, the amount of the fire and salvage units (hereinafter FSU), equipment and evacuation facilities, the duration of the fire isolation and extinguishing as well as its final liquidation. The Monte Carlo method is used for solving the mathematical optimization model. The solving of the mathematical optimization model is conducted by applying the computer_hardware and application program package, written in C++ language.

Key words: mathematical model, optimization, isolation, fire liquidation, fire extinguishing agent, fire extinguishing equipment.

INTRODUCTION

In order to solve the optimization problems, the issue of the optimization criterion selection occupies the first place after the adoption of the target function; the main provisions of the optimization criterion selection are considered within the framework of the decision making theory [1]. The total expenses in the form of the proximate fire damage and the expenses of FSUs on its liquidation were used for determining the fire damage in the works under number [2-4].

Nevertheless, for determining or forecasting such damage, the statistical data, similar to the investigated situation, is needed. Thus, the problem arises concerning the determining and adoption of the necessary criterion for solving the formulated optimization problem, the acceptance of which would not depend upon the statistical data.

Regarding the mathematical model of the optimization of a fire extinguishing time length in the woodworking enterprises` workshops, it may be stated that such optimization models have not been analyzed yet. There are regulatory documents for the approximate determining of the fire liquidation duration that incorporate the numerous statistical data [5]. However, such an approach cannot be substantiated in every particular case. Thus, the problem arises concerning more precise forecasting of a fire liquidation time by means of the development of the mathematical optimization model for determining the effective time for the fire extinguishing in the woodworking enterprises` workshops.

MATERIALS AND METHODS

In the work under number [6], the possibility of applying different decision making criteria for determining the forces and facilities the FSU needs for a fire response, is analyzed. The author analyses the following basic criteria: 1) minimax criterion (MM) as based on a pessimistic algorithm; 2) Baies-Laplace criterion; 3)

Savage`s criterion; 4) Hurwicz's criterion; 5) Hodges-Lehmann criterion; 6) Germeier`s criterion; 7) derivative criterion; 8) criterion of non-interaction; 9) optimistic criterion.

In order to make a decision concerning every aforementioned criterion it is necessary to elaborate a decision making matrix. One should introduce different possible variants of a fire spread and the appropriate variants of decision making with the proper amount of forces and facilities for fire liquidation into such a matrix. The appliance of these criteria for making a decision does not always yield rational results; nevertheless the sufficiently rational decisions may be obtained as based on them. Thus, for instance, an operations researcher T. Saati expresses his opinion regarding the decision making possibility as follows: "…an art of giving bad answers for those practical issues the answers for which, given by means of other methods, are much worse." [7]. In the works under number [8] and [9] the differential criterion was applied for the fire damage appraisal; the criterion include two partial criteria, namely the difference between the proximate fire damages B_o (the first partial criterion) and the expenses of FSUs that participated in its liquidation $B_п$ (the second partial criterion). The difference with regard to modulus should approximate the minimal value and as an exception it may equal zero.

The adoption of such a criterion may be substantiated on account of a general classification of the criterion problems [10]. The problems related to the fire liquidation pertain to the third class. A technical system should operate under different conditions, for each of which the quality of operating is defined by a partial criterion. The partial criteria in the problems of such a class possess the identical nature and dimensionality. The value of these partial criteria may be determined by the constraints for a class A fire presented in the work under number [8]. It should also be noted that the major part of fires in the woodworking enterprises` workshops pertain to the class A. Thus, it is reasonable to apply the criterion for solving the mathematical model of the optimization of fire extinguishing time length. Regarding the development of the mathematical model of the optimization of fire extinguishing time length in the woodworking enterprises` workshops it may be stated again that such optimization models have not been analyzed yet. However, the investigations concerning the determining of fire liquidation duration in relation to the amount of units of the appropriate fire extinguishing equipment were made [11].

The aim of the present paper is to develop the methodology of design and solving of the mathematical model of the optimization of fire extinguishing time length in the woodworking enterprises` workshops on the basis of theoretical and experimental investigations results.

RESULTS AND DISCUSSION

In order to substantiate the developing of mathematical model of the optimization of fire extinguishing time length in the woodworking enterprises` workshops, the predicted time since the moment of fire outbreak till the onset of its extinguishing by means of FSUs of the State Emergency Service (SES) of Ukraine will be determined, namely the predicted pre-burn time $\tau_{в.г}$:

$$\tau_{в.г} = \tau_{в.в}+\tau_{сп}+\tau_{о.о}+\tau_{з.с}+\tau_{зб}+\tau_{сл}+\tau_{роз}, \quad (1)$$

where: $\tau_{в.в}$ – designates the time since the moment of fire outbreak till the fire detection (in real terms the time varies from 4 to 8 min. [12]); an average value $\tau_{в.в}$ equals 6,5 min.; $\tau_{сп}$ – designates the time since the fire detection till the emergency call to FSU (3-4 min.) [12] (an average value of $\tau_{в.в}$ equals 3,5 min.); $\tau_{о.о}$ – designates the time for receiving and processing the call; $\tau_{о.о}$ = 1 min. [13]; $\tau_{з.с}$ – designates the time for mobilization of division forces and fire extinguishing facilities; $\tau_{з.с}$ = 3 min. (According to the Ministry of Internal Affairs of Ukraine order № 325 of 01.07.1993); $\tau_{зб}$ – the time of the fire service personnel assembly; $\tau_{зб}$ = 1 min. [13]; $\tau_{сл}$ – an average time for arriving at the fire scene; $\tau_{сл}$ = 13,9 min. (after the statistical processing of the results of the works under number [14, 15]); $\tau_{роз}$ – the time of operational deployment; $\tau_{роз}$ = 7 min. [12].

On the basis of the aforementioned statistical and regulatory data one may determine the average value of the pre-burn time length by means of the constraint (1):

$$\tau_{в.г} = 6{,}5+3{,}5+1+3+1+13{,}9+7 = 35{,}9 \text{ min.}$$

Whilst analyzing the obtained result one may draw a conclusion that the pre-burn time length is substantial enough that means during the mentioned period of time the burning object will suffer the substantial losses. For this purpose, the fire should be isolated and liquidated as soon as possible. Therefore, it is necessary to urgently develop the optimization model for the fire liquidation duration on the basis of the rational choice of forces and facilities for every fire class that in major cases reduces the damages for a burning object.

At the ***first*** stage the fire area during the pre-burn time is determined. It is based upon the main provisions of the fire spread theory. During the first 10 minutes rate of fire spread equals $0{,}5v_л$, where $v_л$ – designates the linear rate of fire spread, m/min. If the time exceeds 10 minutes, the rate of fire spread equals $v_л$. In this case:

$$\tau_{в.г} = \tau_{в.г.1} + \tau_{в.г.2} ,$$

where: $\tau_{в.г.1} \le 10$ min.; $\tau_{в.г.2} > 10$ min.

Then, the radius of the fire spread appropriately equals:

$$R = R_1 + R_2 .$$

Under such conditions, the circular or angular fire area during the time of $\tau_{в.г} \le 10$ min. will be the following:

$$S_{П1} = 0,25v_л^2 \tau_{в.г.1}^2 \alpha\ , \quad (2)$$

where: α – an angular coefficient that comprises the fire spread form: the circular form – 360º α = 3,14 rad; the angular form – 180º α = 1,57 rad; the angular form – 90º α = 0,785 rad.

The circular or angular fire spread area during the time of $\tau_{в.г} > 10$ min. will be the following:

$$S_П = S_{П1} + S_{П2}\ .$$

Then:

$$\begin{aligned} S_П &= [0,25v_л^2 \cdot 10^2 + (\tau_{в.г} - 10)^2 v_л^2]\alpha = \\ &= [25 + (\tau_{в.г} - 10)^2]v_л^2 \alpha. \end{aligned} \quad (3)$$

For the rectangular fire form with the width b_n provided that $\tau_{в.г} \le 10$ min., the fire area will be the following:

$$S_{П1} = 0,5b_n v_л \tau_{в.г.1}\ . \quad (4)$$

On condition that $\tau_{в.г} > 10$ min. the rectangular fire area will be the following:

$$S_П = b_n v_л (\tau_{в.г} - 5)\ . \quad (5)$$

At the ***second*** stage the amount of the devices for the fire extinguishing agent supply to the point of fire outbreak is determined. For this purpose we will profit by recommendations of the works under number [16, 17]. On the grounds of the recommendations the amount of lances B for the fire extinguishing $(N_B^{Г})$ and protection $(N_B^З)$ is defined:

$$N_B^Г = \frac{Q_n^Г}{Q_B}\ , \quad (6)$$

$$N_B^З = \frac{Q_n^З}{Q_B}\ , \quad (7)$$

where: $Q_n^Г$ i $Q_n^З$ – correspondingly designate the required predicted discharge of extinguishing agent for the fire extinguishing and protection l/sec.; Q_B – the extinguishing agent discharge of the lances B, l/sec. (provided that the extinguishing agent pressure equals 0,4 MPa and the bore diameter equals 13 mm *(d* = 13 mm), the discharge constitutes 3,7 l/sec.):

$$Q_n^Г = S_П I_n^Г\ , \quad (8)$$

$$Q_n^З = 0,25K_з S_П I_n^Г\ , \quad (9)$$

where: $I_n^Г$ – extinguishing agent application rate for the fire extinguishing, l/m^{2}sec. (recommended value for the portable lances $I_n^Г$ = 0,2 l/sq.m per sec.); $K_з$ = 2,0…2,2 – a coefficient that comprises the extension of the protection area as compared to the fire area [11].

On the basis of the received data, the total amount of lances N_Σ for the fire liquidation is defined as follows:

$$N_\Sigma = N_B^Г + N_B^З\ . \quad (10)$$

The defined value of N_Σ is rounded up to the whole number. Then, the amount of laces A (N_A) for fire extinguishing is calculated by the total amount of laces $N_B^Г$ as based on the recommendations [5]:

$$N_A = 0,3N_B^Г\ . \quad (11)$$

Then, the total amount of laces N_B will be as follows:

$$N_B = N_\Sigma - N_A\ , \quad (12)$$

including the laces B for fire extinguishing:

$$N_B^Г = N_B - N_B^З\ . \quad (13)$$

At the ***third*** stage the required number of the divisions $N_в$ for the fire liquidation is defined:

$$N_в = 0,25(2N_A + N_B + 0,17N_\Sigma + 2)\ , \quad (14)$$

where: 0,25 – a coefficient that comprises an average amount of personnel of one division for the fire extinguishing (4 people); $2N_A$ – an amount of personnel for handling one lace A; 0,17 – a coefficient that comprises an amount of personnel for assisting a driver in setting adjusting the fire-fighting appliance for a water supply, for supervising the main lines, working for distributions etc.; 2 – an amount of personnel working at the safety and communication points.

The defined value of $N_в$ is rounded up to the whole number.

At the ***fourth*** stage the required amount of fire-service equipment is defined:
The total amount of:

– Pumper apparatus:

$$N_{n.a} = N_в\ , \quad (15)$$

– Special emergency vehicle:

$$N_{n.c} = 0,011N_n \ge 1\ , \quad (16)$$

where: N_n – the total amount of workers present in the workshop where the fire has broken out.

The defined value of $N_{n.c}$ is rounded up to the whole number.

The special emergency vehicles are used by FSUs that should have in theirs command the personal evacuation facilities and elastic trampoline.

At the ***fifth*** stage the time length of fire isolation, extinguishing and liquidation is determined. For this purpose, the results of a work under number [11] will be applied in the first approximation:

$$\tau_{лок} = \frac{6,39S_{лок}^{0,893}}{2N_A + N_B^Г} K_I K_d\ , \quad (17)$$

where: $S_{лок}$ – an isolation area, m^2; K_I – a coefficient that comprises the fire extinguishing agent application rate in the point of fire outbreak $I_n^Г$ (l/sq. m per sec); K_d – a coefficient that comprises the influence of a bore diameter *d* (mm) (the recommended value of the bore diameter for portable laces is 13 mm).

The values of the coefficients K_I i K_d may be determined by the constraints:

$$K_I = 1,62 - 3,04I_n^Г\ , \quad (18)$$

$$K_d = 1,4983 - 0,0262d\ . \quad (19)$$

The isolation area is determined, providing that the depth of the fire extinguishing agent supply to the point of fire outbreak for portable laces equals 5 m (h = 5 m) [5]:

– circular and angular fires:

$$S_{лок} = [2v_л(\tau_{в.г} - 5)h - h^2]\alpha\,, \qquad (20)$$

– rectangular fire with the one-sided distribution:

$$S_{лок} = b_n h\,, \qquad (21)$$

with the two-sided distribution:

$$S_{лок} = 2b_n h\,. \qquad (22)$$

Then the time of fire extinguishing is defined $\tau_г$:

$$\tau_г = \tau_{лок}\left(\frac{S_П}{S_{лок}} - 1\right). \qquad (23)$$

After that the time length of final fire extinguishing $\tau_{к.г}$ (the final liquidation of flashes after the fire extinguishing) by the constraint:

$$\tau_{к.г} = 0{,}25(\tau_{лок} + \tau_г). \qquad (24)$$

On the grounds of the constraints (17), (23) and (24) the total time of the fire liquidation $\tau_л$ is defined:

$$\tau_л = \tau_{лок} + \tau_г + \tau_{к.г}\,. \qquad (25)$$

At the ***sixth*** stage the computational method of the optimization differential criterion is defined. For this purpose we will profit by the recommendations of the work under number [9]. The fire damage appraisal is conducted by means of two partial criteria, namely the difference between the proximate fire damages B_o (the first partial criterion) and the expenses of FSUs that participated in its liquidation $B_п$ (the second partial criterion). The difference with regard to modulus, in the process of solving the mathematical optimization model, should approximate the minimal value and as an exception it may equal zero, i.e. it may be written as follows:

$$\left|\hat{A}_{ï} - \hat{A}_o\right| \Rightarrow \min\,. \qquad (26)$$

The values of these criteria for a class A fire may be defined by the constraints:

$$\hat{A}_{ï} = C_{\hat{A}}\tau_{ë}^{-0{,}8725}\text{, UAH} \qquad (27)$$

$$B_o = C_o S_{ĭ}\text{ , UAH} \qquad (28)$$

where: C_B=1,68·10[5] – the proportionality coefficient [8]; C_o – an average price of 1 sq.m of the area of an object on which the fire has broken out, UAH/sq.m [18, 19].

At the ***seventh*** stage we will proceed with the development of the mathematical model of the optimization of fire extinguishing time length in the woodworking enterprise`s workshop. For this situation, the model is developed as follows:

the aim function

$$\tau_{ë} \Rightarrow \min\,, \qquad (29)$$

by the criterion

$$\left|\hat{A}_{ï} - \hat{A}_o\right| \Rightarrow \min\,, \qquad (30)$$

by the constraints

$$a_1 \le N_B^{\tilde{A}} \le b_1\,, \qquad (31)$$

$$a_2 \le N_B^{Ç} \le b_2\,, \qquad (32)$$

$$a_3 \le N_A \le b_3\,, \qquad (33)$$

$$a_4 \le \tau_{â.ã} \le b_4\,, \qquad (34)$$

$$p \ge [p], \qquad (35)$$

where: a_1, a_2, a_3 – minimal values of the constraints, i.e. the currently available amount of the facilities and fire-extinguishing apparatus, that during the fire outbreak are on shift at the nearest fire station of FSU; a_4 – minimal predicted value of pre-burn time length, min.; the value a_4 may be defined by the constraint (1) involving such alterations:

$$a_4 = \tau_{в.г} = \tau_{в.в} + \tau_{сп} + \tau_{о.о} + \tau_{з.с} + \tau_{зб} + \tau_{сл} + \tau_{роз},$$

$$\tau_{в.в} = 5\text{ хв},\ \tau_{ñë} = \frac{60Lk_i}{V_{ñë}}\,,$$

where: L – the distance from the FSU to a point of fire outbreak, km; $k_н$ – a coefficient that comprises the unstraightness of a street network (in the practice of urban design its maximum value constitutes 1,4 ($k_н$ = 1,4); $V_{сл}$ – an average speed of fire vehicles, km/h (during the day time $V_{сл}$ = 32 km/h; during the night time – up to 60 km/h [20]); in this case:

$$a_4 = \frac{60Lk_i}{V_{ñë}} + 20{,}5\ \text{min}, \qquad (36)$$

where: b_1, b_2, b_3 – maximum required values of limitations that are defined on the basis of computational constraints (6)…(13) that are specified at the second stage; b_4 – maximum statistical average value of pre-burn time:

$$b_4 = \frac{60Lk_i}{V_{ñë}} + 29\ \text{min}, \qquad (37)$$

where: p – probability of penetration of the investigated probable point into the domain of feasibility; [p] – probability permissible value which influences the number of investigations for the adoption of an optimal value.

The Monte-Carlo method will be applied for solving the optimization model [21, 22]. The domain of feasibility, defined by the constraints (31)…(34), is encircled by m-dimensional parallelepiped in which the investigation is conducted. The most appropriate way of solving the formulated problem is to apply PC (personal computer). The sequence of pseudo-random numbers is developed μ_{ji} within the interval 0…1 by means of the computer transmitter. For the transformation of pseudo-random numbers μ_{ji} that are uniformly distributed in the interval 0…1 into the values $N_B^{\hat{A}}$, $N_B^{Ç}$, $N_{\grave{A}}$ and $\tau_{в.г}$, the type of constraints as for instance for $N_{\grave{A}}$ is used:

$$N_{Ai} = a_3 + \mu_{3i}(b_3 - a_3)\,, \qquad (38)$$

where: μ_{3i} – a pseudo-random number for determining the factor $N_{\grave{A}i}$ in a particular *i*-th calculation cycle.

In the process of calculation during every cycle of a programme operating the value $\tau_{л}$ is determined by a constraint (25) and the values of partial criteria are defined by the constraints (27) and (28) that are compared to the previous cycle values. These operations are conducted unless the condition (35) is satisfied. After the completion of programme operation, the following data is issued for publishing: $S_{П}$ at the beginning of a fire isolation, $\tau_{сл}$, $\tau_{л}$, $N_B^{\tilde{A}}$, $N_B^{Ç}$, $N_{\grave{A}}$, $N_{в}$, $N_{п.а}$, $N_{п.с}$, p.

In order to implement the optimization model, the application program package written in C^{++} language was designed for working with the OS Windows XP on a PC. The time of PC operating constituted 5…7 sec. for the 5 hundreds of trials (N_i − cycles) provided that the probability of penetration of the investigated i-th point into the domain of feasibility equals 0,94…0,96. (p = 0,94…0,96.)

CONCLUSIONS

1. The developed mathematical model of the optimization of fire extinguishing time length in the woodworking enterprises` workshops enables the immediate substantiated determining of forces and facilities for its liquidation.
2. The implementation of the mathematical model of the optimization of fire extinguishing time length into FSUs of the State Emergency Service enables the reducing of fire liquidation duration up to 38% and consequently enables the reducing of fire damages up to 26%.
3. The optimization model requires further development with regard to the equipping of FSUs with the latest fire extinguishing facilities.

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