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MODELING THE OPTIMAL STRUCTURE FOR TERRITORIAL TECHNOGENIC SAFETY SYSTEM

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Abstract. Turbulence surrounding of the development programs of territory technogenic safety systems impacts the implementation of the program. Thus, it raises the need to design constructive tools of mathematical modeling configured to the phases of the development program in order to increase the efficiency of applying limited human, financial material, time and other resources being involved to solve the problem of technogenic safety systems. We consider both a static optimization model of the technological safety system structure and dynamic one taking into account the state of fixed assets of potentially dangerous industrial object, composition and quantity of hazardous substances being applied and stored at some industrial object, other factors that determine the potential possibility of technogenic incident occurrence.

As criteria of the problems one can use forms of known criteria that allow to assess the economic efficiency of different technological safety systems. The main constraints of static and dynamic optimization mathematical models have been proposed and analyzed.

In common the problems being considered are stochastic discrete (discrete-continuous) problems of multi-criteria optimization, and their decision is based on the implementation of the branch and bound approach. The approach allows organizing iterative algorithm to identify desired parameters of TTSS development program product.

Key words: technogenic safety system, turbulence surrounding, technogenic hazards, stochastic discrete programming.

INTRODUCTION

A territorial (realm) technogenic safety system (TTSS) is a complex administrative and technical system operating in a turbulent environment [1]. The turbulence of the system's environment is determined by a lot of factors and main of them are critical technical and technological state of the equipment at potentially dangerous industrial objects (PDO), uncertainty of national economy dynamics as well as violations of technological discipline and high level deterioration of TTSS fixed assets.

Moreover at present TTSS performs its functions under strong resource constraints, including permanent staff reduction and lowering everyday operation regime financing of local units of the State Emergency Service of Ukraine (SESU) along with increasing demands to territorial technogenic safety system both to its structure and management quality. To solve the problem of TTSS conformity to the today's challenges it is necessary to develop formal evaluating means of TTSS effectiveness.

Analyzing the practice of TTSS functioning one can determine state special development programs as the strategically important tool to improve TTSS structure and composition. In this connection the main stage of such a special program is generating the program mission, which is performed within the pre-investment phase of its life cycle. Namely at this stage all the parameters (quantitative characteristics of the TTSS properties) of the optimal structure TTSS would be defined on the basis of construction and implementation of appropriate predictive models.

However, taking into account long-term program performance we can face changing the program environment parameters as well as their priority for management decisions. So, there is also a need to design constructive tools of mathematical modeling in the subsequent phases of the development program in order to increase the efficiency of applying limited human, financial material, time and other resources being involved to solve the problem of TTSS development.

This makes it necessary to develop and use the program approach [1] as the framework of development and implementation of mathematical modeling apparatus intended to point out the TTSS optimal structure and parameters. This paper focuses on developing two kinds of mathematical models concerning TTSS optimal structure and parameters, specifically a static and a dynamic realizations, which are matched the stages of the state special development program.

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Analyzing recent scientific publications on question and related matters one can stress the following points. In the paper [2] some methodological aspects of profiling the mission of the state special development programs in the field of civil defense have been discussed. The article [3] proposes an approach to find the optimal composition of complex technical system at the stage of its designing. The publication [4] deals with the design and analysis of optimization mathematical model intended to determine the structure of a complex technical system being operated under the strong impact generated by the external environment. Paper [5] proposes the quality estimation for functioning complex organizational and technical systems according to the "cost-effectiveness" criterion.

In [6] there is suggested an optimization mathematical model of the structure and parameters of the technogenic safety system on potentially dangerous industrial objects (PDIO) that is considered as a product of some development program. Under modeling the characteristics of possible hazards on the environment and people of the region arose as the result of an technogenic emergency have been taken into account. Publication [7] is concentrated on mathematical models and optimization solution methods supporting dynamic management of limited resources of the construction project as a part of program.

In [8] the whole set of activities on providing territory technogenic safety that belongs to TTSS competence has been divided into 2 types according to means of activity implementation, namely active and passive measures. As passive approach one can consider procedure of rational choice of PDIO technical and technological parameters at its design stage. In what follows we examine the set of active measures ensuring technological safety. Active measures include construction of effective technological safety systems on PDIO and modernization TTSS in general through the implementation of the TTSS optimal structure and parameters adapted to the region characteristics taking into account their dynamics of development at given planning horizon [t_0, t_0 + T], where t_0 is the beginning of the TTSS development program design and implementation.

Optimization method providing optimal allocation of financial resource along the stages of the TTSS development program has been proposed in [9]. The main feature of the method proposed consists of using the subject area specific under problem objective function and constraints definition. As a ground of computation scheme we applied the Balas additive algorithm.

Huge source of possible technogenic hazards is the engineering infrastructure of the city. Large cities in Ukraine suffer from technical and technological imperfections of engineering infrastructure, which increases the risk of technogenic incident. The article [10] discusses the ways to solve the problem of re-engineering water networks as a part of city engineering infrastructure.

Environmental aspects of air pollution by products of industry and human waists are considered in [11 - 13].

Publication [14] deals with the mathematical model and solution method for optimization problem of the allocation of limited resources of a project as a problem of the arrangement of rectangular objects, where objects being placed have variable metric characteristics that are subject to functional dependences. The partial quality criteria and the constraints of the feasible domain of the problem are formalized.

OBJECTIVES

This paper focuses on creating set of constructive tools for modeling the optimal structure and parameters of PDIO technological safety system on given territory as the product of the TTSS program development.

THE MAIN RESULTS OF THE RESEARCH

Taking into account the two-level hierarchical structure of TTSS, namely the level of PDIO and the territory level in whole, let us apply the appropriate decomposition of problem being considered. In other words the problem of modeling the PDIO optimal structure and parameters should be analyzed in accordance with the levels of the TTSS hierarchy.

Leaving aside for the moment the territorial level we concentrate now on the level of PDIO technogenic safety system.

Let $SV_{t_0}^h, h=\overline{1,H}$ be a tuple of variable characterizing current state of h-th element of the set PDIO on the territory being analyzed. Parameters $SV_{t_0}^h$ describe the state of fixed assets of h-th enterprise, composition and quantity of hazardous substances being applied and stored at h-th enterprise and other factors that determine the potential possibility of technogenic incident occurrence.

Besides, a tuple $SV_{t_0}^h$ defines the set U^h of dangerous impacts on the environment and population of the region that would be arise as a result of technogenic incident at h-th PDIO. Furthermore, we assume that the cause of the technogenic incident and, accordingly, set U^h implementation at the h-th PDIO are random equipment failures and systematic failures appeared due to aging of h-th PDIO fixed assets [10].

Suppose, the set:

$$U^h = \{u_i^h\},\ i=\overline{1,I_h}$$

has a discrete character. In general, the sets U^h form the set $U=\{u_i\},\ i=\overline{1,I}$ all the possible dangerous impacts on the environment and population:

$$U = \bigcup_{h=1}^{H} U^h .$$

Let l_i^h be a discrete random variable that quantifies (in monetary terms it will be corresponding damage) the magnitude of the impact u_i^h on the environment and population.

In general, l_i^h takes a set of values:

$$L_i^h = \{l_i^{hb_i}\},\ b_i=\overline{1,B_i} ,$$

with known probabilities $p_i(l_i^{hb_i})$, and the average score Λ_i^h of damage takes the form:

$$\Lambda_i^h = \sum_{b_i=1}^{B_i} l_i^{hb_i} \cdot p_i(l_i^{hb_i}) . \qquad (1)$$

If the probability distribution $p_i(l_i^{hb_i})$ is unknown, they are all considered equiprobable:

$$p_i(l_i^{h1}) = p_i(l_i^{h2}) = ... = p_i(l_i^{hB_i})$$

and

$$\Lambda_i^h = \frac{1}{B_i}\sum_{b_i=1}^{B_i} l_i^{hb_i} , \quad (2)$$

or decision maker can formulate certain hypotheses in the form of "subjective probabilities".

The static model of the technological safety system structure

Let $Z = \{z_m\}$, $m = \overline{1,M}$ be discrete set of components possible for improving the safety system structure of some PDIO in order to counteract the set of hazards $U^h = \{u_i^h\}$, $i = \overline{1,I_h}$.

Enter into consideration the matrix $E = (E_{im})_{i=\overline{1,I};m=\overline{1,M}}$ [15] of effectiveness for a set of components Z. The elements E_{im} are dimensionless values that can be determined on the basis of statistical data, or expert estimates. In the case the vector $\vec{e}_m = (E_{1m}, E_{2m},..., E_{Im})$ determines the degree of effectiveness of the counteract of component z_m on a discrete set of impacts U. Herewith the safety system structure includes only those components that have counteract to at least one impact from U.

Suppose $\vec{s}_h$ be a vector defining some variant of the safety system structure at h-th PDIO. Moreover, $\vec{s}_h^{\,0}$ defines initial state of structure at the time moment t_0, where $\vec{s}_h^{\,0} \in SV_{t_0}^m$.

Denote as s_{hm} the element of the vector $\vec{s}_h$ responsible for the presence or absence of the m-th component in the safety system structure being designed. Note that the elements s_{hm} may be of two kinds. First, an item s_{hm} can take values $\{0,1\}$ indicating the presence or absence of the m-th component in the safety system structure, $m = \overline{1,Q_h}, Q_h \le M$.

For example, it would be the presence or absence of the fire automation system or others elements at h-th PDIO. Second, the element s_{hm} can take discrete values from a finite set of values $s_{hn} \in S_n, |S_n| = V_n$ (e.g., the quantity of fire engines), $n = \overline{1,N_h}, N_h \le M, Q + N = M$. In this case raises the question of defining the total efficiency $E_{nm}(s_{hn})$ of system components z_m.

Assuming that the total efficiency $E_{nm}(s_{hn})$ of component z_m contribution to the overall efficiency TTSS can not exceed 1, and the contribution of each subsequent unit of component z_m is less than the previous, it is possible to define the structure of function $E_{nm}(s_{hn})$ as a logistic or polynomial one.

Thus, the estimate of the number of possible variants for the modernization of PDIO technogenic safety system equals:

$$S = 2^{Q_h}\prod_{n=1}^{N_h} V_n .$$

Let us consider main constraints of optimization mathematical model of the technological safety system structure.

First, one should limit the total cost of the system as well as values of specific resources.

The amount $C_j(\vec{s}_h)$ of j-th resource to develop technogenic safety system of h-th PDIO is equal to:

$$C_j(\vec{s}_h) = \sum_{m=1}^{M} s_{hm}\cdot c_{jm}^{\Delta} , \quad (3)$$

where: c_{jm}^{Δ} is the assessment of the j-th resource value to supply the modernization of the TTSS, including the dismantling obsolete equipment and entering element z_m to the safety system of h-th PDIO. Then the cost of the safety system of h-th PDIO is generally defined as:

$$C(\vec{s}_h) = \sum_{j=1}^{J} C_j(\vec{s}_h)\cdot r_j = \sum_{j=1}^{J} r_j \sum_{m=1}^{M} s_{hm}\cdot c_{jm}^{\Delta} , \quad (4)$$

where: r_j is the cost of j-th resource unit.

Thus restriction of the overall cost of the safety system has a kind:

$$\sum_{j=1}^{J} r_j \sum_{m=1}^{M} s_{hm}\cdot c_{jm}^{\Delta} \le C_{max}^{h} \quad (5)$$

where: C^{max} is the maximum amount of financial resources.

Similarly one can define constraints on the value or cost of certain types of resources.

Another important limitation is the possible incompatibility of the components $\{m_i, m_j\}$ of safety system. To generate the appropriate restriction one should form the conformity matrix $W=(w_{ij})_{M\times M}$, where $w_{ij} = 1$ if the components $\{m_i, m_j\}$ are compatible, and $w_{ij} = 0$ otherwise.

Then constraint on simultaneous presence in the h-th safety system incompatible combination of components is determined as follows:

$$s_{hi}\cdot s_{hj}\cdot w_{ij} = 1, i, j = \overline{1,M}, i \ne j . \quad (6)$$

Each variant $\vec{s}_h$ of the system structure is estimated by the vector quality criterion:

$$F(E,C,\vec{s}) \to \underset{\vec{s}\in G\subset R^M}{extr} , \quad (7)$$

where: G is the set of feasible solutions that is defined by a system of financial, technological, technical, time constraints taking into account the type of functions (3-6).

Criterion (7) makes it possible to evaluate the properties of the solution $\vec{s}_h$ being selected.

The dynamic model of the technological safety system structure

Consider now the main features of the dynamic optimization model of the technological safety system structure.

As before, structure S of h-th PDIO safety system is defined by a set of components:

$$Z(U) = \{z_m\},\ m = \overline{1,M}\ ,$$

which counteract hazard impacts on the environment and population of the territory from possible technogenic incident: $\mathfrak{R} = \mathfrak{R}(Z)$. Under modeling we will assume that time period [0, T] (T – given planning horizon) is divided into intervals [t, t + 1], $t = \overline{0,T-1}$ 0n which impacts of the environment U are constant, i.e. the time will be considered as discrete variable.

On the borders of time intervals it is possible to change the nature of environmental effects. In what follows it causes changes in the safety system structure. Consequently it need to include to the system new components Z^{t_in}, and to eliminate components Z^{t_out} ineffective for the next stage, $Z^{t\_in} \subset Z$.

Let E^n_{tm} denote the effectiveness of system component z_m to counteract to possible hazardous impact u_n in the time period [t, t + 1]. In general, each element z_m of the set $Z(U)$ can be characterized by a efficiency matrix:

$$E_m = (E^n_{tm})_{t=\overline{1,T},n=\overline{1,N}}\ .$$

As TSTB should include only those components that resist at least one destabilizing effect within a specified time interval [0, T], then the matrix E is to be imposed the following condition:

$$\sum_{t=1}^{T}\sum_{i=1}^{I} E_{tim} > 0\ . \qquad (8)$$

Values E_{tim} are dimensionless quantities and can be determined on the basis of statistical data or using peer reviews [4, 5]. Note under certain stages of implementation of safety system development programs TTSS and as a result of changing conditions of performing TTSS values E_{tim} may also change along with the number M, i.e. $M = M(t)$ in accordance with the condition (8).

Assumption 1. Let condition:

$$\begin{aligned}&\exists t \in [0,T]: s^{t-1}_{mh} \neq s^t_{mh} \ \Rightarrow \\ &\qquad \forall \tau \in [t+1,T]: s^{\tau}_{mh} \geq s^t_{mh}\end{aligned}\ . \qquad (9)$$

takes place.

The genesis of the system structure development is represented by matrix

$$\Sigma = (s_{tm})_{t=\overline{1,T},m=\overline{1,M}}\ ,$$

that determines the composition of safety system during the time interval [0, T]. Vectors $\vec{s}_t$ are rows of matrix Σ.

The exogenous parameters of the model. The construction of TTSS needs to spend a lot of resources, $\mathfrak{R} = \{r_j\},\ j = \overline{1,J}$, including material, financial ones, time and others. The resources $\mathfrak{R}$ are spent both on the inclusion new components Z^{t_in} to the system structure and the elimination of inefficient Z^{t_out} components from the system structure.

Suppose that to include the new component to safety system needs c_{jm} units of resource r_j and to withdraw component $z_m \in Z^{t\_out}$ from the system takes b_{jm} units of this resource. Cost ρ_{jt} of unit resource r_j is a function of time and it is equal to:

$$\rho_{jt} = \rho_{j0}(1+\xi)^t\ ,$$

where ξ is the interest rate. Then the values:

$$c_{mt} = \sum_{j=1}^{J} c_{jm} \cdot \rho_{jt} \quad \text{and} \quad b_{mt} = \sum_{j=1}^{J} b_{jm} \cdot \rho_{jt}$$

determine the cost of inclusion (exclusion) component z_m respectively.

Remark 1. When designing the optimal TTSS variant it is advisable to take into account the operating costs of system components during the period of its depreciation.

In summary, we state the problem of defining the optimal system structure for a given quality criterion $F(E,b,c,\Sigma,v)$ as follows:

$$F(E,b,c,\Sigma,s,t) \rightarrow \underset{G \in R^M}{extr}\ . \qquad (10)$$

Analysis of problem constraints. The set G of feasible solutions of the optimization problem (10) is formed by a system of constraints that along with inequalities (8,9) contains the following restrictions:

- on the resources that are used to construct some variant of safety system:

$$C_{jt}(\Sigma) \leq C_{jt}^{max},\ j = \overline{1,J}\ , \qquad (11)$$

where: C_{jt}^{max} is the available value of j-th resource at time t taking into account the discount of a kind:

$$C_{jt}(\Sigma)=\sum_{m=1}^{M}(s_{(t-1)m}-s_{tm})b_{jtm}+c_{jm}(s_{tm}-s_{(t-1)m}),$$
$$t=\overline{1,T}.$$

- on the total cost of safety system variant:

$$C(\Sigma)\le C^{max}, \qquad (12)$$

where: the total amount of resources available to build version of the system:

$$C(\Sigma)=\sum_{j=1}^{J}\sum_{t=1}^{T}C_{jt}(\Sigma)p_{jt}.$$

- on the minimal acceptable level of system components efficiency to counter the destabilizing impacts of possible technogenic incident:

$$\exists i \mid E_{tim}>E_{tig} \text{ for }$$
$$\forall m,g \mid m\ne g, s_{tm}^{k}=1,\ s_{tg}^{k}=1, \qquad (13)$$

- on minimal acceptable level of system efficiency to counter the destabilizing effects of the environment:

$$E_{ti}^{k}\ge E_{ti}^{min}, \qquad (14)$$

where: E_{ti}^{min} is the minimum allowable efficiency to counteract embodiment of the *i*-th hazardous impact in the time period *t*.

- on possible combinations of system components

$$\forall t\ \ o_{km}(s_{tk}+s_{tm})\le s_{tk}s_{tm}, \qquad (15)$$

where: $o_{km}\in\{0,1\}$ – the element of the matrix O designating the compatibility of system components z_k and z_m.

To determine the structure of criteria $F(E,C,\vec{s})$ (7) and $F(E,b,c,\Sigma,v)$ (10) one can use forms of known criteria that allow in some way to assess the economic efficiency of different technological safety systems, for example, the criterion of a maximum average loss prevention [16]; economy criterion of damage [17]; the criterion of minimizing the total cost of safety systems' equipment and industrial exploitation [18], etc.

The exact solution method for the dynamic problem of construction the technogenic safety system

Since the set *Z* of feasible components is of discrete kind and time *t* is the discrete variable then all the possible realizations of the technological safety system structure within $t=\overline{1,T}$ can be represented as decision tree vertices. A decision tree is a convenient way to order the set of feasible solutions for discrete optimization problem according to the ideology of the branch and bound [19] method.

Each node of the decision tree determines some variant $\vec{s}_h$ of the TTSS structure during the interval [*t*, *t* + 1]. The arcs of the decision tree are designated as $z_m t_\tau$ and determine the presence of appropriate component z_m for time period $\tau\in[t,t+1]$ as a part of the technological safety system being constructed.

Each node except the root one has an input arc and

$$(T+1-\tau)\cdot M-m$$

output arcs, which are indexed as $z_{m'}t_{\tau'}$ and satisfy the condition:

$$\left[\begin{array}{l}\tau'=\tau, m'>m,\\ \tau'>\tau.\end{array}\right.$$

As a result of constructing the decision tree is the ordered set *S* containing all manner of variants $\vec{s}_h$. However, some variants $\vec{s}_h$ from *S* would not satisfy certain constraints of kind (3-6) or (8-9), (11-15). So, appropriate set of cutting rules based on constraints () is to be introduced into consideration.

These cutting rules allow discarding elements of the set S, which are not belong to the set of feasible solutions. Moreover, cutting rules being considered also reject part of the solutions, which are not Pareto-optimal ones [20]. As the result one can obtain an reduced set H of structure variants of kind:

$$\mathrm{H} \mid P\subseteq H\subseteq G\subseteq S,$$

where *P* is the set of Pareto-optimal solutions.

CONCLUSIONS

1. The modeling environment to generate optimal structure of the territorial technogenic safety system has been proposed. In general, the problems (7), (10) being considered are stochastic discrete (discrete-continuous) problems of multi-criteria optimization, and their decision is based on the implementation of the branch and bound approach. Taking into account the hierarchical essence of TTSS construction one can define parameters $\vec{\mathrm{s}}_{\mathrm{h}}^{*}$ assigning optimal structure of h-th industrial object that is potentially dangerous, $\mathrm{h}=\overline{1,\mathrm{H}}$ as exogenous ones for the optimization problem of higher hierarchy level, namely for determining the optimal characteristics of territorial technogenic safety system. This approach allows organizing iterative algorithm to identify desired parameters of TTSS development program product.

2. The dynamic optimization problem (10) as well as its static analog (7) refer to the class of NP-hard [21] problems. Thus, the direct application of the branch and bound method to solve the problems of the practical dimension definition does not always point out optimal result in a reasonable time. Therefore, it seems appropriate to use locally-optimal or heuristic approaches to find quasi-optimal solutions.

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