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OPTIMIZATION OF PARALLEL LINKS IN REDUNDANT UTILITY STRUCTURES

The publication states that an important problem in the design, operation and reconstruction of various networks of engineering infrastructure is to determine the reliability of structurally complex systems. Modeling the reliability of technical systems seems to be a rather complex task. It is emphasized that the ways of rational redundancy of a complex structure of systems presuppose the well-known method of minimal paths and connections. The problem of the optimal arrangement of a system with a redundant structure has certain limitations in accordance with the available resources, such as the lower value of the probability of the system's connectivity, which serves as an optimization criterion. The paper investigates a system with identical components. The article discusses many possible forms of the structure of the system. Structural reliability expressions are calculated for all combinations used in determining the lower and upper values of structural reliability. In the process of constructing a redundant structure, it is necessary to determine a variant of its form, which maximizes the value of reliability under the established restrictions on the available resources invested in the construction and operation of the system using the cost parameter for some form of its structure. The peculiarity of the system reliability function is considered when it increases, which has a discrete argument and consists of a number of some functions. In the presented geometric model, a number of operations are used to determine and concretize the requirements for the variants of the forms of the components of the system under study for their different properties, and the forms that do not meet these conditions for the variants of the component in terms of resources are removed. Here the requirements for the probability of connectivity are defined, according to which unsuccessful forms of possible structures of the system are removed. The work uses an algorithm to extract from a set of reasonable options for some options for components by resources. The specified variant of the structure form is assumed to be optimal according to the criteria. If the number of variants of the structure shape is large enough, then to find the optimal solution, another algorithm is used, in which the value of the objective function is checked, which determines the conditions for the probability of connectivity in design decisions. It is noted that in practical application the obtained solutions can be approximate.

***Keywords:** structural modeling, connectivity probability, system reliability, reliability optimization.*

Formulation of the problem

An important problem in the process of design, operation, and reconstruction of various networks of engineering infrastructure is to determine their reliability [0, 0, 0].

Today, the problem of modeling the reliability of technical systems seems to be quite difficult. To solve this problem, research is needed in separate scientific areas. This is explained by the fact that the dimension of the structures of the networks widespread in practice is constantly increasing. Complex solution to reliability problems increases their efficiency and help to obtain qualitatively new results [0, 0]. The reliability of the existing technical systems tends to be constantly decreasing. Delaying essential maintenance, refurbishment, and replacement of system components can lead to disaster [0]. Reliability is an important issue in the design and reconstruction of engineering networks: water supply, gas, electricity, networks of mobile operators, etc. [0, 0].

The main tasks of the reliability study are to establish and substantiate the requirements for the reliability of the system and its components, in the choice of the main directions and rational strategies for project reliability assurance, in the development of issues to ensure the reliability of systems [0, 17].

Analysis of recent research and publications

The ways of rational redundancy of the complex structure of the system using minimal paths are published in [0]. In the study of systems, the fault tree method is used. Sections and minimum paths are determined [0, 0]. Next, the reliability of the systems is calculated [0, 0]. The problem of the optimal structure of a system with a redundant structure and identical components has certain limitations in accordance with the available resources. Here, the lower value of the system connectivity probability serves as an optimization criterion [0]. The solution to the problem is based on the operations of studying a certain number of structures and optimizing their reliability [0]. **The purpose of this work** is to develop optimization models

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for the reliability of systems structures, such as engineering networks of cities with a redundant structure of components.

Statement of the main research material

Let the system under study with identical components have n parts (components) $k_i \in K$, $j \in J = \{1, 2, .., n\}$, $i=1,2,\dots,n$.

The K components are provided with the parameter y_i, which describes the state of the k_i component: $y_i = 1$, if the component k_i is functioning. Otherwise, $y_i = 0$ if the component k_i is out of order. The value $Y = \{y_1, \dots, y_n\}$ simulates the possible states in which the system is located.

The components K of the structure of the system use the following elements: e_{ik} main and h_{it} parallel, having T_j of different types $T_j = \{1, \dots, t^*_j\}$. It is also a set of indices of element types, h_{it} is the number of parallel connections of elements e_{it} of the t-th type, $h_{it} \in [a_{it}, b_{it}]$. Here a_{it} and b_{it} are integers, $i = 1,2, \dots, n$, which are extreme numbers of parallel connections of components. Elements e_{it} have the reliability $r_i(e_{it})$ and other specific properties: $g_{ic}(e_{it})$, $c \in C = \{1, \dots, m\}$, $i \in I = \{1, 2, \dots, m\}$, which, for example, can be the cost of building, operating the system, its energy consumption, etc.

The quantity $\Phi_i = \{\phi_i = (h_{it}, e_{it}) | h_{it} \in [a_{it}, b_{it}], t \in T_i\}$, will be considered as the set of possible forms $\phi_i = (h_{it}, e_{it})$ of the component k_i. Then the reliability of the structure form $\phi_i = (h_{it}, e_{it})$ and its properties are determined by the expression [0]:

$$r_i(\phi_i) = 1 - (1 - r_i(e_{it}))^{\lambda it+1},\ g_{ic}(\phi_i) = (h_{it}+1) g_{ic}(e_{it}),\quad c \in C,\ i \in I. \tag{1}$$

Let $\Phi = \prod_{i \in I} \Phi_i$ be the set of possible forms $\phi = \{\phi_1, \dots, \phi_n\}$ of practical implementation of the structure of the system, and the value of Φ is the number of forms of variants in the corresponding set:

$$\Phi = \prod_{i \in I} \Phi_i = \prod_{i \in I} \left(\sum_{t \in T_i} (b_{it} - a_{it} + 1) \right), \tag{2}$$

where a_{it} and b_{it} are extreme integer numbers of parallel component connections, $i = 1,2, \dots, n$.

In the process of investigating the reliability of the system, the minimum sections of the structure τ_0, $\underline{y}^{(\tau)} = (\underline{y}_1^{(\tau)}, \dots, y_n^{(\tau)})$, $\tau = \overline{1, \tau_0}$, $\underline{x}_j^{(\tau)} = \{0,1\}$, $\underline{y}_j^{(\tau)} = [0,1]$, and the minimum paths of the structure $\overline{y}_1^{(\phi)}, \dots, \overline{y}_n^{(\phi)}$, $\phi = \{\phi_1, \dots, \phi_0\}$ $\overline{y}_j^{(\tau)} = [0,1]$, are determined. Each minimal section of the structure $\underline{y}^{(\tau)}$ corresponds to a set $c(\tau) = (j_1^{(\tau)}, j_2^{(\tau)}, \dots, j_r^{(\tau)})$ of indices $r = 1, \dots, n$, for which the j-th state is equal to zero $\underline{y}^{(\tau)} = 0$. In combinations of $c(\tau_1)$ and $c(\tau_2)$, $\tau_1 \neq \tau_2$ there may be common e_{it} elements for different intersections.

Let us calculate the expressions for structural reliability for all combinations $c(\tau)$, $\tau = \overline{1, \tau_0}$:

$$r_{c(\tau)}(\phi_{i_1^{(\tau)}}, \dots, \phi_{i_r^{(\tau)}}) = 1 - \prod_{i \in c(\tau)} \left(1 - (1 - r_i(\phi_{jt}))\right)^{h_{it}+1}, \tag{3}$$

used in the definition $R_H(\phi)$ – the lower value of structural reliability [0]:

$$R_H(\phi) = R_H(p_{c(1)}(\phi_{i_1^{(1)}}, \dots, \phi_{i_r^{(1)}}), \dots, p_{c(1)}(\phi_{i_1^{(\tau_0)}}, \dots, \phi_{i_r^{(\tau_0)}}) = \prod_{\tau=1}^{\tau_0} r_{c(\tau)}(\phi_{i_1^{(\tau)}}, \dots, \phi_{i_r^{(\tau)}}) \tag{4}$$

Each minimal path of the structure $x_j^{(\phi)}$, $\phi = 1, 2, \dots, \phi_0$ corresponds to a separate combination $d(\phi) = (i_1^{(\phi)}, \dots, i_l^{(\phi)})$, $l = 1,2,\dots,n$ of indices $j \in J$ for which $j \in J$. For all combinations $d(\phi)$, $\phi = 1, 2, \dots, \phi_0$, we find the dependences of reliability:

$$r_{d(\phi)}(\phi_{i_1^{(\phi)}}, \dots, \phi_{i_l^{(\phi)}}) = 1 - \prod_{i \in d(\phi)} \left(1 - (1 - r_i(e_{it}))\right)^{h_{it}+1},\quad \phi = 1, \dots, \phi_0, \tag{5}$$

determining $r_{d(\phi)}$ - the upper value of the level of reliability of the structure of the system:

$$R_B(\phi) = R_B(r_{d(1)}(\phi_{i_1^{(1)}}, \dots, \phi_{i_l^{(1)}}), \dots, r_{d(\phi_0)}(\phi_{i_1^{(\phi_0)}}, \dots, \phi_{i_1^{(\phi_0)}})) = 1 - \prod_{\phi=1}^{\phi_0} r_{d(\phi)}(\phi_{i_1^{(\phi)}}, \dots, \phi_{i_l^{(\phi)}}), \tag{6}$$

The reliability $R(\phi)$ of the system variant is determined [0, 0]:

$$R(\phi) = \sum_{y \in Y} \phi(y) \prod_{i \in J} r_i(\phi_i)^{yi} (1 - r_i(\phi_i))^{1-y_j}, \tag{7}$$

and corresponds to the inequality: $R_H(\phi) \le R(\phi) \le R_B(\phi)$.

In the process of building a redundant structure, it is necessary to determine a variant of its form $\phi = \{\phi_1, \dots, \phi_n\}$, which maximizes the value $R_H(\phi)$ under the established restrictions on the existing resources b_i, invested in the construction and operation of the utility network, and is expressed:

$$R_H(\phi) = \prod_{\tau=1}^{\tau_0} r_{c(\tau)}(\phi_{i_1(\tau)}, ..., \phi_{i_r(\tau)}) \to \max \quad , \qquad (8)$$

with the condition

$$g_i(\phi) = \sum_{i \in I} (h_{it}+1) g(e_{it}) \le b_i, \quad i \in I \quad , \qquad (9)$$

$$\phi = \{\phi_1, ..., \phi_n\} = \prod_{i \in I} \Phi_i \quad , \qquad (10)$$

where the parameter $g_i(\phi)$ is the cost of the ϕ_i form of the network structure.

Some variants of the form corresponding to condition (9) will be considered successful. A successful variant ϕ_{onm} that maximizes expression (8) is optimal.

A feature of the problem is that $R_H(\phi)$ is a growing function of a discrete argument, consisting of a number of some functions $r_{c(\tau)}(\phi_{i_1^{(\tau)}}, ..., \phi_{i_r^{(\tau)}})$. Combinations of expressions $c(\tau_1)$ and $c(\tau_2)$, $\tau_1 \ne \tau_2$ can have common constituents, so the same variable is used in expressions $r_{c(\tau)}(\phi_{i_1^{(\tau)}}, ..., \phi_{i_r^{(\tau_1)}})$ and $r_{c(\tau)}(\phi_{i_1^{(\tau)}}, ..., \phi_{i_r^{(\tau_2)}})$ in a joint component.

In the model (7) - (9), a number of operations [0] are used to define and concretize the requirements for the variants of the forms of the components of the system under study for their different properties and remove the forms that do not meet these conditions for the variants of the component in terms of resources. Here the requirements for the probability of connectivity are defined, according to which unsuccessful forms of possible structures of the system are removed.

An algorithm can be used to extract from a set of reasonable options for given conditions some options for a component by resources e_{it}, $t \in T_i$, $i \in I$, for example. In this case, it becomes possible to correspondingly reduce the upper limit b_{it} of the interval of the number of parallel connections together with the extraction of components $\phi_i = h_{it}, e_{it}$. The algorithm is presented as follows:

1. We will assume that $K_j^{(0)} = K_j$, $j \in J$, $\beta_{jk}^{(0)} = \beta_{jk}$, $b^0{}_{it} = b_{it}$ $k \in K_j^{(0)}$, $s = 0$.

2. Let's calculate the following requirements

$$d_{ij}^{(s)} = b_i - \sum_{l=1, l \ne j} \min_{t \in T_l^{(s)}} \{\alpha_{lt}^{(s)} + 1) g(e_{lt})\} .$$

The number of the remaining types of components is determined by the formula:

$$T_i^{(s+1)} = \left\{ t \,|\, \left(\frac{d_{ij}^{(s)}}{g_{ij}(e_{jt})} - 1 \right) \ge a_{jt}, \quad t \in T_j^{(s)}, \quad j \in J \right.$$

and new boundaries are defined:

$$b_{jt}^{(s+1)} = \min\left(b_{jt}^{(s)}, \min\left(\frac{d_{ij}^{(s)}}{g_{ij}(e_{jt})} - 1 \right) \right), \quad t \in T_j^{(s)}, \quad j \in J$$

3. If $b_{jt}^{(s+1)} = b_{jt}^{(s)}$, $T_j^{(s+1)} = T_j^{(s)}$, then the settlement process is considered complete. Then we assume that $b'_{jt} = b_{jt}^{(s)}$, $T'_j = T_j^{(s+1)}$. Otherwise, it is necessary to increase the value and go to step 2. This algorithm is over. After s_0 the sequence of his actions is formed by some sets $T'_j \le T_j$, boundaries, and sets of possible options for components $\Phi'_j \subseteq \Phi_j$ $j \in J$ in the structure of the system. Using this algorithm can lead to different options in this situation:

1. If an empty set is obtained $\Phi'_i = \varnothing$ for one component k_i, then it cannot be used, and problem (6), (8) has no solution.

2. There are many variations of the shape $\Phi'_i = \prod_{j \in J} \Phi' \ne \varnothing$. Then a certain variant of the form ϕ' of the structure of the system is determined:

$$R_H(\phi) = \prod_{\tau=1}^{\tau_0} r_{c(\tau)}(\phi_{i_1(\tau)}, ..., \phi_{i_r(\tau)}) \to \max ,$$

$$\phi = \{\phi_1, ..., \phi_n\} = \prod_{i \in I} \Phi_i \; .$$

Accordingly, the features of the function $R_H(\phi)$ and the components of the variant ϕ' are present in the sets and do not depend on each other.

According to criterion 1 [0], a successful variant of the form of the structure ϕ' is assumed to be optimal. If the variant of the form of the structure ϕ' is unsuccessful, and the number of variants $|\Phi'_i| = \prod_{j \in J} |\Phi'|$ of the set Φ' is small $\Phi' < N$, where the number is assigned taking into account the computational capabilities of the technique, then the optimal variant of ϕ* is determined on the set Φ' by checking each variant or by discrete optimization algorithms [0].

3. If the number of options in the set Φ' is large enough: $|\Phi'| >> N$, then a different algorithm is used to find the optimal one.

Then the condition for the value of the objective function is checked:

$$R_H(\phi) \geq R_{onm} \quad , \tag{11}$$

where $R_{onm} \in \left(\min_{\phi \in \Phi} R_H(\phi), \quad \max R_H(\phi) \right)$. The size determines the conditions for the probability of connectivity in design decisions.

An algorithm designed to search for and extract unsuccessful options from Φ_i according to the conditions of the component probability connectivity is represented [0]:

1. We assign

$K_j^{(0)} = K'_j$, $\alpha_{jk}^{(0)} = \alpha_{jk}$, $k \in K'_j$, $j \in J$, s=0.

2. Let's calculate

$$\overline{\phi} = \max_{h_{it} \in [\alpha_{it}^{(s)}, \beta_{it}^{(s)}]} R_H(\phi), \overline{v} = (\overline{v}_1, ..., \overline{v}_n)$$

$$\overline{\phi}_i = (\overline{h}_{it}, \overline{e}_{it}) = \min\{\phi_i \mid \phi_i \in \Phi'_i\ R_H(\phi_1, ..., \phi_n) \geq R_{onm}\}$$

Let's define the conditions:

$$r_{i\,onm}^{(s)} = R_H(\overline{\phi}_1, ...\hat{\phi}_i, ..., \phi_n)$$

Let's find a set of components that do not meet the given conditions:

$$\overline{T}_i^{(s+1)} = \{t \mid R_H(\phi_1, ..., \phi_n) < r_i^{(s)}, \ \hat{\phi}_i \in \Phi'_i, t \in T_i^{(s)}\},\ j \in J\ ,$$

and many types of components $T_i^{(s+1)} = T_i^{(s)} \setminus \overline{T}_i^{(s+1)}$ that have not been seized. The limits of the interval of the number of parallel connections are

$$a_{it}^{(s+1)} = \max(a_{it}^{(s)}, \min(h_{it} \mid R_H(\overline{\phi}_1, ..., (h_{it}, e_{it}), ..., \overline{\phi}_n))) \geq r_{i\,onm}$$

$$h_{it}^{(s+1)} \in [a_{it}^{(s)}, b_{it}^{(s)}], \qquad h \in H_i^{(s)}$$

3. If $a_{it}^{(s+1)} = a_{it}^{s}, T \in T_i^{(s+1)}, T_i^{(s+1)} = T_i^{(s)}$, then the search should be stopped. Otherwise, go to item 2 with an increase in the value s=s+1. This algorithm is over, for the number of K'_j and the limits α'_{jk}, $j \in J$ are final. Using this operation gives new sets and limits, a reduced set of options $\boldsymbol{\Phi}'' \subseteq \boldsymbol{\Phi}$.

Solution (7), (9) is intended for optimization, but the criterion of the model is the value $R_H(\phi)$, not the function (6). In practical application, the solutions obtained can be approximate.

Conclusions

The formalization of geometric models is carried out to optimize the structural connectivity of networks using the redundancy of links. Operations were developed and algorithms for solving problems were used.

The developed optimization models are based on the method of minimum connections and optimization of the efficiency of systems with an unbranched network of components. Reliability optimization models and methods are applicable in the design and reconstruction of various engineering networks.

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ОПТИМІЗАЦІЯ ПАРАЛЕЛЬНИХ ЗВ’ЯЗКІВ У НАДЛИШКОВИХ СТРУКТУРАХ ІНЖЕНЕРНИХ МЕРЕЖ

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У публікації зазначено, що важливою проблемою в проектуванні, експлуатації та реконструкції різних мереж інженерної інфраструктури є визначення надійності структурно-складних систем. Моделювання надійності технічних систем вбачається достатньо складною та комплексною задачею. Підкреслено, що шляхи раціонального резервування складної структури систем передбачають відомий метод мінімальних *шляхів та перетинів. Задача оптимальної будови системи з надлишковою структурою має певні обмеження відповідно до наявних ресурсів, такі як нижнє значення ймовірності зв'язності системи, що слугує критерієм оптимізації. Вирази структурної надійності обчислюються для всіх комбінацій, що застосовуються у визначенні нижнього та верхнього значень структурної надійності. У процесі побудови надлишкової структури необхідно визначати її форму, що максимізує величину надійності за встановлених обмежень на наявні ресурси, вкладені в побудову та функціонування системи з використанням параметру витрат на деяку форму її структури. Розглядається особливість функції надійності системи, коли вона є зростаючою, що має дискретний аргумент і складається з ряду деяких функцій. У представленій моделі використано ряд операцій визначення та конкретизації вимог для варіантів форм складових досліджуваної системи за різними їх властивостями та вилучено форми, що не відповідають цим умовам на варіанти компонента по ресурсам. Тут визначаються вимоги ймовірності зв'язності, відповідно до яких вилучаються невдалі форми можливих структур системи. У роботі використовується алгоритм для вилучення з множини доцільних варіантів деякі варіанти компонентів по ресурсам. Зазначено, що вдалий варіант форми структури за критеріями приймається оптимальним. Якщо число варіантів форми структури є достатньо великим, то для знаходження оптимального рішення застосовується інший алгоритм, в якому перевіряється значення цільової функції, яке визначає умови ймовірності зв'язності у проектних рішеннях. Зазначено, що у практичному застосуванні отримані рішення можуть бути наближеними.*

Ключові слова: *структурне моделювання, ймовірність зв'язності, надійність системи, оптимізація надійності.*