UDC 519.87:004.02

AN EFFICIENT METHOD FOR SOLVING THE PROBLEM OF CHANNEL POWER DISTRIBUTION TAKING INTO ACCOUNT FUZZY CONSTRAINTS ON CONSUMPTION VOLUMES

Ivohin E. V. – Dr. Sc., Professor, Professor of the Department of System Analysis and Decision Support Theory, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine.

Adzhubey L. T. – PhD, Associate Professor, Associate Professor of the Computational Mathematics Department, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine.

Gavrylenko V. V. – Dr. Sc., Professor, Professor of the Department of Information Systems and Technologies, National Transport University, Kyiv, Ukraine.

Rudoman N. V. – Senior lecturer of the Department of Information Systems and Technologies, National Transport University, Kyiv, Ukraine.

ABSTRACT

Context. An efficient algorithm has been developed for solving the problem of rational distribution of the power of data transmission channels with fuzzy restrictions on consumption volumes. A standard solution method based on a fuzzy optimization problem is considered. A constructive variant of finding a solution based on the backtracking method is proposed.

Objective. The goal of the work is to develop an algorithm for solving the problem of rational distribution of the power of data transmission channels with fuzzy restrictions on consumption volumes based on the backtracking method.

Method. This paper The article proposes a method for solving the problem of rational distribution of the power of data transmission channels, taking into account fuzzy restrictions on consumption volumes. A feature of such tasks is the inability to meet the needs of the end user at the expense of the resources of different suppliers. The method of solution based on fuzzy problems of mathematical programming is considered. A constructive algorithm for solving the problem based on the backtracking method has been developed. Computational experiments have been carried out.

Results. The developed method for solving the problem of rational distribution of data transmission channel capacities, taking into account fuzzy restrictions on consumption volumes, made it possible to solve the problem of constructing an optimal configuration of a three-level information and computer network with a given number of communication servers and taking into account fuzzy consumption volumes.

Conclusions. Methods for solving the problem with fuzzy restrictions on the consumption volumes of end users are investigated. A fuzzy optimization problem is formulated, which allows taking into account the interval specified volumes for the connection values. A variant of solving fuzzy optimization problems in the case of using fuzzy numbers is proposed. A multi-criteria problem of efficient distribution of communication channel powers with fuzzy restrictions is formulated. A variant of the algorithm with a return is proposed, which allows solving the obtained problem. The approach is illustrated by a number of numerical examples for the problem of forming a network structure with a given number of end users and different allowable bandwidths of communication servers.

KEYWORDS: data transfer, power distribution, fuzzy constraints, optimal solution, backtracking algorithm.

ABBREVIATIONS

LP is a linear programming.

NOMENCLATURE

i is an index of information provider;

j is an index of communication servers;

k is an index of end users;

N_1 is a number of data transmission channels;

N_2 is a number of communication servers;

N_3 is a number of end users (subscribers);

A_i^+ is a value of the maximum bandwidth of the data; transmission channel of the provider *i*;

B_j^+ is a value of the maximum bandwidth of the communication node *j*;

C_k^- is a minimum value of the k data transmission channel bandwidth;

C_k^+ is a maximum value of the k data transmission channel bandwidth;

t_k is a throughput of the k user station;

T_i is an optimal values of data transmission bandwidths of the provider *i*;

x is a solution of LP task;

n is a number of variables;

m is a number of constraints;

χ_A is a characteristic function;

X is an universal set;

$\widetilde{A}$ is a fuzzy set (subset) ;

$\mu_{\widetilde{A}}$ is a membership function of the fuzzy set;

x_j are the elements of fuzzy mathematical programming task solution;

$\widetilde{b}_i$ are the fuzzy constraints;

$\widetilde{a}_{ij}$ are the fuzzy production coefficients;

Z_l is a lower optimal value of LP task;

Z_u is a top optimal value of LP task;

L is the $\min(Z_l, Z_u)$;

U is the $\max(Z_l, Z_u)$;

DOI 10.15588/1607-3274-2022-2-12

$\mu_{\tilde{G}}$ is a membership function of the fuzzy set of LP optimal values;

$\mu_{\tilde{F}_i}$ are the membership functions of the fuzzy constraints;

λ is a parameter of Bellman-Zadeh fuzzy solution;

C_k are the current values of the throughput of communication channels *k*;

p an algorithm's step for multiobjective optimization problem solving;

$t^{*(p)}$ is a vector of "ideal assessments";

G_p is a range of acceptable value for the multiobjective optimization problem solving;

ξ_s is a value level of criterion that should be changed;

Δt is a value for decreasing t_k;

q is a number of largest (first of N_3) values t_k;

s is an index of backtracking algorithm step.

INTRODUCTION

The tasks of finding optimal solutions arise in the process of development and practical implementation of methods for effective management of various organizational, technological and information systems.

An important characteristic of optimization problems is the desire to find the optimal solution (optimality principle). In practice, there are a number of constraints that do not allow finding such a solution. In these cases, the question is raised of finding not optimal, but rational (compromise, effective) solutions that satisfy the problem statement. It is often necessary to find a compromise between the effectiveness of solutions and the cost of finding them. Serious difficulties arise when solving optimization problems under conditions of incomplete information, as well as in the case when random or subjective factors (parameters) play a significant role.

One of the applied problems in which there can be uncertainty in setting the parameters is the problem of distributing the limited capacities of data transmission channels between different nodes of the Internet providers network. Suppose that there is a local computer network of an enterprise (organization, educational institution) that provides users with access to the Internet. User access to the global network and obtaining the necessary information is carried out using several communication servers located on the territory of the information and computer center of the enterprise and connected by high-speed external communication channels with Internet providers. The bandwidth levels of the servers are within the bandwidth (bandwidth) of the local network (for example, 1Gb per second).

It is assumed that the network implements the conditions for efficient channel switching (relative to their bandwidth), which are provided by programmable network devices (communication servers, routers). The structure of the network and the information distributed in it in the general case can be very diverse. In this case, we consider the problem of distribution of limited capacities with the following constraints:

– information is distributed from the provider to subscribers (nodes) through switching servers via communication channels with a bandwidth that takes into account the specified bandwidth;

– each network subscriber is serviced by one switching server;

– the throughput of receiving information for switching nodes and subscribers is limited both from above (fundamental limitations of the provider's capabilities) and from below (the minimum need for subscribers to receive information).

The problem of determining the bandwidth of an external connection is considered, which makes it possible to maximize the total bandwidth of user communication channels by changing the total power of communication servers, taking into account both the needs and wishes of subscribers (users) and the capabilities of the information and computing center.

The object of study is the process of rational distribution of the power of data transmission channels with fuzzy restrictions on consumption volumes.

The subject of study is the development of the efficient algorithm for solving the problem of rational distribution of the power of data transmission channels with fuzzy restrictions on consumption volumes.

The purpose of the work is the research of mathematical models and methods for solving the problem of rational distribution of the power of data transmission channels with fuzzy restrictions on consumption volumes and solving the problem of constructing the optimal configuration of a three-level information and computer network.

1 PROBLEM STATEMENT

An information and computer network is considered, including N_1 data transmission channels (global network providers), N_2 communication servers and N_3 end users (subscribers). We denote by A_i^+, $i=\overline{1,N_1}$, the values of the maximum bandwidth of the data transmission channel that provider *i*, $i=\overline{1,N_1}$, is able to provide; B_j^+, $j=\overline{1,N_2}$, – the value of the maximum bandwidth of the data transmission channel that the communication node *j*, $j=\overline{1,N_2}$, can provide; ; C_k^-, C_k^+, $k=\overline{1,N_3}$, – values of the minimum and maximum bandwidth of the data transmission channel, which must be provided to the subscriber *k*, $k=\overline{1,N_3}$; t_k – throughput of the *k*-th subscriber station, $k=\overline{1,N_3}$. Then, assuming that the power distribution of communication channels satisfies the conditions of additivity and proportionality, we can consider the problem of distributing a limited homogeneous resource (bandwidth of communication channels) with transport-type constraints in order to find the optimal data transmission plan. This ensures the effective functioning

DOI 10.15588/1607-3274-2022-2-12

of the system for providing users with Internet access, which consists in finding the optimal values of data transmission bandwidths T_i of the *i*-th information provider (provider), $i = \overline{1, N_1}$, and the optimal values of the bandwidths t_k of using local communication channels of the *k*-th user, $k = \overline{1, N_3}$.

Formally, the statement of problem can be written as

$$\max t_1;\ \max t_2;\ \ldots \max t_{N_3}, \qquad (1)$$

with the following constraints

$$\sum_{k=1}^{N_3} t_k \le \sum_{i=1}^{N_1} A_i^+;$$

$$t_k \le B_j^+,\ j = \overline{1, N_2},\ k = \overline{1, N_3};$$

$$C_k^- \le t_k \le C_k^+,\ k = \overline{1, N_3}; \qquad (2)$$

$$\sum_{j=1}^{N_2} B_j^+ \le \sum_{i=1}^{N_1} A_i^+ \le \sum_{k=1}^{N_3} C_k^+.$$

2 REVIEW OF LITERATURE

The solution of the formulated problem was considered in [1–7] on the basis of solving problems of optimal resource allocation. The problems of efficient use of a homogeneous resource were considered using the example of time distribution in the form of a classical problem of distributing resources of a given volume over a set of categories (works) [8]. The setting of such tasks consists in finding a cost plan for the available resource (such a resource is most often considered time) for the execution of a group of tasks, in which the total (final) use of the resource is optimal.

In a number of papers [9–11] to find a solution, an approach is proposed that uses multi-index problems of the transport type [11]. In the noted works, meaningful formulations of such applied problems are given and their mathematical models are constructed.

When solving applied multi-index optimization problems, special interest is given to formulations related to the class of problems of integer linear programming [11]. One of the approaches to the development of algorithms for solving such optimization problems is the use of streaming methods. Known efficient flow algorithms [12] make it possible to construct solution methods that have acceptable estimates of computational complexity compared to estimates of general methods for solving linear programming problems.

Solutions obtained on the basis of models of three-index transport problems [10] allow solving the problem of distribution of a homogeneous resource for cases where the cost and resource consumption factors are known a priori.

In [13, 14], a model of a two-level production and transport problem was considered with a criterion that takes into account the optimal cost indicators for the production and transportation of resources, the volumes of production and consumption of which are given.

3 MATERIALS AND METHODS

Let's assume that the needs of network subscribers to increase the speed of obtaining one or another amount of information are known. The wishes (preferences) of subscribers are set regarding a possible increase in consumption volumes (bandwidths) for transmitting information from the provider to the user node. To implement the changes, it is necessary to update the capacities of the switching servers of the network by deploying new, more powerful computers or by increasing the number of existing servers. In other words, it is necessary to conduct a study on updating the resources of the server park of the information and computing center, which makes it possible to increase the total bandwidth of a group of switching servers. At the same time, the value of the total capacity of servers, both in the case of an increase in the capacity of the existing fleet of computers, and in the case of an increase in the number of servers, is assumed to be the same.

If the values of consumption parameters are random variables with known distribution functions, then it can be solved by stochastic programming methods. However, in practice these parameters are often unknown and only the range of possible values can be determined for them. A problem of this type can be called a problem with multiple values of the coefficients. Within the framework of this problem, it makes no sense to talk about maximizing the objective function, since the values of this function are not numbers, but sets of numbers. In this case, it is necessary to find out what preference relation this function generates on the set of alternatives, and then determine which products should be considered rational in the sense of this preference relation.

The next step on the way of detailing and refining the model considered here is the description of the problem parameters in the form of fuzzy sets (numbers) [15]. Additional information is introduced into the model in the form of a membership function of these fuzzy sets. These functions can be considered as a way for an expert to approximate his unformalized idea of the real value of a given parameter. Membership function values are the weights that experts assign to the various possible values of this parameter.

Fuzzy sets are a mathematical model of object classes with fuzzy or blurry boundaries. In other words, an element can have some degree of membership in the set, and it is intermediate between full membership and complete non-membership.

Traditional (ordinary) set theory can be viewed as a special case of fuzzy set theory. An ordinary subset A of a set X can be represented as a fuzzy set, which is given by the characteristic function $\chi_A : X \to \{0,1\}$

$$\chi_A(x) = \begin{cases} 0: & x \notin A, \\ 1: & x \in A. \end{cases}$$

In accordance with the idea of Zadeh [15], a fuzzy subset of a given universal set X is formulated as follows.

DOI 10.15588/1607-3274-2022-2-12

Definition 1. A fuzzy subset $\tilde{A}$ of the universal set X, is a collection of pairs $\tilde{A} = \{(\mu_{\tilde{A}}(x), x)\}$, where $\mu_{\tilde{A}}(x): X \to [0,1]$ is the mapping of the set X into the unit segment [0,1], which is called the membership function of the fuzzy set.

The value of the membership function $\mu_{\tilde{A}}(x)$ for an element $x \in X$ is called the degree of membership. The interpretation of the degree of membership $\mu_{\tilde{A}}(x)$ is a subjective measure of how much an element $x \in X$ corresponds to a concept, the meaning of which is formalized by a fuzzy set $\tilde{A}$.

Let $X = R^1$ is a universal set.

Definition 2. [16] A fuzzy triangular number (triplet) $\tilde{A}$ is an ordered triplet of numbers (a, b, c), $a \le b \le c$, defining a membership function $\mu_{\tilde{A}}(x)$ of the form

$$\mu_{\tilde{A}}(x) = \frac{x-a}{b-a},\ x \in [a,b];$$
$$\mu_{\tilde{A}}(x) = \frac{c-x}{c-b},\ x \in [b,c]; \tag{3}$$
$$\mu_{\tilde{A}}(x) = 0,\ x \notin [a,c].$$

A fuzzy triangular number of the form (a, b, b), called a left fuzzy triangular number, is determined by the membership function of the form

$$\mu_{\tilde{A}}(x) = 0,\ x < a;$$
$$\mu_{\tilde{A}}(x) = \frac{x-a}{b-a},\ x \in [a,b]; \tag{4}$$
$$\mu_{\tilde{A}}(x) = 1,\ x > b,$$

and the fuzzy triangular number of the form (b, b, c), called the right fuzzy triangular number, is the membership function $x \in R^n$

$$\mu_{\tilde{A}}(x) = 1,\ x < b;$$
$$\mu_{\tilde{A}}(x) = \frac{c-x}{c-b},\ x \in [b,c]; \tag{5}$$
$$\mu_{\tilde{A}}(x) = 0,\ x > c.$$

After such clarification, we can proceed to the next statement of the problem of fuzzy mathematical programming [17]. A linear view model is specified

$$\sum_{j=1}^{n} \tilde{c}_j x_j \to \max, \tag{6}$$

in which the values of the coefficients $\tilde{c}_j$, $j = \overline{1,n}$, are given fuzzy in the form of fuzzy sets of given universal sets. In addition, there are constraints

DOI 10.15588/1607-3274-2022-2-12

$$\sum_{j=1}^{n} \tilde{a}_{ij} x_j \le \tilde{b}_i,\ i = \overline{1,m},\ x_j \ge 0,\ j = \overline{1,n}, \tag{7}$$

and the values of the coefficients $\tilde{a}_{ij}$, $\tilde{b}_i$, $i = \overline{1,m}$, $j = \overline{1,n}$, are also described in the form of the corresponding fuzzy sets. It is required to make a rational choice of a solution $x \in R^n$, that, in a certain sense, maximizes the given fuzzy linear form (6).

We call such a statement of the fuzzy optimization problem a linear programming problem with fuzzy parameters. One of its variants is a problem with fuzzy resource constraints on the right side.

Consider a LP problem with a given goal function

$$\max_x \sum_{j=1}^{n} c_j x_j \tag{8}$$

and fuzzy constraints on resources of the form

$$\sum_{j=1}^{n} a_{ij} x_j \le \tilde{b}_i,\ i = \overline{1,m}, \tag{9}$$
$$x \ge 0;\ x \in R^n,$$

where the right parts of constraints (9) are given as fuzzy right triangular numbers with corresponding membership functions of the form (3). Here, the allowable deviations determine the values of the boundary changes of the model resources.

This formulation does not restrict the general form of optimization problems with fuzzy constraints [18,19]. Indeed, one can consider a linear programming problem with fuzzy resources in the form of an optimization problem for the goal function (8) in the presence of a system of mixed constraints

$$\sum_{j=1}^{n} a_{ij} x_j \ge \tilde{b}_i,\quad i = \overline{1,m_1},$$
$$\sum_{j=1}^{n} a_{ij} x_j \le \tilde{b}_i,\quad i = \overline{m_1+1,m_2},$$
$$\sum_{j=1}^{n} a_{ij} x_j = \tilde{b}_i,\quad i = \overline{m_2+1,m},$$

where the right parts of the first m_1 constraints are given by left fuzzy triangular numbers $\tilde{b}_i = (b_i - b_i^0, b_i, b_i)$, $b_i^0 \ge 0$, $i = \overline{1,m_1}$, the right parts of the next group of constraints are given by right fuzzy triangular numbers $\tilde{b}_i = (b_i, b_i, b_i + b_i^0)$, $b_i^0 \ge 0$, $i = \overline{m_1+1,m_2}$, and the right parts of the last $m - m_2$ constraints are given by fuzzy triangular numbers $\tilde{b}_i = (b_i - b_i^l, b_i, b_i + b_i^r)$, with allowable deviations $0 \le b_i^l \le b_i$, $b_i^r \ge 0$, $i = \overline{m_2+1,m}$.

This LP model can be rewritten in the form (7)–(8) by replacing the first m_1 conditions with the next constraints $\sum_{j=1}^{n}(-a_{ij})x_j \le -\tilde{b}_i$, $\tilde{b}_i = (-b_i, -b_i, -b_i + b_i^0)$, $i = \overline{1, m_1}$, and the last $m - m_2$ conditions – with a system of constraints $\sum_{j=1}^{n}(-a_{ij})x_j \le -\tilde{b}_i$, $\tilde{b}_i = (-b_i, -b_i, -b_i + b_i^l)$; $\sum_{j=1}^{n} a_{ij}x_j \le \tilde{b}_i$, $\tilde{b}_i = (b_i, b_i, b_i + b_i^r)$; $i = \overline{m_2 + 1, m}$. Thus, we can assume that the general form of a linear programming problem with fuzzy resource constraints on the right side is given by model (8)–(9).

The optimization problem under consideration can be solved as a parametric linear programming problem [20]. This method is universal, not always taking into account the specifics of the task.

We use an approach based on the defuzzification of problem (8)–(9). To do this, we calculate the optimal values of the levels of the objective function Z_l and Z_u by solving two LP problems:

$$Z_l = \max_x \sum_{j=1}^{n} c_j x_j , \quad (10)$$

$$\sum_{j=1}^{n} a_{ij}x_j \le b_i , \quad i = \overline{1, m}, \ x \ge 0; x \in R^n , \quad (11)$$

And

$$Z_u = \max_x \sum_{j=1}^{n} c_j x_j \quad (12)$$

$$\sum_{j=1}^{n} a_{ij}x_j \le b_i + b_i^0 , \quad i = \overline{1, m}, \ x \ge 0; x \in R^n . \quad (13)$$

Let be $L = \min(Z_l, Z_u)$, $U = \max(Z_l, Z_u)$. The fuzzy set of optimal values of problem (8)–(9) specified in R^n (we denote it by $\tilde{G}$) is described by the membership function of the form

$$\mu_{\tilde{G}}(x) = \begin{cases} 0, & \sum_{j=1}^{n} c_j x_j < L, \\ (\sum_{j=1}^{n} c_j x_j - L)/(U - L), & L \le \sum_{j=1}^{n} c_j x_j \\ 1, & \sum_{j=1}^{n} c_j x_j > U, \end{cases} \quad (14)$$

and the fuzzy sets of each constraint (we denote them by $\tilde{F}_i$, $i = \overline{1, m}$) from (9) are determined by the membership functions

$$\mu_{\tilde{F}_i}(x) = \begin{cases} 1, & \sum_{j=1}^{n} a_{ij}x_j < b_i, \\ (b_i + b_i^0 - \sum_{j=1}^{n} a_{ij}x_j)/b_i^0, & b_i \le \sum_{j=1}^{n} a_{ij}x_j \le b_i \\ 0, & \sum_{j=1}^{n} a_{ij}x_j > b_i + b_i^0, \end{cases} \quad (15)$$

$$i = \overline{1, m} .$$

Based on the definition of the Bellman-Zadeh fuzzy solution [21], the fuzzy linear programming problem (8)–(9) can be written in the form of an optimization problem of the following form: find the value of the parameter $\lambda \in [0,1]$, that is the solution of the LP problem

$$\max_x \lambda. \quad (16)$$

in the presence of constraints

$$\begin{aligned} &\mu_{\tilde{G}}(x) \ge \lambda, \\ &\mu_{\tilde{F}_i}(x) \ge \lambda, \quad i = \overline{1, m} . \\ &x \ge 0. \end{aligned} \quad (17)$$

Substituting (14) and (15) into (17), we write the final form of the optimization problem

$$\begin{aligned} &\max_x \lambda \\ &\lambda(U - L) - \sum_{j=1}^{n} c_j x_j + L \le 0, \\ &\sum_{j=1}^{n} a_{ij}x_j \le b_i + b_i^0 - \lambda b_i^0, i = \overline{1, m}, \\ &x \ge 0, 0 \le \lambda \le 1. \end{aligned} \quad (18)$$

This problem is a classical linear programming problem, for finding solutions to which any variant of the simplex method can be applied.

Let us assume that in the formulation of the problem of distributing the power of data transmission channels, the current values of the throughput of communication channels of each subscriber k, C_k, $k = \overline{1, N_3}$, are known, and the values of C_k^+, $k = \overline{1, N_3}$, determine the values of the bandwidths that are planned by users as a result of updating communication equipment. Obviously, it is possible to fully satisfy the expansion of the bandwidth of subscriber channels only under the condition $\sum_{j=1}^{N_2} B_j^+ \ge \sum_{k=1}^{N_3} C_k^+$.

Formally, the statement of problem can be written as

DOI 10.15588/1607-3274-2022-2-12

$$\max t_1;\ \max t_2;\ \ldots \max t_{N_3}, \tag{19}$$

with the following constraints

$$t_k \in \operatorname{supp} \tilde{t}_k = [C_k, C_k^+],\ k = \overline{1, N_3};$$

$$\sum_{k=1}^{N_3} t_k \le \sum_{i=1}^{N_1} A_i^+;$$

$$t_k \le B_j^+,\ j = \overline{1, N_2},\ k = \overline{1, N_3}; \tag{20}$$

$$\sum_{j=1}^{N_2} B_j^+ \le \sum_{i=1}^{N_1} A_i^+ \le \sum_{k=1}^{N_3} C_k^+.$$

We will assume that the capacities of communication channels available to users satisfy the conditions $\sum_{k=1}^{N_3} C_k \le \sum_{k=1}^{N_3} t_k \le \sum_{i=1}^{N_1} A_i^+$, and the values of the possible expansion of the channel capacity are determined by right-hand fuzzy triangular numbers in the form (C_k, C_k, C_k^+), $k = \overline{1, N_3}$, with linear membership functions (5).

This problem is a multiobjective optimization problem. To solve it, methods are used that allow finding a compromise (effective) solution by reducing the problem to a single-criterion one in the form of a convolution of criteria or to a sequence of single-criteria optimization problems [22]. In the case of fuzzy constraints, each such problem can be reduced to an optimization problem of the form (17), (18) with subsequent solution by the method proposed above.

Taking into account the specifics of the obtained problem, the most rational method is the sequential introduction of constraints [22]. A characteristic feature of this method, which makes it possible to use it to find an effective solution, is the sequential (at each step) introduction of constraints on the width of the communication channel, at which unsatisfactory values of the criteria are achieved.

Following the search methodology, at each algorithm's step $p = 1,2,\ldots$, an "ideal assessment" $t^{*(p)} = = (t_1^{*(p)}, t_2^{*(p)}, \ldots, t_{N_3}^{*(p)})$, $p = 1,2,\ldots$, is formed, where $t_k^{*(p)}$, $k = \overline{1, N_3}$, are the optimal values of each of the criteria (19) $\max t_k$, $k = \overline{1, N_3}$, on a given range of acceptable values G_p, $G_1 = \{t_k = C_k^+; k = \overline{1, N_3}\}$, $G_{p+1} = = \{t_k \in G_p; k = \overline{1, N_3} \mid t_s \ge \xi_s\}$, $s \in \{1,2,\ldots,N_3\}$ is the number of the criterion, the value of which is the least consistent with the compromise solution. It is clarified to what level ξ_s the value of this criterion should be changed, and a search for a new solution is performed, taking into account the additional constraint.

This method allows solving the problem of efficient distribution of channel capacities, taking into account fuzzy constraints on consumption volumes, however, to use it at each step, it is necessary to evaluate the compliance of the current solution with a certain "ideal" solution, which, as a rule, is formed with the participation of an expert. In addition, the solution procedure turns out to be cumbersome, leading to the multiple solution of optimization problems of the form (10)–(13) and the construction of a Bellman-Zade fuzzy solution (18).

Additionally it is easy to formalize this process by applying the back tracking solution search procedure [23].

From the condition of the problem of optimizing the distribution of channel powers, taking into account fuzzy constraints on consumption volumes (19)–(20), it follows that

$$\sum_{k=1}^{N_3} C_k^+ \ge \sum_{j=1}^{N_2} B_j^+ \ge \sum_{k=1}^{N_3} C_k. \tag{21}$$

Obviously, in this case, it is impossible to allocate the maximum expected power of communication channels to all subscribers. We will look for a solution on rational distribution based on the scheme of the back tracking algorithm.

Algorithm.

Step 0. Without loss of generality, we will assume that the order of users is ordered in non-increasing order of the planned capacities of communication channels. We put the required values in the initial solution $t_k = C_k^+$, $k = \overline{1, N_3}$.

Step s=1,2,... We check the fulfillment of condition

$$\sum_{k=1}^{N_3} t_k \le \sum_{j=1}^{N_2} B_j^+. \tag{22}$$

If inequality (22) is satisfied, the algorithm terminates, otherwise:

a) determine the q, $q \in [1, N_3]$, largest (first of N_3) values t_k, $k = \overline{1, N_3}$.

b) decrease the values t_k, $k = \overline{1, q}$, by $\Delta t > 0$: $t_k = t_k - \Delta t$, $k = \overline{1, q}$.

Obviously, the total demand in this case decreases.

Change $s = s + 1$ and move on to the next step.

4 EXPERIMENTS

The algorithm proposed above for finding a solution in the problem of rational distribution of the power of communication channels, taking into account fuzzy constraints on consumption volumes (19)–(20), was used to calculate the values of throughput resources in a network with 1 Internet provider, 2 (3, 4) routers (communication servers) and 17 end users (collective subscribers).

The bandwidth of user connections to communication servers was initially 350, 250, 250, 245, 180, 180, 165, 165, 160, 145, 140, 140, 140, 120, 110, 80, 80 Mb/s (total capacity 2900 Mb/s). In order to expand consumer traffic, it is proposed to upgrade equipment in the form of a possible increase in the number of servers or/and increase their capacity. The bandwidth of the communication channel with the provider remains constant and equals 10 Gb/s. The total throughput capacity of communication servers after the upgrade is planned to be 3 Gb/s.

DOI 10.15588/1607-3274-2022-2-12

To determine the rational distribution of the size of communication channels, consumers were asked to determine the required size of connections to communication servers. Based on the given amount of traffic, it was planned to use 2, 3 or 4 servers with a total capacity of 3 Gb/s.

Computational experiments on the efficient distribution of the power of communication channels were carried out using the above algorithm for the classical solution of optimization problems with fuzzy constraints on consumption levels (fuzzy approach) and the algorithm using the backtracking approach. In the latter case, both a consistent uniform decrease in consumer requests by the value $\Delta t > 0$ (app1) and a proportional decrease in the values of requests were applied, taking into account the required volumes of traffic increase (app2).

5 RESULTS

The results of the numerical experiments performed are shown in Table 1.

As follows from the results obtained, the application of the proposed algorithm made it possible to obtain the most efficient (close to optimal) solutions in the considered distribution problem for a configuration with two communication servers with a maximum bandwidth of 1500 Mb/s. The best solution to the problem using the method of efficient channel power distribution, taking into account fuzzy constraints, was obtained for the connection option with 3 routers. At the same time, it slightly differs from the solution with two servers, which suggests that the best option in the considered distribution problem is the variant with two communication servers. It should also be noted that the solution based on the algorithm using the return scheme does not require significant computational resources, which allows us to speak about the constructiveness of the method. The resulting solution was used as the basis for the technical modernization of equipment to ensure the operation of network subscribers.

Table 1 – The results of numerical experiments on the efficient distribution of the power of communication channels

Consumers																	
p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	p12	p13	p14	p15	p16	p17	Sum
Init Power, Мб/с (*Max Sum Power*=2900 Мб/с)																	
350	250	250	245	180	180	165	165	160	145	140	140	140	120	110	80	80	2900
Plan Power, Мб/с (*Max Sum Power*=3000 Мб/с)																	
370	275	275	260	195	185	180	175	165	155	150	150	145	125	115	90	90	3100
Results for K communication servers, Мб/с																	
Approuch: **app1**																	
$CommunicationPower \times K = 1500 \times 2$																	
363	268	268	253	188	183	173	168	158	148	143	143	138	118	108	85	90	2995
$CommunicationPower \times K = 1000 \times 3$																	
359	264	264	249	184	179	169	164	154	144	139	139	134	114	105	83	90	2934
$CommunicationPower \times K = 750 \times 4$																	
357	262	262	247	182	177	167	162	152	142	137	137	132	112	107	89	90	2914
Approuch: **app2**																	
$CommunicationPower \times K = 1500 \times 2$																	
354	254	254	254	184	184	174	169	164	149	149	149	144	124	114	89	90	2999
$CommunicationPower \times K = 1000 \times 3$																	
352	252	252	252	182	182	172	167	162	147	147	147	142	122	112	87	90	2967
$CommunicationPower \times K = 750 \times 4$																	
350	250	250	250	180	180	170	165	160	145	145	145	140	120	110	85	90	2935
Approuch: **fuzzy**																	
$CommunicationPower \times K = 1500 \times 2$																	
361	266	266	251	186	181	171	166	160	150	146	144	141	121	110	83	82	2985
$CommunicationPower \times K = 1000 \times 3$																	
362	267	267	252	187	182	173	167	160	150	147	142	140	120	110	82	81	2989
$CommunicationPower \times K = 750 \times 4$																	
355	260	260	245	180	175	165	160	150	150	145	140	135	118	108	79	75	2900

DOI 10.15588/1607-3274-2022-2-12

6 DISCUSSION

Several remarks should be noted. First, the amount Δt of change in the power of communication channels in the backtracking algorithm, which is set at the beginning of the work, depends on the values of the optimized data transfer volumes and affects the rate of convergence of the algorithm. The choice of small values Δt leads to a more accurate rational distribution of powers, but slows down convergence. Otherwise, for large values Δt, the solution is reached faster, but its quality in terms of the obtained volumes, as a rule, turns out to be lower.In addition, in the proposed version of the algorithm, a rational solution is sought at the expense of the most demanding subscribers in terms of volume. Obviously, the search procedure can be restructured to use other similar principles or to evenly distribute the redundancy of the total traffic request among all network users.

CONCLUSIONS

The problem of optimal power distribution of communication channels in information-computer networks with a three-level architecture is considered. Approaches for its solution are studied, the problem statement with fuzzy constraints on the consumption volumes of end users is considered. A fuzzy optimization problem is formulated, which allows taking into account the interval specified volumes for the connection values. A variant of solving fuzzy optimization problems in the case of using fuzzy numbers is proposed. A multi-objective problem of efficient power distribution of communication channels with fuzzy constraints is formulated. A variant of the algorithm with a return is proposed, which allows solving the obtained problem. The approach is illustrated by a number of numerical examples of a problem with a given number of end users and different allowable bandwidths of communication servers.

The results obtained were analyzed, which made it possible to make a decision on the method of upgrading the communication equipment. The proposed approach based on the method using the return scheme turned out to be a constructive way to solve the problem considered in the article.

ACKNOWLEDGMENTS

The work is the result of research carried out by the Faculty of Computer Science and Cybernetics of the Taras Shevchenko National University of Kyiv and the Department of Information Systems and Technologies of the National Transport University during the implementation of the project within the CISCO educational program to optimize the power distribution of data transmission channels based on the information and computing center.

REFERENCES

1. Afraimovich L. G., Prilutskii M. Kh. Multiindex Resource Distributions for Hierarchical Systems, *Automation and remote control,* 2006, Vol. 67, No. 6, pp. 1007–1016.
2. Prilutskii M.Kh. Many-Criteria Distribution of a Homogeneous Resource in Hierarchical Systems, *Automation and Remote Control*, 1996, No. 2, C. 24–29.
3. Afraimovich L.G. Multiindex transportation problems with 2-embedded structure, *Automation and remote control,* 2013, Vol. 74, pp. 90–104. DOI: 10.1134/S0005117913010086
4. Filgus D.I. Optimisation of the process of managing requests in distributed information systems, *International Journal of Applied and Fundamental Research*, 2018, Iss.4, pp. 34–42. DOI: 10.17513/mjpfi.12179
5. Schrijver A., Letchford A. N. Theory of Linear and Integer Programming, *The Journal of the Operational Research Society*, Vol. 51, Iss. 7, pp. 892–893. DOI: 10.2307/253980
6. Levner E. Multiprocessor Scheduling, Theory and Applications. London, IntechOpen, 2007. [Online]. Available from: https://www.intechopen.com/books/3596. DOI: 10.5772/52
7. Pentico D. W. Assignment problems: A golden anniversary survey, *European Journal of Operational Research*, 2007. Vol. 176, pp. 774–793. DOI: 10.1016/j.ejor.2005.09.014
8. Ivokhin E., Makhno M. On an approach to construction of structured fuzzy sets and their application for description of fuzzy time response, *Journal of Automation and Information Science,* 2017, 49(10), pp. 55–63. DOI: 10.1615/JAutomatInfScien.v49.i10.60
9. Spieksma F.C.R. P.M. Pardalos, L.S. Pitsoulis (Eds.). Multi index assignment problems: complexity, approximation, applications, *Nonlinear Assignment Problems. Algorithms and Applications*. Dordrecht, Kluwer Academic Publishers, 2000. – P. 1–11. DOI:10.1007/978-1-4757-3155-2_1
10. Crama Y., Spieksma F.C.R. Approximation algorithms for three-dimensional assignment problems with triangle inequalities, *European Journal of Operational Research*. – 1992, Vol. 60, pp. 273–279. DOI: 10.1016/0377-2217(92)90078-N
11. Afraimovich L. G., Prilutskii M. K. Multiindex optimal production planning problems, *Automation and remote control,* 2010, Vol. 71, pp. 2145–2151. DOI: 10.1134/S0005117910100139.
12. Orlin J.B. A Faster strongly polynomial minimum cost flow algorithm, *Operations research*, 1993, Vol. 41, Issue 2, pp. 338–350. DOI: 10.1145/62212.62249
13. Lukac Z., Hunjet D., Neralic L. Solving the production-transportation problem in the Petroleum Industry, *Revista Investigacion Operacional*, 2008, Vol. 29, Issue 1, pp. 63–70.
14. Ivokhin E., Apanasenko D., Navrodskiy V. About production-transport problem reduction to the two-level problem of discrete optimization and its application, *Bulletin of Taras Shevchenko Nathional University of Kiev: Ekonomics*, 2018, No. 3(198), pp. 48–53. DOI:10.17721/1728-2667.2018/198-3/6
15. Zadeh L. A. Fuzzy sets, *Information and Control,* 1965, Vol. 8, pp. 338–353. DOI: 10.1016/S0019-9958(65)90241-X
16. Bellman R. E., Zadeh L. A. Local and fuzzy logics, *Modern Uses of Multiple-Valued Logics, edited by J. M. Dunn and G. Epstein, D. Reidel*. Dordrecht-Holland, 1977, pp. 103 – 165. DOI: 10.1007/978-94-010-1161-7_6
17. Dubois D., Prade H. Systems of linear fuzzy constraints, *Fuzzy Sets and Systems*, 1980, Vol. 3, Issue 1, pp. 37–48. DOI: 10.1016/0165-0114(80)90004-4
18. Bablu Jana, Tapan Kumar Roy Multi-Objective Fuzzy Linear Programming and Its Application in Transportation Model, *Tamsui Oxford Journal of Mathematical Sciences*, 2005, 21(2), pp. 243–268.
19. Zimmermann H. J. Fuzzy programming and linear programming with several objective functions, *Fuzzy Sets and*

DOI 10.15588/1607-3274-2022-2-12

System, 1978, No. 1, pp. 45–55. DOI:10.1016/0165-0114(78)90031-3

20. Vajda S. Linear programming, *Linear Programming.* Dordrecht, Springer, 1981, 15 p. DOI: 10.1007/978-94-011-6924-0_1
21. Bellman R. E., Zadeh L. A. Decision making in a fuzzy environment, *Management Science,* 1970, No. 17, pp.141–164. DOI: 10.1287/mnsc.17.4.B141
22. Pavlov Yu. P., Andreev R. D. Decision Support Fundamentals, *In Decision Control, Management, and Support in Adaptive and Complex Systems: Quantitative Models*. Hershey, PA, IGI Global, 2013. DOI: 10.4018/978-1-4666-2967-7.ch001
23. Watson Des. A Practical Approach to Compiler Construction. Springer, 2017, 254 p. DOI: 10.1007/978-3-319-52789-5

Received 15.01.2022.
Accepted 22.02.2022.

УДК 519.87:004.02

ЕФЕКТИВНИЙ МЕТОД РОЗВЯЗАННЯ ЗАДАЧІ РОЗПОДІЛУ ПОТУЖНОСТЕЙ КАНАЛІВ З УРАХУВАННЯМ НЕЧІТКИХ ОБМЕЖЕНЬ НА ОБСЯГИ СПОЖИВАННЯ

Івохін Є. В. – д-р фіз.-мат. наук, професор, професор кафедри системного аналізу та теорії прийняття рішень Київського національного університету імені Тараса Шевченка, Київ, Україна.

Аджубей Л. Т. – канд. фіз.-мат. наук, доцент, доцент кафедри обчислювальної математики Київського національного університету імені Тараса Шевченка, Київ, Україна.

Гавриленко В. В. – д-р. фіз.-мат. наук, професор, професор кафедри інформаційних систем і технологій Національного транспортного університету, Київ, Україна.

Рудоман Н. В. – старший викладач кафедри інформаційних систем і технологій Національного транспортного університету, Київ, Україна.

АНОТАЦІЯ

Актуальність. Важливою характеристикою задач оптимізації функціонування та управління різними технологічними та інформаційними системами є намагання знайти оптимальний розв'язок. На практиці існує низька обмежень, що пов'язана з невизначеністю параметрів і яка не дозволяє знайти такий розв'язок. У цих випадках ставиться питання про знаходження не оптимальних, а раціональних розв'язків, що задовольняють постановці задачі. Однією з прикладних задач, в яких може виникати невизначеність параметрів, є задача розподілу обмежених потужностей каналів передачі даних між різними вузлами мережі.

Ціль. Мета роботи – розробити алгоритм розв'язання задачі раціонального розподілу потужності каналів передачі даних з нечіткими обмеженнями на обсяги споживання на основі методу бектрекінгу.

Метод. У статті пропонується метод розв'язання задачі раціонального розподілу потужності каналів передачі даних з урахуванням нечітких обмежень на обсяги споживання. Особливістю таких завдань є неможливість задоволення потреб кінцевого користувача з допомогою ресурсів різних постачальників. Розглянуто метод розв'язання на основі нечітких задач математичного програмування. Розроблено конструктивний алгоритм розв'язання задачі на основі методу пошуку із поверненням. Проведено обчислювальні експерименти.

Результати. Розроблений метод вирішення задачі раціонального розподілу потужностей каналів передачі даних з урахуванням нечітких обмежень на обсяги споживання дозволив роз'язати задачу побудови оптимальної конфігурації трирівневої інформаційно-обчислювальної мережі із заданим числом серверів зв'язку та з урахуванням нечітких обсягів споживання.

Висновки. Досліджено способи розв'язання задачі з нечіткими обмеженнями на обсяги споживання кінцевих споживачів. Сформульовано нечітку задачу оптимізації, що дозволяє враховувати інтервально задані величини підключень. Запропоновано варіант розв'язання нечітких оптимізаційних задач у випадку використання нечітких чисел. Сформульовано багатокритеріальну задачу ефективного розподілу потужностей каналів зв'язку з нечіткими обмеженнями. Запропоновано варіант алгоритму з поверненням, що дозволяє розв'язати отриману задачу. Підхід проілюстровано результатами чисельних розрахунків для прикладної задачі формування структури мережі з заданою кількістю кінцевих користувачів і різними допустимими обсягами пропускних здатностей комунікаційних серверів.

КЛЮЧОВІ СЛОВА: передача даних, розподіл потужності, нечіткі обмеження, оптимальний розв'язок, алгоритм з поверненням.

УДК 519.87:004.02

ЭФФЕКТИВНЫЙ МЕТОД РЕШЕНИЯ ЗАДАЧИ РАСПРЕДЕЛЕНИЯ МОЩНОСТЕЙ КАНАЛОВ С УЧЕТОМ НЕЧЕТКИХ ОГРАНИЧЕНИЙ НА ОБЪЕМЫ ПОТРЕБЛЕНИЯ

Ивохин Е. В. – д-р физ.-мат. наук, профессор, профессор кафедры системного анализа и теории принятия решений Киевского национального университета имени Тараса Шевченко, Киев, Украина.

Аджубей Л. Т. – канд. физ.-мат. наук, доцент, доцент кафедры вычислительной математики Киевского национального университета имени Тараса Шевченко, Киев, Украина.

Гавриленко В. В. – д-р. физ.-мат. наук, профессор, профессор кафедры информационных систем и технологий Национального транспортного университета, Киев, Украина.

Рудоман Н. В. – старший преподаватель кафедры информационных систем и технологий Национального транспортного университета, Киев, Украина.

АННОТАЦИЯ

Актуальность. Важной характеристикой задач оптимизации функционирования и управления различными системами является стремление найти оптимальное решение. На практике существует ряд ограничений, связанная с неопределенностью параметров, которая не позволяет найти такое решение. В этих случаях ставится вопрос о нахождении не оптимальных, а рациональных решений, удовлетворяющих постановке задачи. Одной из прикладных задач, в которых может возникать неопределенность в задании параметров, является задача распределения ограниченных мощностей каналов передачи данных между различными узлами сети.

DOI 10.15588/1607-3274-2022-2-12

Цель. Цель работы – разработать алгоритм решения задачи рационального распределения мощности каналов передачи данных с нечеткими ограничениями на объемы потребления на основе метода бэктрекинга.

Метод. В статье предлагается метод решения задачи рационального распределения мощности каналов передачи данных с учетом нечетких ограничений на объемы потребления. Особенностью таких задач является невозможность удовлетворения потребностей конечного пользователя за счет ресурсов разных поставщиков. Рассмотрен метод решения на основе нечетких задач математического программирования. Разработан конструктивный алгоритм решения задачи на основе метода поиска с возвратом. Проведены вычислительные эксперименты.

Результаты. Разработанный метод решения задачи рационального распределения мощностей каналов передачи данных с учетом нечетких ограничений на объемы потребления позволил решить задачу построения оптимальной конфигурации трехуровневой информационно-вычислительной сети с заданным числом серверов связи и с учетом нечетких объемов потребления.

Выводы. Исследованы способы решения задачи с нечеткими ограничениями на объемы потребления конечных пользователей. Сформулирована нечеткая задача оптимизация, позволяющая учитывать интервально заданные объемы на величины подключений. Предложен вариант решения нечетких оптимизационных задач в случае использования нечетких чисел. Сформулирована многокритериальная задача эффективного распределения мощностей каналов связи с нечеткими ограничениями. Предложен вариант алгоритма с возвратом, позволяющий решить полученную задачу. Подход проиллюстрирован рядом числовых примеров для задачи формирования структуры сети с заданным числом конечных пользователей и разными допустимыми объемами пропускных способностей коммуникационных серверов.

КЛЮЧЕВЫЕ СЛОВА: передача данных, распределение мощности, нечеткие ограничения, оптимальное решение, алгоритм с возвратом.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Afraimovich L. G. Multiindex Resource Distributions for Hierarchical Systems / L. G. Afraimovich, M. Kh. Prilutskii // Automation and remote control. – 2006. – Vol. 67, No. 6. – P. 1007–1016.
2. Prilutskii M.Kh. Many-Criteria Distribution of a Homogeneous Resource in Hierarchical Systems / M. Kh. Prilutskii // Automation and Remote Control. – 1996. – № 2. – P. 24–29.
3. Afraimovich L. G. Multiindex transportation problems with 2-embedded structure/ L. G. Afraimovich// Automation and remote control. – 2013. – Vol. 74. – P. 90–104. DOI: 10.1134/S0005117913010086
4. Filgus D.I. Optimisation of the process of managing requests in distributed information systems / D. I. Filgus // International Journal of Applied and Fundamental Research. – 2018. – Issue4. – P. 34–42. DOI: 10.17513/mjpfi.12179
5. Schrijver A. Theory of Linear and Integer Programming / A. Schrijver, A. N. Letchford // The Journal of the Operational Research Society. – Vol. 51, Issue 7. – P. 892–893. DOI: 10.2307/253980
6. Levner E. Multiprocessor Scheduling, Theory and Applications / E. Levner. – London : IntechOpen, 2007. [Online]. Available from: https://www.intechopen.com/books/3596. DOI: 10.5772/52
7. Pentico D. W. Assignment problems: A golden anniversary survey / D. W. Pentico // European Journal of Operational Research. – 2007. – Vol. 176. – P. 774–793. DOI: 10.1016/j.ejor.2005.09.014
8. Ivokhin E. On an approach to construction of structured fuzzy sets and their application for description of fuzzy time response / E. Ivokhin, M. Makhno // Journal of Automation and Information Science. – 2017. – 49(10). – P. 55–63. DOI: 10.1615/JAutomatInfScien.v49.i10.60
9. Spieksma F. C. R. Multi index assignment problems: complexity, approximation, applications / P. M. Pardalos, L. S. Pitsoulis (Eds.). // Nonlinear Assignment Problems. Algorithms and Applications. – Dordrecht : Kluwer Academic Publishers. 2000. – P. 1–11. DOI: 10.1007/978-1-4757-3155-2_1
10. Crama Y. Approximation algorithms for three-dimensional assignment problems with triangle inequalities / Y. Crama, F. C. R. Spieksma // European Journal of Operational Research. – 1992. – Vol. 60. – P. 273–279. DOI: 10.1016/0377-2217(92)90078-N
11. Afraimovich, L. G. Multiindex optimal production planning problems / L. G. Afraimovich, M. K. Prilutskii // Automation and remote control. – 2010. – Vol. 71. – P. 2145–2151. DOI: 10.1134/S0005117910100139
12. Orlin J. B. A Faster strongly polynomial minimum cost flow algorithm / J. B. Orlin // Operations research. – 1993. – Vol. 41, Issue 2. – P. 338–350. DOI: 10.1145/62212.62249
13. Solving the production-transportation problem in the Petroleum Industry / Z. Lukac, D. Hunjet and L. Neralic // Revista Investigacion Operacional. – 2008. – Vol. 29, Issue 1. – P. 63–70.
14. Ivokhin E. About production-transport problem reduction to the two-level problem of discrete optimization and its application / E. Ivokhin, D. Apanasenko, V. Navrodskiy // Bulletin of Taras Shevchenko Nathional University of Kiev: Economics. – 2018. – № 3 (198). – P. 48–53. DOI: 10.17721/1728-2667.2018/198-3/6
15. Zadeh L. A. Fuzzy sets / L. A. Zadeh // Information and Control. – 1965. – Vol. 8. – P. 338–353. DOI: 10.1016/S0019-9958(65)90241-X
16. Bellman, R. E. Local and fuzzy logics / R. E. Bellman, L. A. Zadeh // Modern Uses of Multiple-Valued Logics, edited by J. M. Dunn and G. Epstein, D. Reidel, Dordrecht-Holland, 1977. – P. 103–165. DOI: 10.1007/978-94-010-1161-7_6
17. Dubois D. Systems of linear fuzzy constraints / D. Dubois, H. Prade // Fuzzy Sets and Systems. – 1980. – Vol. 3, Issue 1 – P. 37–48. DOI: 10.1016/0165-0114(80)90004-4
18. Bablu Jana Multi-Objective Fuzzy Linear Programming and Its Application in Transportation Model / Bablu Jana, Tapan Kumar Roy // Tamsui Oxford Journal of Mathematical Sciences. – 2005. – 21(2). – P. 243–268.
19. Zimmermann H. J. Fuzzy programming and linear programming with several objective functions / H. J. Zimmermann // Fuzzy Sets and System. – 1978. – No. 1. – P. 45–55. DOI: 10.1016/0165-0114(78)90031-3
20. Vajda S. Linear programming / S. Vajda. // In: Linear Programming. – Dordrecht : Springer, 1981. – 15 p. DOI: 10.1007/978-94-011-6924-0_1
21. Bellman R. E. Decision making in a fuzzy environment / R. E. Bellman, L. A. Zadeh // Management Science. – 1970. – No. 17. – P. 141–164. DOI: 10.1287/mnsc.17.4.B141
22. Pavlov Yu. P. Decision Support Fundamentals / Yu. P. Pavlov, R. D. Andreev // In Decision Control, Management, and Support in Adaptive and Complex Systems: Quantitative Models. – Hershey, PA : IGI Global, 2013. DOI: 10.4018/978-1-4666-2967-7.ch001
23. Watson Des. A Practical Approach to Compiler Construction / D. Watson. – Springer, 2017. – 254 p. DOI: 10.1007/978-3-319-52789-5

DOI 10.15588/1607-3274-2022-2-12

UDC 681.3.07

MODELING OF IEEE 802.11 COMPUTER NETWORKS OPERATION AT INCREASED INTERFERENCE INTENSITY

Khandetskyi V. S. – Dr. Sc., Professor, Head of the Department of Electronic Computing Machinery, Oles Honchar Dnipro National University, Dnipro, Ukraine.

Karpenko N. V. – PhD, Associate Professor of the Department of Electronic Computing Machinery, Oles Honchar Dnipro National University, Dnipro, Ukraine.

ABSTRACT

Context. High level of industrial noise increases the loss of information frames during transmission, which in turn decreases the network throughput. We propose a mathematical model of IEEE 802.11 networks operation under conditions of increased interference intensity.

Objective. The purpose of this paper is to express in an explicit analytical form the effect of bit error rate (BER) on the probability of frame transmission and the network throughput.

Method. We have proposed the method for constructing a model that allows you to directly calculate the dependence of the frame transmission probability on the number of stations operating in saturation mode, which is convenient for engineering calculations. The values of the model coefficients were selected by comparing the calculation results with the results obtained using the known Bianchi model, which describes the network operation in the form of a Markov process. In the range of up to 23 stations working with one access point, which corresponds to a collision probability of up to 0.5, the indicated dependences for both models satisfy each other with an accuracy sufficient for the practical application. An expression for the network throughput has been defined.

Results. The results of the model development were used to take into account the effect of interference intensity on the information transfer process. This made it possible to explicitly express the effect of BER on the probability of frame transmission and the network throughput in the case of variations in the length of the frames and with a different number of competing stations. The degree of throughput reduction has been determined for BER = 10^{-5}, $5\cdot10^{-5}$, 10^{-4} and increasing value of minimum contention window.

Conclusions. In this work, a mathematical model has been developed for direct calculation of the probability of frame transmission and network throughput at different levels of BER.

KEYWORDS: IEEE 802.11 networks, mathematical model, frame, transmission probability, collision, throughput, interference intensity.

ABBREVIATIONS

BER is a bit error rate;

CSMA/CA is a Carrier Sense Multiple Access with Collision Avoidance;

DCF is a Distributed Coordination Function;

FER is a frame error rate;

OFDM is an Orthogonal Frequency-Division Multiplexing;

WLAN is a Wireless Local Area Network.

QAM is Quadrature Amplitude Nodulation.

NOMENCLATURE

ACK is a frame acknowledgment;

DIFS is an interframe space;

SIFS is an short interframe space;

$E[Fr]$ is an average frame payload size;

H is a frame header transmission time;

L is length of the frame data field in bits;

m is a number of window doublings allowed;

MAC_{hdr} is a frame channel layer header transmission time;

N is a number of features characterizing original sample;

n is a number of competing stations;

p is a probability that a transmitted frame encounters a collision;

P_b is a bit error rate;

P_f is a frame error rate;

PHY_{hdr} is a frame physical layer header transmission time;

R is a data transfer rate;

$R_{control}$ is a control information transfer rate;

S is a network throughput;

SIFS is a short inter-frame space;

T_c is an average time the channel is sensed busy because of collision;

T_{sc} is an average time the channel is sensed busy because of successful transmission;

W is a contention window;

W_0 is a minimum value of contention window;

W_{avg} is an average backoff window;

α is a multiplicative constant coefficient;

β is a power constant coefficient;

δ is a propagation delay;

η is a number of empty slots;

σ is a duration of one slot;

T is a probability of frame transmission according to the proposed model;

τ is a frame transmission probability by the station in the Bianchi model;

T_s is a probability of successful frame transmission in a noisy channel.

INTRODUCTION

The IEEE 802.11 WLANs are increasingly being used for applications with stringent performance requirements

DOI 10.15588/1607-3274-2022-2-13

due to their ease of deployment and low costs. An important component of these WLANs performance is the implementation of the contention resolution process known as DCF [1]. The DCF is a distributed process created to achieve fair medium sharing among single type stations without any centralized scheduling control of the medium. A distributed channel access process is based on CSMA/CA algorithm.

Even though the maximum physical layer rates are increasing with the introduction of new generation WLANs such as 802.11ac and 802.11ax, the effective throughput remains low, especially with a significant number of simultaneously operating stations and a high level of industrial interference. In its most basic form, the DCF consists of a carrier sensing function and a random backoff protocol. Carrier sensing allowed stations to wait when the medium is busy and to resume transmission attempts until the medium becomes free. If two or more stations have frames to send, the probability exists that their transmissions will immediately collide as soon as the medium becomes free. To avoid collisions, stations will backoff their attempts to transfer frames for a random number of slot times, based on a random variate selected from a contention window. If two or more competing stations select the same transmission slot times, their transmissions will collide again. They will detect the collision base on the lack of the positive acknowledgement of the frame reception from the access point. Stations that collide will increase their contention window size and repeat transmission, and reset the contention window upon eventual successful transmission.

High level of industrial interference increases BER in transmission channel. The result is an increased loss of information frames during transmission, which in turn decreases the network throughput. The problem lies in the limited ability of algorithmic support to cope with the complexity of the wireless channel due to fading, collisions, co-channel and external industrial interference. Network nodes cannot distinguish one type of loss from another because the symptoms are the same – lack of positive acknowledgment from the access point.

The object of study is the process of information transmission in wireless computer networks of the IEEE 802.11 standard.

The subject of study is the class of mathematical models that describe the operation of wireless networks with infrastructure topology.

The purpose of the work is to express in an explicit analytical form the effect of BER on the probability of frame transmission and the network throughput.

1 PROBLEM STATEMENT

The performance analysis of IEEE 802.11 DCF networks based on bidimensional Markov – chain model with ideal channel conditions showed [2–4] that the frame transmission probability by the station in a randomly chosen slot time is

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1)+pW_0[1-(2p)^m]}, \qquad (1)$$

where $W_0 = CW_{\min}$, $CW_{\max} = 2^m W_0$.

In a special case $m = 0$ the probability τ results to be independent of p, and (1) becomes the much simpler one independently found in [5] for the constant backoff window problem $\tau = 2 / (W_0 + 1)$.

However, in general, τ depends on the collision probability p, which is still unknown. The probability p that a transmitted frame gets into a collision is the probability that, in a time slot, at least one of the $n - 1$ remaining stations transmit. At steady state, each remaining station transmits a frame with probability τ. This yields [2]

$$p = 1-(1-\tau)^{n-1}. \qquad (2)$$

The purpose of this work is to develop a mathematical model expressing explicitly the dependence of the probability of successful frame transmission on the number of stations operating in saturation mode. Within the framework of this model, it is necessary to study the similar dependence for network throughput, and to determine the effect of the BER value on the probability of frame transmission and the throughput with varying frame lengths and a different number of competing stations.

2 REVIEW OF THE LITERATURE

Collisions are more likely to happen when there are many stations in the network with large numbers of frames to send. This situation is well modeled by applying a saturation load. In this mode every station always has a frame available for transmission after the completion of each successful transmission. In a well cited work published by Bianchi [2] and later updated by Tinnirello, Bianchi, and Xiao [3], the authors proved, with a Markov – chain analytical model and with network simulation that the DCF mechanism will converge to a stable and fair allocation of the medium under a saturation load, and provided throughput performance prediction as a function of station transmits probability in a randomly chosen slot time and number of competing stations.

The model takes into account all the exponential backoff protocol details, and allows define the saturation throughput performance of DCF for both standardized access mechanisms [6]. Bianchi showed that if the traffic is saturated, nodes can be modeled as being equally likely to send in any slot, and this assumption also roughly holds for unsaturated traffic which nearly Poisson [7, 8].

The system throughput S is defined as ratio of average payload information transmitted in a time interval to the length of this interval

$$S = \frac{E[\text{payload information transmitted in an interval time}]}{E[\text{length of an interval time}]}. \qquad (3)$$

DOI 10.15588/1607-3274-2022-2-13

In accordance with [2]

$$S = \frac{P_{tr} \cdot P_s \cdot E[Fr]}{(1-P_{tr})\eta\sigma + P_{tr}P_s T_{sc} + P_{tr}(1-P_s)T_c}, \quad (4)$$

where $P_{tr} = 1-(1-\tau)^n$, $P_s = n\tau(1-\tau)^{n-1}/P_{tr}$. In accordance with DCF

$$T_{sc} = H + \frac{E[Fr]}{R} + SIFS + \delta + ACK + DIFS + \delta, \quad (5)$$

$$T_c = H + \frac{E[Fr]}{R} + DIFS + \delta. \quad (6)$$

Contention window is initially set to W_0. If p is the collision probability, then the frame is successfully transmitted with probability $(1-p)$ and the average backoff window is $(W_0-1)/2$. If the first transmission fails, the frame is successfully transmitted on the second attempt with probability $p(1-p)$ and the average backoff window W_{avg} is $(2W_0-1)/2$, and so on. Based on the average backoff window, the probability that a station attempts to transmit in an arbitrary slot is given by $1/W_{avg}$ [9]. The probability that during the transmission of an arbitrary station there is no other active station is $(1-1/W_{avg})^{n-1}$. Thus the collision probability is given by

$$p = 1-(1-\frac{1}{W_{avg}})^{n-1}. \quad (7)$$

The probability that a station accessed a channel depends on whether the channel was idle or busy in the previous time slot. The authors in [10] proposed an analytical model taking into account this post – *DIFS* effect by extending the Markovian model developed in [2]. Their analysis did show some impact of the post – *DIFS* slot. However, the obtained numerical results for collision probability seem too low for such a saturated WLAN networks.

The authors of [11] have proposed the method wherein contending stations make their windows dynamically converge in a fully distributed way solely by tracking the number of idle slots between consecutive transmissions.

In [12] authors propose that initially if the intensity of collisions is low the contention window is increased in $\sqrt{2}$ factor then after four collisions the size of the contention window will be doubled in consecutive collisions.

3 MATERIALS AND METHODS

Methods for describing functioning of wireless networks with infrastructure topology using Markov chains modeling as the basic allowed the authors [2–4] to express the probability of frame transmission as a function on the collision probability in form (1). In turn, the probability of collision depends on the probability of the frame transmitting and the number of stations competing for access to the transmission channel (2). This system of equations (Bianchi model) explicitly is not solved. Data obtained by numerical solution of equations (1) and (2) with $W_0 = 16$ and $m = 6$ are presented in Table 1 and Table 2.

This model does not demonstrate an explicit dependence of the probability of a successful frame transmission τ on the number of simultaneously operating stations n, which would be appropriate for engineering calculations.

For these reasons, by analogy with (7), we propose to determine the probability of frame transmission to the access point as follows

$$\tau = T = \frac{2}{[1+\alpha(n-1)]^{-1} \cdot 2^{\beta(n-1)} \cdot W_0 + 1}. \quad (8)$$

With $n = 1$ (one station in the network) $T = 2/(W_0 + 1)$. This corresponds to expression (1) at zero collision probability. The values of the coefficients α and β were selected by comparing the results of calculating τ in accordance with the Bianchi model (presented in Tables 1 and 2), and the results of calculating T according to expression (8) at the same values of n. The corresponding dependences $\tau(n)$ and $T(n)$ for $\alpha = 0.05$, $\beta = 0.2$ and $\alpha = 0.1$, $\beta = 0.2$ are shown in Fig. 1.

As can be seen from the graphs in Fig. 1 in the region $1 \le n \le 23$, which corresponds to the collision probability $0 \le p \le 0.5$, the dependences $T(n)$, calculated in accordance with (8), generally correspond to the dependence $\tau(n)$, calculated in accordance with the Bianchi model. With a further increase in the number of competing stations $n > 35$, which corresponds to $p > 0.55$, the above dependences diverge: the values of the dependences $T(n)$ are practically zero, and $\tau(n)$ decreases very slowly and reaches 5% of the initial value only at $n = 285$.

Table 1 – Results of calculations using the Bianchi model in the range $p = 0 - 0.50$

p	0	0.10	0.17	0.25	0.30	0.35	0.40	0.45	0.50
τ	0.118	0.105	0.094	0.080	0.070	0.060	0.049	0.039	0.031
n	1	2	3	4	6	8	11	16	23

Table 2 – Results of calculations using the Bianchi model in the range $p = 0{,}55 - 1{,}00$

p	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00
τ	0.024	0.018	0.013	0.010	0.008	0.006	0.004	0.003	0.0025	0.002
n	35	52	79	121	185	285	443	705	1190	7000

DOI 10.15588/1607-3274-2022-2-13

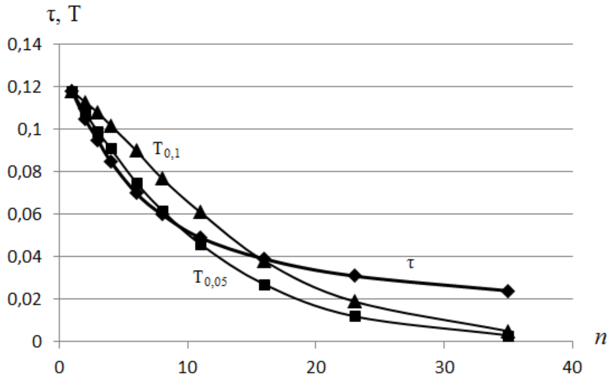


Figure 1 – Dependencies of frame transmission probability (τ, T) on the number of simultaneously operating stations n at $W_0 = 16$: $T_{0.05}$ corresponds to α = 0.05, β = 0.2, and $T_{0.1}$ corresponds to α = 0.1, β = 0.2 in (8)

Let us determine the system throughput S (4) taking into account (8). We represent T (8) in the form $T = 2/(Q + 1)$, where

$$Q = [1 + \alpha(n-1)]^{-1} \cdot 2^{\beta(n-1)} \cdot W_0. \quad (9)$$

Then we obtain

$$S = \frac{2n \cdot E[Fr]}{2n(T_s - T_c) + (Q-1)[(\frac{Q+1}{Q-1})^n T_c - (T_c - \eta\sigma)]}. \quad (10)$$

Let's calculate the dependence $S(n)$, using the values of Q, which correspond to $T_{0.05}$ and $T_{0,1}$, as well as expressions (5), (6). Wherein:

$$\begin{aligned} T_{sc} - T_c &= SIFS + ACK + \delta, \\ H &= PHY_{hdr} + MAC_{hdr}, \\ PHY_{hdr} &= 4\,\mu s \cdot 5\,OFDM\ symbols, \\ ACK &= PHY_{hdr} + L(ACK)/R_{control}. \end{aligned} \quad (11)$$

Here T_C is defined by expression (6). In the calculations, we used the following parameters values [13, 14]: $SIFS = 16$ μs, $DIFS = 34$ μs, $\delta = 0.33$ μs (the distance between the transmitter and the receiver was taken to be 100 m), $\sigma = 9$ μs, $PHY_{hdr} = 20$ μs, $L(ACK) = 112$ bits, $R_{control} = 6$ Mbit/s, $L(MAC_{hdr}) = 288$ bits, $R = 54$ Mbit/s, $W_0 = 16$.

The corresponding dependences of the throughput S on the number of simultaneously operating stations n at $W_0 = 16$ are shown in Fig. 2.

Note that $n = 79$ corresponds to the collision probability $p = 0.65$.

An increase in the data transfer rate R to 300 Mbit/s does not change the general nature of dependence $S(n)$. However, the maximum values of $S_{0.05}$ and $S_{0.1}$ increase to 47.3 and 51.6 Mbit/s, respectively.

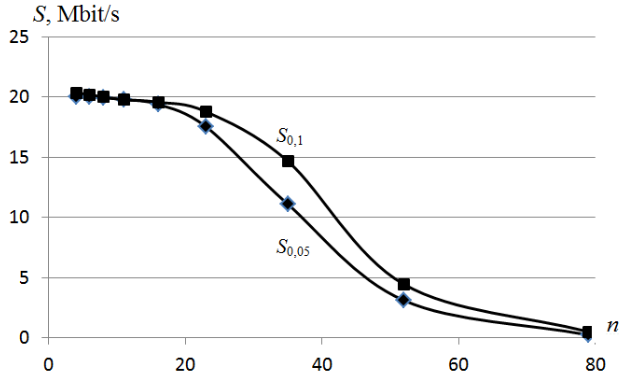


Figure 2 – Throughput S versus the number of competing stations n for $W_0 = 16$: $S_{0.05}$ corresponds to α = 0.05, β = 0.2, and $S_{0,1}$ corresponds to α = 0.1, β = 0.2 in (8)

Let us consider the influence of the initial value of the contention window $W_0 = CW_{min}$ on the dependence $S(n)$. To do this, we will double the value of W_0 ($W_0 = 32$) and repeat the procedure of selecting the coefficients α and β in expression (8). The closest to τ(n) dependences T(n) were obtained at α = 0.1, β = 0.15 ($T_{0,1}$) and α = 0.15, β = 0.2 ($T_{0.15}$). They are shown in Fig. 3.

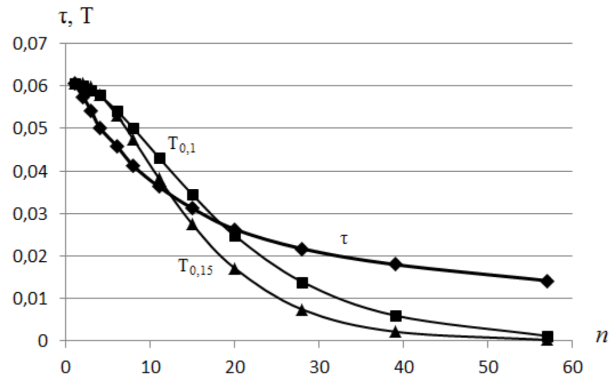


Figure 3 – Dependencies of frame transmission probability (τ, T) on the number of simultaneously operating stations n at $W_0 = 32$: $T_{0.1}$ corresponds to α = 0.1, β = 0.15, and $T_{0.15}$ corresponds to α = 0.15, β = 0.2 in (8)

In Fig. 3, $n = 57$ corresponds to the collision probability $p = 0.55$. With a further increase in the number of competing stations $n > 57$, dependence τ(n) decreases very slowly and reaches 5% of the initial value only at $n = 780$.

The corresponding dependences $S(n)$ for $W_0 = 32$ are generally similar to the dependences shown in Fig. 2. In this case, the maximum values of S are lower by about 20%, and practically zero values S are achieved at $n = 81$, which corresponds to $p = 0.60$.

4 RESULTS

This section summarized the results of investigation of the BER effect on the throughput with varying frame lengths and a different number of competing stations.

We use for transmission a discrete in time Gaussian channel without memory. In such a channel, bit errors are independent and equally distributed over the bits of the

DOI 10.15588/1607-3274-2022-2-13

frame [15]. Probability that a frame will be transmitted undistorted is equal:

$$q = (1 - P_{b1})(1 - P_{b2})(1 - P_{b3})...(1 - P_{bL}) = (1 - P_b)^L, \qquad (12)$$

where $P_{b1} = P_{b2} = P_{b3} = \ldots = P_{bL} = P_b$.

In this case, the probability of frame distortion is equal to:

$$P_f = 1 - (1 - P_b)^L. \qquad (13)$$

In conditions of increased interference intensity, the probability of successful frame transmission to the access point can be determined as follows:

$$T_S = T(1 - P_b)^L, \qquad (14)$$

where T is determined by equation (8).

With the $L = 12000$ bits and BER $= 10^{-5}$, the multiplier $(1 - P_b)^L = 0.89$, with BER $= 5 \cdot 10^{-5}$ this factor is 0.55, and with BER $= 10^{-4}$, which corresponds to a high noise intensity – 0.30. Taking into account (14), the expression for the throughput S takes the following form:

$$S = \frac{2n(1-P_b)^L \cdot E[Fr]}{2n(1-P_b)^L (T_s - T_c) + [Q + 1 - 2(1-P_b)^L]\left\{\left[\frac{Q+1}{Q+1-2(1-P_b)^L}\right]^n T_c - (T_c - \eta\sigma)\right\}}. \qquad (15)$$

The corresponding dependences for $S_{0.05}$ ($\alpha = 0.05$, $\beta = 0.2$) at $W_0 = 16$, and $(1 - P_b)^L = 0.89$, 0.55, 0.30 are shown in Fig. 4. Similar dependences for $S_{0.15}$ ($\alpha = 0.15$, $\beta = 0.2$) at $W_0 = 32$ and the same values of $(1 - P_b)^L$ are shown in Fig. 5.

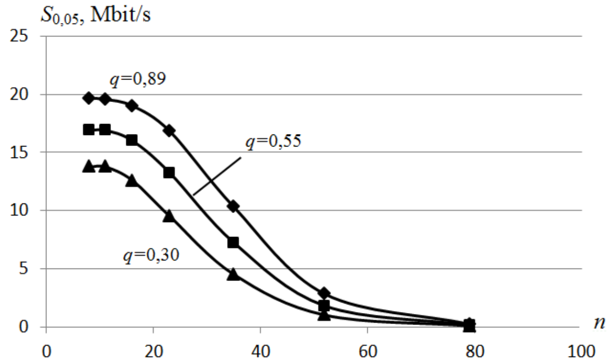


Figure 4 – Dependences of the throughput $S_{0.05}$ ($\alpha = 0.05$, $\beta = 0.2$) at $W_0 = 16$ on the number of competing stations n at different levels of $q = (1 - P_b)^L$

As follows from the plots shown in Fig. 4 and 5, with an increase in the interference intensity (BER) and, as a consequence, a decrease in the value of q, the throughput S decreases. As before, this effect increases with the expansion of the initial contention window W_0.

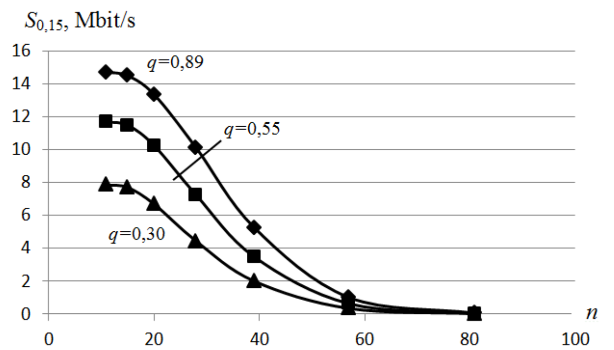


Figure 5 – Dependences of the throughput $S_{0.05}$ ($\alpha = 0.05$, $\beta = 0.2$) at $W_0 = 16$ on the number of competing stations n at different levels of $q = (1 - P_b)^L$

5 DISCUSSION

Along with the main advantages of the Bianchi model, such as versatility of the solution, compliance with the DCF – process and algorithm CSMA/CA, this model has some disadvantages.

First, this model does not make it possible to directly calculate the probability of frame transmission depending on the number of stations simultaneously working with one access point. The same applies to throughput calculation. This complicates the use of the Bianchi model in engineering practice.

Secondly, as follows from the results shown in Table 2, with an increase in the probability of collisions beyond $p = 0.5$, the convergence of the $\tau(n)$ dependence worsens and it decreases very slowly.

With such as intensive traffic, the dependence $\tau(n)$, corresponding to the original model (1)–(2), has only a qualitative character.

When studying the effect of noise, we used a channel for transmission in which the bit errors are independent and equally distributed over the bits of the frame. The probability of a successful transmission by a station depends on the BER and the number of competing stations. There is a practical interest in expressing explicitly the dependence of the network throughput on the BER for different frame lengths and different number of simultaneously operating stations. This allows the engineering staff to directly calculate the throughput based on the noise level and the quantitative characteristics of the network.

A reduction in the electromagnetic interference influence on the transmission of a frame is observed with a decrease in its size. But this increases the relative weight of overhead, that is, the service information required to ensure a successful transfer [16, 17]. All this affects the value of throughput and its dependence on the number of competing stations. The study of these processes will be carried out in the next work.

CONCLUSIONS

The scientific novelty. For the first time in an explicit analytical form, the influence of interference intensity

DOI 10.15588/1607-3274-2022-2-13

(BER) on the probability of frame successful transmission and the network throughput is determined in case of variations in the frame length and the traffic intensity. The resulting expression for the throughput makes it possible to evaluate the combine effect of the BER and the intensity of collisions, which depends on the number of stations operating in the network.

The practical significance. The practical significance of this work consists in the possibility of carrying out the engineering calculations in an explicit analytical form of the wireless network throughput at different layers of BER, different frame lengths and minimum contention window sizes for a given number of stations operating in the network.

One of the priorities of IEEE 802.11 technologies is their use for the automation of production processes in mechanical engineering, metallurgy and a number of other industries. A common factor that reduces the efficiency of wireless networks is the increased interference level in the shops of industrial enterprises, due to the operation of technological equipment. Therefore, the study of such networks operation at increased interference intensity (BER = 10^{-5}–10^{-4}) carried out in this paper is of significant practical importance.

Prospects for further research. Increasing the data transfer rate in the IEEE 802.11ac and IEEE 802.11ax networks to several Gbps necessitates the use of extended channels with a width of 160 MHz, which leads to an increase in the noise power in the channel. Improving the coding, that is, moving from 256 QAM to 1024 QAM increases the data rate too. However, being denser, subcarriers are more susceptible to mutual interference. Therefore, 1024 QAM technology provides speed improvements at a shorter distance from the access point and under normal conditions the signal to noise ratio decreases sufficiently fast as the coverage area is expanded. Thus, the use of modern high-speed technologies for wireless data transmission in industrial conditions requires the development of methods and means to increase the interference immunity of computer networks.

Improving the interference immunity in wireless networks can be achieved by reducing the size of transmitted frames. However, this increases the relative weight of service information, which reduces the throughput. The study of these processes on the basis of the mathematical model developed in this paper is promising.

ACKNOWLEDGEMENTS

The work was carried out at the Department of Electronic Computing Machinery of the Oles Honchar Dnipro National University within the framework of research project “Methods of data processing and transmission in computer systems and networks”, No 0119U100963.

REFERENCES

1. Roshan P., Leary J. 802.11 Wireless LAN Fundamentals. Cisco Press, Indianapolis, IN 46240, USA, 2004, 296 p. ISBN 5-8459-0701-2.
2. Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function, *Journal of selected areas in communications,* 2000, No. 3, Vol. 18, P. 535–547. DOI: 10.1109/49.840210
3. Tinnirello I., Bianchi G., Xiao Y. Refinements of IEEE 802.11 distributed coordination function modeling approaches, *IEEE Transactions on Vehicular Technology,* 2010, No. 3, Vol. 59, pp. 1055–1067. DOI: 10.1109/TVT.2009.2029118
4. Tay Y. C., Chua K. C. A capacity analysis for the IEEE 802.11 MAC protocol, *Wireless Networks*, 2001, No.2, Vol.7, pp. 159–171. DOI: 10.1023/A:1016637622896
5. Bianchi G., Fratta L., Oliveri M. Performance evaluation and enhancement of the CSMA/CA MAC protocol for 802.11 wireless LAN’s, *Proceedings of PIMRC '96 – 7th International Symposium on Personal, Indoor, and Mobile Communications*. Taipei, Taiwan, Oct. 1996, Vol. 2, pp. 392–397. DOI: 10.1109/PIMRC.1996.567423
6. Matthew Gast. 802.11 Wireless Networks: The Definitive Guide. O’ Reilly Media, Inc., 2005, 630 p. ISBN 0596100523, 9780596100520
7. Krishman Michael N., Pollin Sofie, Zakhor Avideh Local Estimation of Collision Probabilities in 802.11 WLANs with Hidden Terminals, *Electrical Engineering and Computer Sciences University of California at Berkeley. Technical Report No. UCB/EECS-2009-2, January,* 2009, 11 p. [Electronic resource]. Access mode: https://www2.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-2.pdf
8. Malone D., Duffy K., Leith D. Modeling the 802.11 Distributed Coordination Function in Non-saturated Heterogeneous Conditions, *IEEE/ACM Transaction on Networking,* 2007, No. 1, Vol. 15, pp. 159–172. DOI: 10.1109/TNET.2006.890136
9. Yu Hai L. Collision Probability in Saturated IEEE 802.11 Networks. / Yu Hai L. and Sakurai Taka // Australian Telecommunication Networks & Applications Conference (ATNAC), Australia, Dec. 2006, 5 p. ISBN: 0977586103 9780977586103
10. Foh C. H., Tantra J. W. Comments of IEEE 802.11 saturation throughput analysis with freezing of backoff counters, *IEEE Communication Letters,* 2005, No. 2, Vol. 9, pp. 130–132. DOI: 10.1109/LCOMM.2005.02008
11. Heusse M., Rousseau F., Guillier R., Duda A. Idle Sense: An optimal access method for high throughput and fairness in rate diverse wireless LANs, *Proc. of ACM SIGCOMM.* – 2005, No. 4, Vol. 35, pp. 121–132. DOI: 10.1145/1090191.1080107
12. Singh Rishipal, Lobiyal D. K. Delay analysis of IEEE 802.11 DCF with modified Binary Exponential Backoff, *International Journal of Wireless & Mobile Networks (IJWMN),* 2011, No. 3, Vol. 3, pp. 151–161. DOI : 10.5121/ijwmn.2011.3312
13. Chang Z., Alanen O., Huovinen T., Nixtila T., Ong E. H., Kneckt J., Ristaniemi T. Performance analysis of IEEE 802.11ac DCF with hidden nodes, *IEEE 75th Vehicular Technology Conference (VTC Spring)*, 2012, 5 p. DOI: 10.1109/VETECS.2012.6240054
14. Patidar R., Roy S., Henderson T. R., Mehrnoush M. Validation of Wi-Fi network simulation on ns-3, *University of Washington Technical Report, August 7, 2017, Seattle, WA, 98195*, 13p. [Electronic resource]. Access mode: https://depts.washington.edu/funlab/wp-content/uploads/2015/03/ns3-TR.pdf

DOI 10.15588/1607-3274-2022-2-13

15. Cover T. Elements of Information Theory. John Wiley & Songs, 1991, 328 p. ISBN:9780471241959
16. Tanenbaum A., Wetherall D. Computer Networks, 5th edition. New Jersey, Pearson Prentice Hall, 2011, 960 p. ISBN-13: 978-0132126953
17. Kurose James F., Keith W. Ross Computer Networking. A Top – Down Approach, 6th edition. New Jersey, Pearson Education, Inc, 2013, 889 p. ISBN-13: 978-0-13-359414-0

Received 15.02.2022.
Accepted 22.03.2022.

УДК 681.3.07

МОДЕЛЮВАННЯ РОБОТИ КОМП'ЮТЕРНИХ МЕРЕЖ IEEE 802.11 В УМОВАХ ВИСОКОЇ ІНТЕНСИВНОСТІ ЗАВАД

Хандецький В. С. – д-р техн. наук, професор, завідувач кафедри електронних обчислювальних машин Дніпровського національного університету імені Олеся Гончара, Дніпро, Україна.

Карпенко Н. В. – канд. фіз.-мат. наук, доцент кафедри електронних обчислювальних машин Дніпровського національного університету імені Олеся Гончара, Дніпро, Україна.

АНОТАЦІЯ

Актуальність. Високий рівень промислового шуму збільшує втрати інформаційних фреймів в процесі передачі, що, у свою чергу, зменшує пропускну здатність мережі. Ми пропонуємо математичну модель роботи мереж IEEE 802.11 в умовах підвищеної інтенсивності завад.

Мета цієї статті полягає в тому, щоб в явній аналітичній формі відобразити вплив інтенсивності бітових помилок (BER) на імовірність передачі фрейму і пропускну здатність мережі.

Метод. Запропоновано метод побудови моделі, яка дозволяє безпосередньо обчислити залежність імовірності передачі фрейму від кількості станцій, працюючих в режимі насичення, що є зручним для інженерних розрахунків. Значення коефіцієнтів моделі були обрані шляхом порівняння результатів обчислень з результатами, одержаними при використанні відомої моделі Біанкі, яка описує функціонування мережі у вигляді Марковського процесу. В діапазоні до 23 станцій, які працюють з однією точкою доступу, що відповідає імовірності колізії до 0,5, означені залежності для обох моделей відповідають одне одному з точністю, що відповідає практичним вимогам. Одержано вираз для пропускної здатності мережі.

Результати. Результати розробки моделі були використані для урахування впливу інтенсивності завад на процес передачі інформації. Це дозволило в явному вигляді виразити вплив інтенсивності бітових помилок на імовірність передачі фрейму і пропускну здатність мережі у випадку варіацій довжини фрейму і кількості конкуруючих станцій. Ступінь зменшення пропускної здатності була визначена для BER = 10^{-5}, $5 \cdot 10^{-5}$, 10^{-4} і збільшення величини мінімального конкурентного вікна.

Висновки. У даній роботі була розроблена математична модель для безпосереднього обчислення імовірності передачі фрейму та пропускної здатності мережі при різних рівнях інтенсивності завад.

КЛЮЧОВІ СЛОВА: IEEE 802.11 мережі, математична модель, фрейм, імовірність передачі, колізія, пропускна здатність, інтенсивність завад.

УДК 681.3.07

МОДЕЛИРОВАНИЕ РАБОТЫ КОМПЬЮТЕРНЫХ СЕТЕЙ IEEE 802.11 В УСЛОВИЯХ ВЫСОКОЙ ИНТЕНСИВНОСТИ ПОМЕХ

Хандецкий В. С. – д-р техн. наук, профессор, заведующий кафедрой электронных вычислительных машин Днепровского национального университета имени Олеся Гончара, Днепр, Украина.

Карпенко Н. В. – канд. физ.-мат. наук, доцент кафедры электронных вычислительных машин Днепровского национального университета имени Олеся Гончара, Днепр, Украина.

АННОТАЦИЯ

Актуальность. Высокий уровень промышленного шума увеличивает потери информационных фреймов, что, в свою очередь, уменьшает пропускную способность сети. Мы предлагаем математическую модель работы сетей IEEE 802.11 в условиях повышенной интенсивности помех.

Цель данной статьи состоит в том, чтобы в явной аналитической форме отобразить влияние интенсивности битовых ошибок (BER) на вероятность передачи фрейма и пропускную способность сети.

Метод. Предложен метод построения модели, которая позволяет непосредственно вычислить зависимость вероятности передачи фрейма от количества станций, работающих в режиме насыщения, что удобно для инженерных расчетов. Значения коэффициентов модели были выбраны путем сравнения результатов вычислений с результатами, полученными при использовании известной модели Бианки, которая описывает функционирование сети в виде Марковского процесса. В диапазоне до 23 станций, которые работают с одной точкой доступа, что соответствует вероятности коллизии до 0,5, указанные зависимости для обеих моделей соответствуют друг другу, с точностью, соответствующей практическим требованиям. Получено выражение для пропускной способности сети.

Результаты. Результаты разработки модели были использованы для учета влияния интенсивности помех на процесс передачи информации. Это позволило в явном виде выразить влияние интенсивности битовых ошибок на вероятность передачи фрейма и пропускную способность сети в случае вариаций длины фрейма и количества конкурирующих станций. Сте-

DOI 10.15588/1607-3274-2022-2-13

пень уменьшения пропускной способности была определена для BER = 10^{-5}, $5 \cdot 10^{-5}$, 10^{-4} и повышения величины минимального конкурентного окна.

Выводы. В данной работе была разработана математическая модель для непосредственного вычисления вероятности передачи фрейма и пропускной способности сети при различных уровнях интенсивности помех.

КЛЮЧЕВЫЕ СЛОВА: IEEE 802.11 сети, математическая модель, фрейм, вероятность передачи, коллизия, пропускная способность, интенсивность помех.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Roshan P. 802.11 Wireless LAN Fundamentals / P. Roshan, J. Leary. – Cisco Press, Indianapolis, IN 46240, USA. – 2004. – 296 p. ISBN 5-8459-0701-2.
2. Bianchi G. Performance analysis of the IEEE 802.11 distributed coordination function / G. Bianchi // Journal of selected areas in communications. – 2000. – No. 3, Vol. 18. – P. 535–547. DOI: 10.1109/49.840210
3. Tinnirello I. Refinements of IEEE 802.11 distributed coordination function modeling approaches. / I. Tinnirello, G. Bianchi, Y. Xiao // IEEE Transactions on Vehicular Technology. – 2010. – No.3. – Vol.59. – P. 1055–1067. DOI: 10.1109/TVT.2009.2029118
4. Tay Y.C. A capacity analysis for the IEEE 802.11 MAC protocol. / Y. C. Tay, K. C. Chua // Wireless Networks. – 2001. – No. 2, Vol. 7. – P. 159–171. DOI: 10.1023/A:1016637622896
5. Bianchi G. Performance evaluation and enhancement of the CSMA/CA MAC protocol for 802.11 wireless LAN's. / G. Bianchi, L. Fratta, M. Oliveri // Proceedings of PIMRC '96 – 7th International Symposium on Personal, Indoor, and Mobile Communications, Taipei, Taiwan, Oct. 1996. – Vol. 2. – P. 392–397. DOI: 10.1109/PIMRC.1996.567423
6. Matthew Gast. 802.11 Wireless Networks: The Definitive Guide / Gast Matthey. – O' Reilly Media, Inc., 2005. – 630 p. ISBN 0596100523, 9780596100520
7. Krishman Michael N. Local Estimation of Collision Probabilities in 802.11 WLANs with Hidden Terminals./ Krishman Michael N., Pollin Sofie, Zakhor Avideh // Electrical Engineering and Computer Sciences University of California at Berkeley. Technical Report No. UCB/EECS-2009-2, January, 2009. – 11 p. [Electronic resource]. – Access mode: https://www2.eecs.berkeley.edu/Pubs/TechRpts/2009/EECS-2009-2.pdf
8. Malone D. Modeling the 802.11 Distributed Coordination Function in Non-saturated Heterogeneous Conditions. / D. Malone, K. Duffy, D. Leith // IEEE/ACM Transaction on Networking. – 2007. – No. 1, Vol. 15. – P. 159–172. DOI: 10.1109/TNET.2006.890136
9. Yu Hai L. Collision Probability in Saturated IEEE 802.11 Networks. / Yu Hai L. and Sakurai Taka // Australian Telecommunication Networks & Applications Conference (ATNAC), Australia, Dec. 2006. – 5 p. ISBN: 0977586103 9780977586103
10. Foh C. H. Comments of IEEE 802.11 saturation throughput analysis with freezing of backoff counters. / C. H. Foh, J. W. Tantra // IEEE Communication Letters. – 2005. – No. 2, Vol. 9. – P. 130–132. DOI: 10.1109/LCOMM.2005.02008
11. Idle Sense: An optimal access method for high throughput and fairness in rate diverse wireless LANs / [M. Heusse, F. Rousseau, R. Guillier, A. Duda] // Proc. of ACM SIGCOMM. – 2005. – No. 4, Vol. 35. – P. 121–132. DOI: 10.1145/1090191.1080107
12. Singh Rishipal. Delay analysis of IEEE 802.11 DCF with modified Binary Exponential Backoff. / Singh Rishipal, D. K. Lobiyal // International Journal of Wireless & Mobile Networks (IJWMN). – 2011. – No. 3, Vol. 3. – P. 151–161. DOI: 10.5121/ijwmn.2011.3312
13. Performance analysis of IEEE 802.11ac DCF with hidden nodes / [Z. Chang, O. Alanen, T. Huovinen et al.] // IEEE 75th Vehicular Technology Conference (VTC Spring). – 2012. – 5 p. DOI: 10.1109/VETECS.2012.6240054
14. Patidar R. Validation of Wi-Fi network simulation on ns-3 / [R. Patidar, S. Roy, T. R. Henderson, M. Mehrnoush] // University of Washington Technical Report: August 7, 2017, Seattle, WA, 98195. – 13 p. [Electronic resource]. – Access mode: https://depts.washington.edu/funlab/wp-content/uploads/2015/03/ns3-TR.pdf
15. Cover T. Elements of Information Theory. / T. Cover. – John Wiley & Songs, 1991. – 328 p. ISBN:9780471241959
16. Tanenbaum A. Computer Networks / A. Tanenbaum, D. Wetherall. – 5th edition. New Jersey : Pearson Prentice Hall, 2011. – 960 p. ISBN-13: 978-0132126953
17. Kurose James F. Computer Networking. A Top – Down Approach, 6th edition. / James F. Kurose, Keith W. Ross. – New Jersey : Pearson Education, Inc, 2013. – 889 p. ISBN-13: 978-0-13-359414-0

DOI 10.15588/1607-3274-2022-2-13

UDC 004.942

MODEL OF THE PROCESS OF GEOSPATIAL MULTI-CRITERIA DECISION ANALYSIS FOR TERRITORIAL PLANNING

Kuznichenko S. D. – PhD, Associate Professor, Dean of the Faculty of Computer Science, Management and Administration, Odessa State Environmental University, Odesa, Ukraine.

ABSTRACT

Context. The process of multi-criteria decision analysis for territorial planning and rational placement of spatial objects, based on modeling the properties of the territory, is considered.

Objective. Development of technology for multi-criteria decision analysis for territorial planning based on the apparatus of the theory of fuzzy sets and functions of geoinformation analysis.

Method. An object-spatial approach to the formation of a set of alternatives and criteria is proposed, according to which the process of multicriteria decision analysis is divided into two stages: macro- and microanalysis.The macroanalysis stage involves the assessment of the ecological and socio-economic properties of the territory using geomodeling functions. The paper provides a formalized description of the macroanalysis stage, including methods for assessing the qualitative and quantitative impact of spatial objects on the properties of the territory and decomposing objects into thematic layers of criteria. At the stage of microanalysis, the ranking of alternatives is performed taking into account the chosen decision-making strategy. The method of standardization of criteria attributes using fuzzy set membership functions and the modification of the method for calculating the coefficients of relative importance (weights) of criteria, taking into account the spatial heterogeneity of the preferences of the decision maker, are considered. A comparative analysis of the methods for aggregating the estimates of alternatives according to different criteria has been carried out. A feature of the presented technology of geospatial multi-criteria decision analysis of decisions for territorial planning is the possibility of its integration into modern geographic information systems.

Results. The procedure of geospatial multi-criteria decision analysis was implemented in the environment of the geographic information system ESRI ArcGIS 10.5 and was studied in solving the spatial problem of rational location of an enterprise.

Conclusions. The proposed object-spatial approach to multi-criteria decision analysis makes it possible to explicitly take into account the spatial heterogeneity of geographic data, which is the result of the influence of geographic objects on the properties of the territory. The developed technology can be used to solve a wide range of problems related to determining the most rational placement of various capital construction and infrastructure facilities.

KEYWORDS: geographic information systems, spatial modeling, multicriteria decision analysis, fuzzy sets.

ABBREVIATIONS

AHP is an analytic hierarchy process;
DEM is a digital elevation model;
DM is a decision maker;
DSS is a decision support system;
FAHP is a fuzzy analytic hierarchy process;
GIS is a geographic information system;
LMCA is a local multicriteria analysis;
MF is a membership function;
OAT is one-at-a-time
WLC is a weighted linear combination.

NOMENCLATURE

A is a set of alternatives;
$\tilde{A}$ is a fuzzy set;
At is a set of attribute data;
C is a set of evaluation criteria;
D is a decision rule that specifies the order in which actions are performed on a set of alternatives (selection, ranking, sorting of alternatives);
d_{ik} is a distance between the i-th alternative and the k-th reference location;
d_{Sik} is a standardized distance for a pair of locations i and k;
F is a procedure for criteria-based evaluation;
F_v is a function of territorial influence;
Fv_j is a influence function of the j-th object;
$\{Fv_{ij}\}$ is a set of functions of the territorial influence of the j-th objects on the i-th local parts of the territory;
G is a decision maker's preference system;
Gm is a set of geometric properties of the object;
gl is a linear object;
gp is a point object;
$gpol$ is a polygon object;
$H = \{h_i\}$ is a set of local areas into which the territory is divided;
L is a set of coordinates defining the geometry of the object;
M is a number of territory objects;
N is a number of alternatives;
$O = \{o_j\}$ is a set of objects belonging to the territory;
P is a property of the territory;
P_i is a set of properties of local areas h_i of the territory;
P_{ij} is a value of the influence of the j-th object in the i-th point or local area h_i of the territory;
P_j is a value of the influence of the j-th object at its location;
Pr is a procedure for assessing the properties of the territory;
R is a number of properties of the territory that must be taken into account in the decision-making problem;
Rj is a influence range of the j-th object;
r_{ij} is a distance between the i-th point (local area) of the territory and the j-th object;
T is a territory as an object of management;

DOI 10.15588/1607-3274-2022-2-14

t is a number of map layers;

$V()$ is a integral estimate of the alternative;

w_j is a global weight of the j-th criterion;

w_{ij} is a local weight of the i-th decision alternative according to the j-th criterion;

X is a universal set;

X_i are the sets of characteristics of the territory that are significant for solving the spatial problem;

$\mu_a(x)$ is a fuzzy set membership function;

$v()$ is a evaluation of the alternative by the criterion;

$\Phi_{AGG}()$ is a function of aggregating the influence of objects in the i-th point of the territory.

INTRODUCTION

Modern GIS are an important component of DSS due to the advanced functions of storing, processing and analyzing geodata, modeling tools and visualization tools. Spatial problems, in particular the problem of determining the suitability of territories for accommodating enterprises, capital construction facilities and infrastructure, are always multi-criteria in nature [1], therefore, spatial DSS are often used in cases where a large number of alternatives must be evaluated based on a set of conflicting and incommensurable criteria .

GIS allows for the process of making optimal spatial decisions due to the available functions of geoinformation data processing. The capabilities of a GIS to generate a set of alternatives and select the best solution are usually based on the operations of Surface analysis, Proximity analysis, and Overlay analysis.

Overlay operations allow you to define alternatives that simultaneously satisfy a set of criteria in accordance with the decision rule, but they have limited ability to include the preferences of DM.

A feature of the spatial problems of territorial planning is the need to take into account the complex environmental and socio-economic properties of the territory, as well as the impact of objects on the natural and anthropogenic environment. This justifies the need to take into account expert knowledge and use methods based on expert assessments. The integration of multi-criteria decision-making methods allows expanding the capabilities of GIS, structuring the problem in geographic space, taking into account both qualitative and quantitative evaluation criteria and value judgments (i.e., preferences for criteria and/or alternatives) [2–4].

Geospatial multicriteria decision analysis will be considered as a combination of spatial modeling tools with multicriteria decision making methods for evaluating and analyzing alternative solutions to a spatial problem. It is assumed that the problem is characterized by a finite, explicitly given set of alternatives. The goal of multi-criteria analysis is to rank alternatives by a finite number of attributes. At the same time, it is necessary to know the importance (weight) of attributes and the evaluation of alternatives regarding attributes. Most modern GIS do not contain built-in full-featured tools that can implement the complex procedure of multi-criteria decision analysis. Separate attempts to fully integrate tools for multi-criteria decision analysis and GIS within the framework of a universal interface have revealed problems associated with the lack of flexibility and interactivity of such systems, which cannot provide the required freedom of action for analysts [5]. Therefore, the development of a universal technology for geospatial multicriteria decision analysis that provides a solution to this problem is an urgent task for researchers.

DOI 10.15588/1607-3274-2022-2-14

The object of study of this work is the decision support process for territorial planning.

The subject of the study is object-spatial models and methods for assessing the properties of the territory and geospatial multi-criteria decision analysis for territorial planning.

The aim of the study is to develop a technology for multi-criteria decision analysis for territorial planning based on the apparatus of the theory of fuzzy sets and the functions of geoinformation analysis.

1 PROBLEM STATEMENT

When performing a geospatial multi-criteria analysis of decisions at the macro and micro levels, territorial spatial factors or conditions in which the processes under study take place should be taken into account. It is advisable to consider the territory as a complex system, and the model for assessing the state (properties) of the territory, formed as a result of the impact of objects located on it, as the basis for decision-making. At the same time, the objectives of the assessment, methods and scales of assessment, assessment criteria $C=\{C_1,C_2,\ldots,C_n\}$, alternatives $A=\{a_1,a_2,\ldots,a_m\}$ and the procedure for criteria-based assessment F should be defined. In this regard, the procedure for estimating the properties of the territory Pr, which determines the data representation model and the semantics of the spatial relations of objects, should be developed and included in a formalized record of the geospatial multi-criteria decision analysis:

$$\langle A, C, Pr, F, G, D \rangle. \quad (1)$$

Most of the traditional approaches to the analysis of spatial issues are extensions and adaptations of existing decision making methods. As a rule, they take into account spatial variability only implicitly and assume the spatial homogeneity of preferences and value judgments of DM. For instance, when aggregating estimates of alternatives using the weighted sum method, it is customary to calculate one weight for each criterion, despite the fact that in spatial problems the weight of the criterion often depends on the location of the alternative and may have a local value at different points in the territory. For example, the relationship between two properties of a territory may be markedly different in one region compared to another.

Based on the presence of the local weight w_{ij}, assigned to the i-th solution alternative (in the i-th location with coordinates x_i, y_i) according to the j-th criterion, the aggregation of the estimates of the alternatives $v(a_{ij})$, for example, using the weighted sum method, should look like:

$$V(A_i) = \sum_{j=1}^{N} w_{ij} v\left(a_{ij}\right). \quad (2)$$

At the same time, an important task remains the development of methods for determining the local weighting coefficients of criteria that will take into account the spatial heterogeneity of the territory.

2 REVIEW OF THE LITERATURE

An analysis of recent studies and publications demonstrates that the synergy of multi-criteria decision making methods and GIS is a fundamental tool for solving spatial problems in many areas [6–8]. Over the past few decades, significant progress has been made in the development of methods for multicriteria analysis of the suitability of territories [9, 10] and the choice of locations for spatial objects [11–13]. This study continues the cycle of works devoted to the problems of integration of geoinformation technologies and methods of multi-criteria decision making for solving problems of management and territorial development [14–18]. They raise the issues of creating, applying and optimizing the technology of geospatial multi-criteria analysis of solutions for GIS applications.

Spatial problems are often characterized by incompleteness and fuzziness of the initial data, as well as criteria represented by qualitative values that are difficult to formalize. Uncertainties arise due to the use of discretization operations and generalization of a set of geographic data. In addition, there are uncertainties in the value judgments and preferences of DM. The most attractive approach to solving such problems is the use in the methods of multicriteria analysis of the solutions of the «soft» computing apparatus, the theory of fuzzy sets [19].

A review of scientific research over more than 20 years [3] showed that the following multi-criteria methods are most often used in GIS applications: weighted WLC [20], AHP [21], reference point methods [22] , and outranking methods [23]. One of the most popular is the AHP method, which is based on pairwise comparisons on a ratio scale. In [24], its FAHP is presented, in which triangular fuzzy numbers are used to account for uncertainty in expert comparisons, and two approaches of FAHP means Fuzzy Extent Analysis and α-cutbased method.

As a rule, the greatest contribution to the uncertainty when using the AHP method is made by the criteria weights determined by pairwise comparison. Weights can be changed during analysis. Corresponding weight sensitivity on multi-criteria evaluation results is generally difficult to be quantitatively assessed and spatially visualized. In [25] developed a unique methodology to analyze weight sensitivity caused by both direct and indirect weight changes using the OAT technique (mostly known as local sensitivity analysis). The method was integrated into a comprehensive framework in the GIS environment. The framework was implemented as AHP-SA2 tool with spatial visualization capability.

In [26] spatial uncertainty and sensitivity analysis of land suitability maps is proposed. The resulting sensitivity maps delineate regions of weight dominance, where a particular weight greatly influences the uncertainty of suitability scores.

As noted earlier, most studies did not take into account the spatial heterogeneity of geographic data inherent in decision-making, especially in the area of territory management. In recent years, new research trends have emerged associated with a paradigm shift from spatial implicit to spatially explicit multicriteria analysis [27]. LMCA introduces the concept of spatial weight and spatially explicit value function [28, 29]. In [30], the OWA method is proposed, which can be used to take into account various risk-taking scenarios. In [31], local forms of reference point methods were developed. The weighting of criteria with a correction for proximity was proposed in [32]. The calculation of local weights is based on the idea of adjusting preferences according to spatial relationships between alternatives and some reference locations. Thus, the method explicitly recognizes the concept of spatial preference heterogeneity.

An analysis of publications shows that most of the works devoted to spatial multi-criteria analysis focus on the procedure for evaluating alternatives, taking into account the uncertainty and spatial heterogeneity of decision makers' preferences. However, while paying little attention to the preparation of initial data, namely the evaluation criteria and a variety of alternatives. To create a universal technology for multi-criteria analysis, it is necessary to have a formalized description of the process of decomposition of territory objects into separate thematic layers and the process of evaluating the properties of the territory as a result of the influence of objects located on them. This study describes the methodology and gives recommendations for the quantitative determination of the territorial influence of objects and the calculation of the integrated properties of the territory, as well as the ranking of alternatives, taking into account locally adapted decision-making methods.

3 MATERIALS AND METHODS

The properties of the territory can be considered as the result of the action (influence) of individual objects o_j located on local sections h_i into which the territory is divided. In this case, the territory T can be represented as $T \subset O \times H$.

One will consider the property of the territory P as a set of local or aggregated characteristics of the territory that are significant for solving the spatial problem, which can be obtained as a result of calculations or expert assessment. The set of connected objects of the territory influences the properties of the territory through the spatial influence functions F_v:

$$O \xrightarrow{F_v} P. \quad (3)$$

DOI 10.15588/1607-3274-2022-2-14

In general, P can be represented by a set of n sets X_i of characteristics of the territory that are significant for solving the spatial problem, for example, these can be indicators of the ecological, social or economic state of the territory:

$$P = \bigcup_{i=1}^{n} X_i. \qquad (4)$$

Characteristics (or indicators for assessing the properties of the territory) can be local, complex or integral. According to their type, indicators can be divided into qualitative and quantitative, respectively, be measured or calculated or determined by experts. The qualitative composition and the number of local indicators by which the property of the territory is assessed can vary from several units to several tens, and depend on the nature of the spatial decision-making problem. For example, to determine the location of a solid domestic waste landfill, it is necessary to take into account more than several dozen quantitative and qualitative indicators of the properties of the territory, which may include landscape, environmental, economic, social, and other characteristics [15].

A property of a territory is defined as an ordered set of properties of local parcels:

$$P = \left\{P_i \mid P_i = \left\{P_{ij}\right\}\right\}, i = 1 \div n, \ j = 1 \div m. \qquad (5)$$

The magnitude of the influence of the j-th object at the i-th point or local area of the territory determined through the distribution function of the influence of this object as:

$$P_{ij} = P_j \cdot F_{vj}\left(r_{ij}\right). \qquad (6)$$

The value of the influence function depends on the set of properties of the territory (relief, slope, soil type, etc.), as well as on the distance r_{ij} between the j-th object and the i-th point of the territory. The territorial influence function can be specified analytically, for example, on the basis of equations describing known physical processes (pollution transfer models, illumination distribution, etc.) or socio-economic impact models. The Fv function can be set as a value function built on the basis of expert estimates.

The impact of a set of objects O on the i-th point (local section) of the territory is determined by aggregating the values of the influence of individual objects:

$$P_i = \Phi_{AGG}\left(P_j \cdot F_{vj}\left(r_{ij}\right)\right). \qquad (7)$$

In general, the influence aggregation function is nonlinear and may include logical operations.

Taking into account the representation of the territory property model as a two-dimensional discrete system consisting of a set of elementary sections h_i or points of the territory defined by x, y, coordinates, the property of the territory can be represented as a function of the surface $P_{x,y} = f_p(x, y)$. Thus, from the point of view of geoinformatics, each of the properties of the territory can be represented in in the form of a coordinate-defined surface (for example, transport accessibility, pollution of the territory, flood damage, etc.). The application of an approach based on the description of the properties of the territory by means of the surface function allows one to solve the problems of placing infrastructure objects at different levels in the same way.

In a geographical context, the process of multi-criteria analysis of spatial planning decisions includes a set of geographically defined alternatives, usually local areas (eg, land parcels) and a set of evaluation criteria, presented as thematic map layers. Estimates of alternatives according to different criteria (attributes of criteria) are determined in accordance with the model for evaluating the properties of the territory. The analysis consists in combining the attributes of the criteria in accordance with the preferences of the decision maker, using the decision rule (combination rule).

The diagram of the process of geospatial multi-criteria decision analysis is presented in Fig.1.

Provided that the criteria layers are represented in a raster data model, which has the form of a two-dimensional x×y discrete rectangular grid. Each raster cell is an alternative, which is described by its spatial data (geographic coordinates) and attribute data (criteria scores). The decision matrix in this case has the form shown in Table 1.

The macroanalysis stage (Fig. 1) provides for the procedure for assessing the properties of the territory using geomodeling functions. At this stage, data on the spatial problem is collected, the objects are decomposed into thematic layers, the qualitative or quantitative territorial impact of the objects is calculated, the properties of the territory are evaluated according to objects of the same type, many criteria and alternatives are formed, taking into account the restrictions imposed on the solution.

Microanalysis (Fig. 1) is a stage that involves the analysis of alternatives using the methods of multi-criteria decision making. At the stage of microanalysis, certain decision-making strategies are formed, taking into account the preferences of the decision maker. A feature of the stage is the integration of geomodeling functions and decision-making methods.

Recommendations – the stage of visualizing the results of the analysis of decisions and providing recommendations to decision makers. The results of the analysis, as a rule, are visualized in the form of a comprehensive map of a set of acceptable solutions formed in accordance with the chosen procedure for analyzing alternatives (selection, ranking, sorting, etc.).

Sensitivity analysis is crucial for model validation and calibration, it is used as a tool to check the stability of the final result to small changes in the input data (for example, criteria weights) and to reduce uncertainty in the process of geospatial multi-criteria decision analysis.

DOI 10.15588/1607-3274-2022-2-14

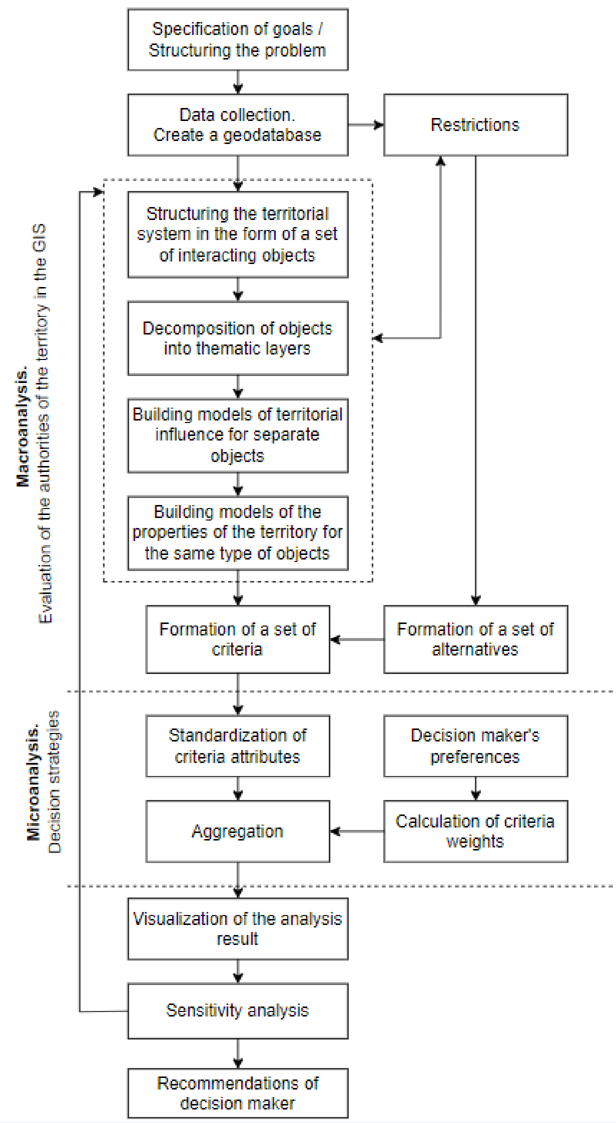


Figure 1 – Diagram of the process of geospatial multi-criteria decision analysis

Table 1 – Decision Matrix

Alternative	Coordinates		Criterion/attribute, C_j			
A_i	X	Y	C_1	C_2	…	C_n
A_1	x_1	y_1	a_{11}	a_{12}	…	a_{1n}
A_2	x_2	y_2	a_{21}	a_{22}	…	a_{2n}
A_3	x_3	y_3	a_{31}	a_{32}	…	a_{3n}
…	…	…	…	…	…	…
A_m	x_m	y_m	a_{m1}	a_{m2}	…	a_{mn}
Weight, w_j	w_{ij}		w_1	w_2	…	w_n

Let us consider in more detail the stage of macroanalysis of the process of geospatial multi-criteria analysis of solutions (Fig. 1). Structuring a territorial system in the form of a set of interacting objects involves the representation of an object in the form of a tuple of sets of homometric, spatial and attributive properties, taking into account the influence of *Fv* that it exerts on the territory:

$$O = \langle Gm, L, At, F_v \rangle . \quad (8)$$

Let's take a closer look at the procedure for decomposing territory objects into thematic layers. Let be given some finite set of objects O belonging to the territory. It is necessary to select from the set of objects O a subset of objects $O_p \in O$, which determine the properties of the territory in accordance with the spatial problem being solved. Further, the set of objects O_p should be decomposed into subsets of objects O_r, which by their influence determine the properties of the territory that are important for the task (for example, the development of the transport network, soil type, environmental safety, etc.), which need to be combined into separate thematic layers of criteria:

$$O_p = \bigcup_{r=1}^{R} O_r , \quad \bigcap_{r=1}^{R} O_r \neq \varnothing . \quad (9)$$

The decomposition of objects is performed based on the analysis of their spatial and attribute information, as well as the functions of influence on the territory.

The geometric properties of objects have the highest priority in decomposition $Gm = \{gp, gl, gpol\}$. The entire set of objects O_p is divided into three classes of point objects according to a geometric feature K_1, linear K_2 and polygonal K_3 objects. A thematic layer can only contain objects of the same geometric type (an object cannot be both a point and a polygon), so classes have the following properties: $O_p = K_1 \cup K_2 \cup K_3$, $K_1 \cap K_2 \cap K_3 = \varnothing$, where

$$K_i = \{ o_j \in O \mid o_j \sim k_i \}, \; i = 1,2,3, \quad O_p = \bigcup_{j=1}^{3} O_j . \quad (10)$$

The priority of attribute properties of objects is next after geometric ones. Each of the subset of objects O_j belonging to a certain geometric type which is further decomposed by the attribute criteria $At = \{Q, N\}$. Attribute information consists of a set of qualitative properties Q, which determine whether an object belongs to a certain thematic group (transport infrastructure, water bodies, settlements, etc.) and N – a set of quantitative characteristics of the properties of the object. For example, for objects belonging to the thematic group "Settlements", you can perform a decomposition by population.

At the last step, the decomposition is performed according to a variety of types of *Fv* influence functions, i.e. by functional attribute. At the same time, the type of influence that can be both positive and negative should be taken into account.

After the decomposition of objects, an *Mp* map can be obtained, which is a set of thematic layers L_i:

$$Mp = \{ L_i \}, \; i = \overline{1, t}, \quad (11)$$

DOI 10.15588/1607-3274-2022-2-14

$$L_i = \left\{ O_j^i \right\},\ j = \overline{1,n}. \quad (12)$$

Each thematic layer is a criterion for the decision-making task (Table 1). Schematically, the decomposition of a set of objects into thematic layers is shown in Fig. 2.

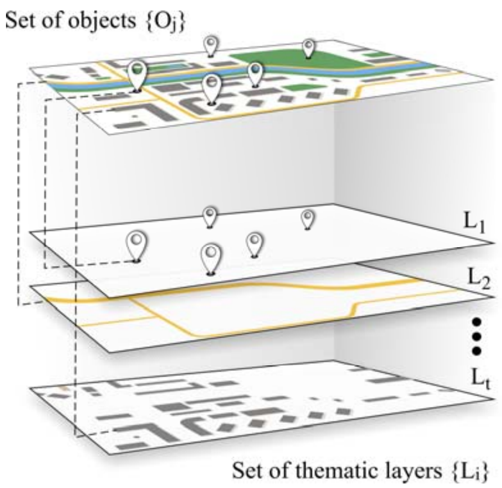


Figure 2 – Diagram of the decomposition of objects into thematic layers

We will consider a stationary model of territories with constant properties, in which P_j = const and F_v = const, that is

$$P_{ij} = P_j \cdot F_v\left(R_j\right). \quad (13)$$

To build models of territorial influence, various types of influence functions can be used, the parameters of which can be determined from the physical principles of distribution, experimentally or expertly. Often, a normal distribution law is used for this, which accurately describes the spatial impact caused by a large number of poorly correlated factors.

Expert assessment methods are most often used to determine the parameters of models reflecting the spread of social or economic properties of the territory.

The most effective mechanism for the formal description of models based on expert opinions is the theory of fuzzy sets [19]. A fuzzy set of a universal set X is defined as a set of ordered pairs:

$$\tilde{A} = \left\{ \left(x, \mu_a(x) \right) \mid x \in X \right\}, \mu_a(x) : x \to [0,1]. \quad (14)$$

Membership function indicates the degree to which element x belongs to a fuzzy subset $\tilde{A}$. The larger the $\mu_a(x)$, the more the element of the universal set corresponds to the properties of a fuzzy subset. The specific value of the membership function is called the degree or coefficient of membership. This degree can be defined as a functional dependency. The definition of the territorial influence model is, in fact, the definition of the influence of an object on a nearby territory in the form of an affiliation function $F_v\left(r_{ij}\right) = \mu\left(r_{ij}\right)$. We will consider the membership degree as the intensity of the manifestation of the function of territorial influence at a certain point of the local area of the territory.

One of the simplest membership functions is a piecewise linear (triangular and trapezoidal) function. Expert parameters of such membership function (territorial influence) are the easiest to determine. It is sufficient to determine the value of the distance r_{ij}, at which the influence of the object is practically unchanged, and the distance R, at which the influence of the object can be neglected. A continuous membership function approximating a trapezoidal one is a Gaussian-type curve. The generalized Gaussian function has the greatest versatility, examples of which are shown in Fig. 3.

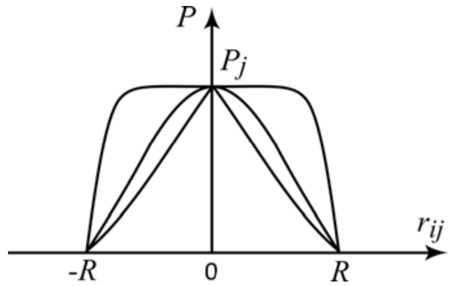


Figure 3 – Examples of graphs of territorial influence functions based on the generalized Gaussian function

Defining the influence functions as the membership degree to a fuzzy set makes it possible not to further standardize the attributes of alternatives, since their values are already in the range [0, 1].

The impact of multiple objects O on the $i$point (local area) of the territory is determined by aggregating the impact values of individual objects (7). The function of aggregating the impacts of objects at the i point of the territory can have a different form and, as a rule, is determined from the context of a spatial problem.

The task of aggregating estimates can arise in two cases: firstly, if necessary, to aggregate the influence of the same type of objects forming a certain property of the territory; secondly, to aggregate the influence of various objects to obtain a comprehensive property of the territory. The same aggregation approaches can be used for both cases.

Fuzzy logic operations can be used to determine the resulting impact of objects belonging to the same class.

The fuzzy union (or OR) of the influences of objects (Fig. 4 a) is defined as:

$$\bigcup_{i=1}^{n} P_i = \max\left(P_1, P_2, ..., P_n\right). \quad (15)$$

The fuzzy intersection (or AND) of the influences of objects (Fig.4 b) is defined as:

DOI 10.15588/1607-3274-2022-2-14

$$\bigcap_{i=1}^{n} P_i = \min\left(P_1, P_2, ..., P_n\right). \quad (16)$$

The use of the fuzzy intersection operation (16) leads to the evaluation of the property based on the lowest value of the influence of objects, the fuzzy union operation (15) takes into account only the maximum values of the influence of objects on the nearby territory.

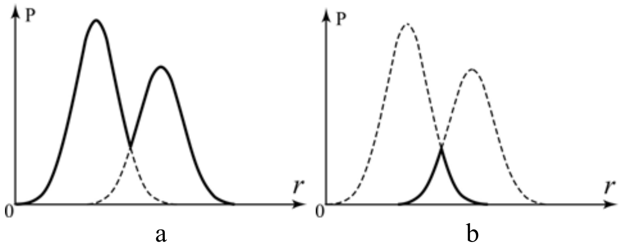


Figure 4 – Graphs of the resulting model: a – by the maximum value of influence from individual objects; b – by the minimum value of influence from individual objects

To obtain a complex (integral) assessment of the properties of a territory from objects belonging to different classes and having certain weights of importance, the weighted sum (2) operation adapted to the model of the properties of territories, that is, taking into account spatial variations and the division of the territory into local areas, can be used.

For the *h* surrounding and the local weight w^h_j for the *j* criterion, a local form of the weighted sum operator of the form can be determined:

$$P(A_i^h) = \sum_{j=1}^{n} v(a_{ij}^h) w_j^h. \quad (17)$$

The diagram of the process of assessing the properties of the territory is shown in Fig. 5. It reflects the main stages of the process, starting with the decomposition of all objects significant for the spatial problem into layers before constructing integral layers of the territory properties. If the objects of the same type of thematic layer have different influence functions, then it is assumed that a set of layers of territory properties is built separately for each object, followed by their combination by one of the aggregation operators to obtain an integral thematic layer.

At the stage of microanalysis, a wide range of decision-making methods can be applied. The main steps of the stage are determining the weights of criteria and aggregating the attributes of alternatives, which are estimates of alternatives according to different criteria (properties of the territory), into a general integral assessment. At the same time, it is important to take into account the preferences of decision-maker, which can be characterized by subjectivity, uncertainty and different attitudes to risk. In addition, local adaptation of methods may be necessary, in the case when there is a spatial heterogeneity of decision-maker's preferences in the problem.

4 EXPERIMENTS

Let's consider an example of using geospatial multi-criteria decision-making to select a suitable location for an enterprise. Let's assume that the main goals are to reduce construction costs and provide the enterprise with human resources (labor). We will identify as the main factors that can affect the reduction of construction costs, the slope of the territory and the proximity of the transport network. Potential sources of labor are nearby settlements, while the main source is a large district center with the largest population. Thus, in order to provide the enterprise with cheap labor, it is advisable to place it as close as possible to populated areas, which will additionally make it possible to reduce transportation costs for the delivery of workers.

The decomposition of the territory objects important for solving the problem according to geometric, attributive and functional features leads to the formation of three thematic layers:

1) DEM is a raster layer, which is a representation of the earth surface of the territory, in the form of a matrix of cells, each of which is characterized by a certain height;

2) transport network – a layer of linear objects, representing paved roads;

3) settlements – a layer of polygonal objects representing the administrative boundaries of settlements located on the territory under consideration.

Next, it is necessary to assess the functional impact of these objects on the territory.

The slope is determined by the steepness in each cell of the raster surface. The smaller the slope value, the flatter the earth's surface is. In GIS, the slope can be calculated as the rate of elevation change from one DEM cell to another.

The Euclidean proximity metric can be used to determine the distance to roads and settlements. In GIS, the Euclidean distance between two objects $O_1(x_1, y_1)$ and $O_2(x_2, y_2)$ is defined as:

$$d(O_1, O_2) = \sqrt{\left(x_1 - x_2\right)^2 + \left(y_1 - y_2\right)^2}. \quad (18)$$

Performing the calculation according to (18) transforms the vector layer of objects into a raster layer, which is a continuous surface of a given property.

DOI 10.15588/1607-3274-2022-2-14

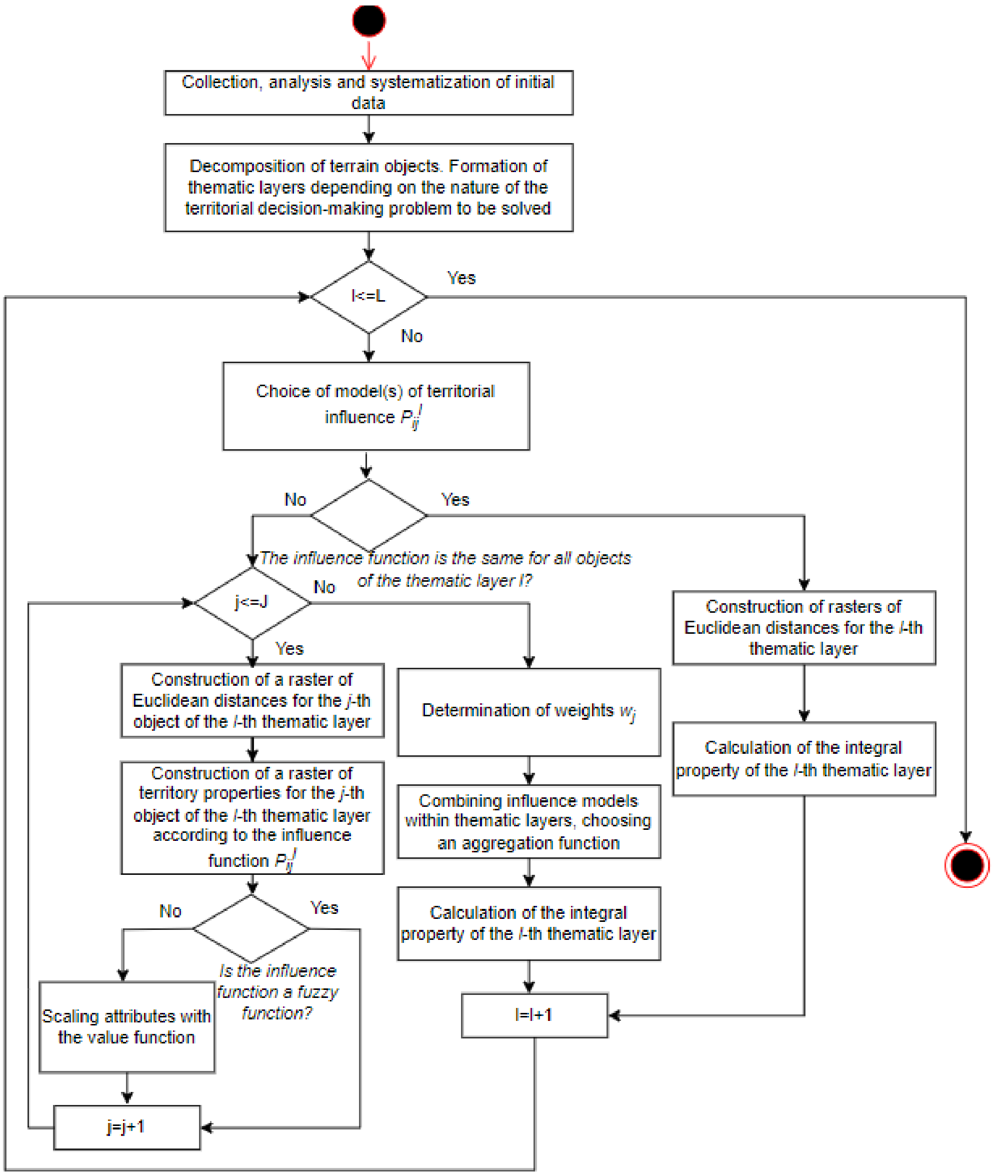


Figure 5 – Diagram of the assessing process of the territory properties

Let's standardize the raster layers of criteria using the fuzzy set membership functions built on the basis of expert evaluation. The values of the alternative attributes will be transferred to the range [0, 1], where the unsuitable areas are marked with zero, and the areas with the maximum degree of suitability are marked with 1. A general view of the membership functions used in the experiment is shown in Fig. 6. Detailed information about thematic layers, influence functions, control points of membership functions used to standardize attributes, as well as weights of the importance of criteria is given in Table 2.

Let's consider two scenarios of multi-criteria analysis of solutions. In the first scenario, the global weight of the importance of the criteria will be used, i.e. a constant weight w_j is set for the j criterion (Table 2). The integral estimate will be obtained by the weighted sum method:

$$V(A_i) = \sum_{j=1}^{N} w_j v\left(a_{ij}\right). \qquad (19)$$

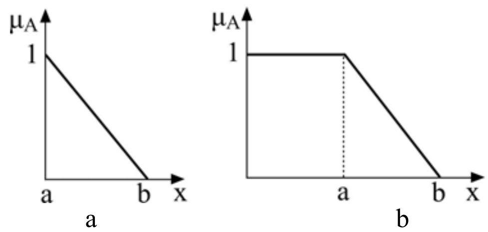


Figure 6 – Membership functions used to standardize attributes: a – linear monotonically decreasing; b – piecewise linear decreasing

In the second scenario, local importance weights will be used [32]. So the weight distribution of the "Slope" criterion will be recalculated depending on the distance

DOI 10.15588/1607-3274-2022-2-14

from the transport network. In this case, the location of the linear road object is the reference location. Similarly, the weight of the criterion "Distance to settlements" will have a local value, depending on the proximity of the district center (reference location).

The weight of the proximity-adjusted criterion, w_{ij}, assigned to the i alternative of the relative j criterion is defined as:

$$w_{ij} = w_j \frac{d_{ik}^S}{1/n \sum_{i=1}^{m} d_{ik}^S}. \tag{20}$$

Standardized distance for a pair of locations i and k:

$$d_{Sik} = \frac{\min_i \{d_{ik}\}}{d_{ik}}. \tag{21}$$

The distances to the reference locations will be calculated using the Euclidean distance metric.

Thus, the local weight will be obtained by modifying the global weight of the criterion, taking into account the distance d_{ik}, normalized by the average distance of all alternatives to the reference location. An example of calculating local weights for five alternatives is given in Table 3. According to (20), the global weight of the criterion is changed by redistributing the total weight nw_j, depending on the spatial relationship (proximity) between the reference location and the alternative solution.

Local weights will be used to calculate the integral evaluation of alternatives using the weighted sum aggregation operator (2).

5 RESULTS

Scenario 1 and scenario 2 were implemented in the ArcMap 10.5 GIS environment. The results of geospatial modeling are presented in Fig. 7. Thematic layers of criteria (Table 2) based on the proposed influence functions and in accordance with the macroanalysis procedure (Fig. 1 and Fig. 5) were transformed into raster layers of slope, distance to the transport network and distance to settlements. Next, the layers were standardized in accordance with the membership functions shown in Figure 6. Standardization was performed using the functions of Raster Calculator and Reclassify of the Spatial Analyst library. As a result, a standardized slope raster (Fig. 7 a), a standardized distance raster to the transport network (Fig.7 b) and a standardized distance raster to settlements (Fig.7 c) were obtained.

The complex applicability map according to scenario 1 (Fig. 7 d) is constructed using the weighted sum operator based on the global weights of the criteria given in Table 2.

Scenario 2 assumed the calculation of local weights. Standardized rasters of the distances of alternatives to the district center and the transport network were obtained based on the expression:

$$d_{Sik} = \frac{\max_i \{d_{ik}\} - d_{ik}}{\max_i \{d_{ik}\} - \min_i \{d_{ik}\}}. \tag{22}$$

Table 2 – Characteristics of thematic layers (criteria) of a spatial decision-making problem

Criterion	Thematic layers	Influence function	Standardization		Weight
			control points of the membership function (Fig. 6)		
			a	b	
Slope	raster	$F_v = f'(x,y)$	5%	15%	0,4
Distance to transport network	linear	$F_V = \sqrt{(x - x_{gl})^2 + (y - y_{gl})^2}$	0	500 m	0.3
Distance to settlements	polygonal	$F_V = \sqrt{(x - x_{gpol})^2 + (y - y_{gpol})^2}$	0	10 km	0.3

Table 3 – Proximity-adjusted weights

Alternatives	Euclidean distance d_{ik}	Standardized distance d_{Sik}	Weight	
			global w_j	local w_{ij}
A1	6	0.33	0.3	0.172
A2	3	0.67	0.3	0.345
A3	5	0.40	0.3	0.207
A4	2	1.00	0.3	0.517
A5	4	0.50	0.3	0.259
Mean	4	0.58		
Minimum	2	0.33		
Sum (w_j)			1.5	1.5

DOI 10.15588/1607-3274-2022-2-14

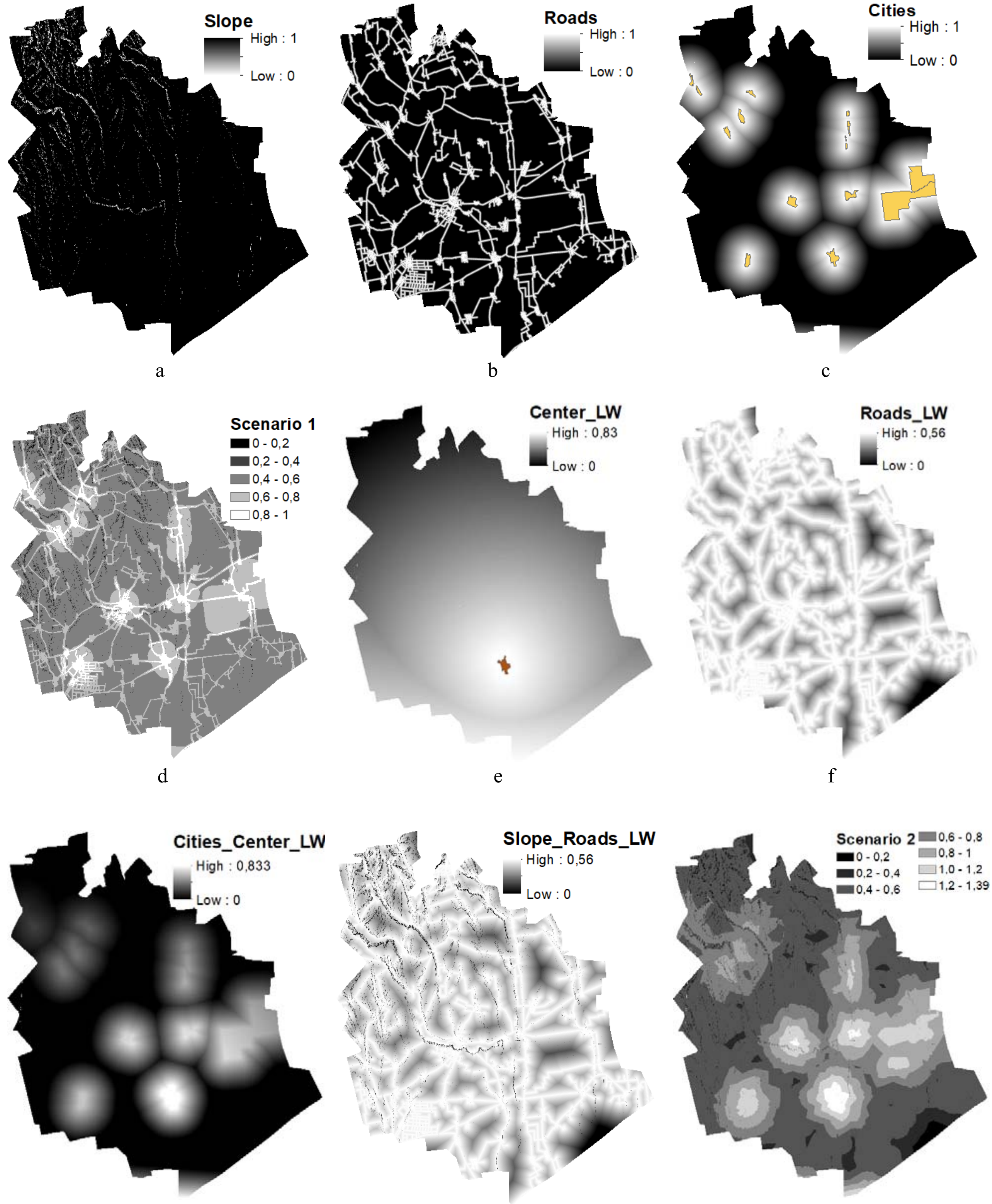


Figure 7 – Results of spatial modeling in accordance with the initial data of scenario 1 and scenario 2: a – standardized layer of the slope of the territory; b – standardized layer of distances to the transport network; c – standardized layer of distances to settlements; d – integrated suitability map (scenario 1); e – raster of local weights of the criterion ”Settlements adjusted for the proximity of the district center”; f – raster of local weights of the criterion “Slope adjusted for the proximity of the transport network”"; g – estimates of alternatives according to the criterion “Slope adjusted for the proximity of the transport network”; h – estimates of alternatives according to the criterion “Settlements adjusted for the proximity of the transport network”; proximity of the district center; i – comprehensive applicability map (scenario 2)

DOI 10.15588/1607-3274-2022-2-14

The minimum distance $\min_i \{d_{ik}\}$ taken as the size of the raster cell, which, when modeled for all maps, is 27 m. The average value of standardized distances is obtained using the Get Raster Properties tool of the Data Management library. The global weight w_j (20) for the criteria of scenario 2 is assumed to be 0.5. The field of local weights for the criterion "Settlements adjusted for the proximity of the district center" is shown in Fig. 7 e, and for the criterion "Slope adjusted for the proximity of the transport network" in Fig. 7 f.

Estimates of alternatives according to the criteria "Slope" and "Settlements" were multiplied by the corresponding local weights adjusted for proximity, the results are presented in Fig. 7 g and Fig. 7 h respectively. The final complex applicability map was obtained using a locally adapted version of the weighted sum operator (2) and is shown in Fig. 7 i.

6 DISCUSSION

For all scenarios of geospatial analysis, the previously considered macroanalysis procedure was applied (Fig. 1), which includes the decomposition of objects into thematic layers and the assessment of the properties of the territory based on the model of the territorial influence of objects. Scaling of criteria is performed using piecewise linear membership functions. As a result, the values of the criteria attributes were transferred to the range [0, 1], where 1 is the highest, and 0 is the lowest degree of suitability of an alternative according to a given criterion (Fig. 7 a, b, c). This makes it possible to further aggregate alternative estimates by various methods, such as using fuzzy overlay (union or intersection operations) so with the weighted sum operator.

In scenario 1, the weighted sum and global weights method is used for aggregation. The weight of the "Slope" criterion is assumed to be 0.4, however, as can be seen in Fig. 7, and most (92.6%) of the studied territory has a degree of suitability equal to 1 according to this criterion, therefore it has little influence on the final result. The criteria "Distance to the transport network" and "Distance to settlements" have an equal weight of 0.3 and have the same effect on the prioritization, which leads to a scattered distribution of alternatives with a high rating throughout the territory. As a result, alternatives with high suitability were concentrated around sections of the road network located within the boundaries of settlements (Fig. 7 d). The plots with a degree of suitability of 0.8 and higher accounted for 5.56% of the entire research area.

The results of the experiment in scenario 2 showed that the local weights calculated for the criteria "Slope adjusted for the proximity of the transport network" and "Settlements adjusted for the proximity of the district center" have a significant impact on the ranking of alternatives. They allow us to quantify the spatial displacement to the focal (important for decision-making) objects. Thus, in the considered spatial problem, the solutions with a high rating shifted towards the district center (Fig. 7 i).

The proposed algorithm made it possible to calculate the local weight at each point (section) of the territory, redistributing the global weight of the criterion depending on the spatial relationship (proximity) between the focal location and the alternative solution. The resulting raster of weights is then used to aggregate estimates of alternatives by the weighted sum operator. Note that an important parameter of modeling is the size of the raster cell. It is assumed that it must be the same for all criteria for correctly performing the overlay operation. It should be chosen taking into account the analyzed distances and the necessary modeling accuracy. Thus, for scenario 2, plots with a high degree of suitability of more than 1.0 accounted for 6.59%, and more than 1.2–0.98% of the entire study area.

The use of local weights provides an alternative representation of complex preferences and reduces the number of criteria, which in turn significantly simplifies the stage of microanalysis and integration of the model into the GIS environment. In addition, the approach based on local weights simulates cognitive reasoning, which makes the analysis procedure more transparent and understandable for the decision-maker.

CONCLUSIONS

The urgent task of developing a model of the process of geospatial multi-criteria analysis of decisions on territorial planning and rational placement of capital construction and infrastructure facilities has been solved.

The scientific novelty of the obtained results lies in the fact that an approach to multi-criteria decision analysis is proposed, which is based on a model for assessing the properties of territories and spatially adapted decision-making methods. The properties of the territory are evaluated based on the influence functions of adjacent objects. A universal technology has been proposed that allows for spatial analysis without restrictions on the maximum and minimum sizes of land plots. Taking into account the spatial variation of the properties of the territory and the different degrees of detail of objects, allows to increase the accuracy of spatial analysis, as well as its practical value.

The practical significance of the results obtained lies in the fact that the technology of geospatial multi-criteria analysis of solutions has been developed, which is based on existing functions of information geoprocessing and can be fully integrated into the GIS environment. The results of the simulation allow us to recommend the proposed model for use in practice, in particular for the tasks of rational placement of important infrastructure facilities.

The prospects for further research are to improve the model of the geospatial multi-criteria decision analysis process in order to take into account various decision-making strategies, in particular in conditions of risk and uncertainty.

ACKNOWLEDGEMENTS

The work is supported by the state budget scientific research project of Odessa State Environmental University "Geoinformation and intelligent decision-making

DOI 10.15588/1607-3274-2022-2-14

technologies in the tasks of assessing the environmental safety of territories" (state registration number 0119U003671) and by the international project "Multi-level Local, Nation- and Regionwide Education and Training in Climate Services, Climate Change Adaptation and Mitigation (№ 619285-EPP-1-2020-1-FI-EPPKA2-CBHE-JP).

REFERENCES

1. Chakhar S., Mousseau V. Spatial multicriteria decision making, *Encyclopedia of GIS*. New York, Springer-Verlag, 2008, pp. 747–753. DOI:10.1007/978-3-319-23519-6_839-2
2. Chakhar S., Martel J. M. Enhancing geographical information systems capabilities with multicriteria evaluation functions, *Journal of Geographic Information and Decision Analysis*, 2003, Vol. 7, No. 2, pp. 69–71.
3. Malczewski J. GIS-based multicriteria decision analysis: a survey of the literature, *International Geographical Information Science*, 2006, Vol. 20, No. 7, pp. 703–726.
4. Malczewski J., Rinner C. Multicriteria Decision Analysis in Geographic Information Science. New York, Springer, 2015, 331 p. DOI:10.1007/978-3-540-74757-4
5. Lidouh K. On themotivation behind MCDA and GIS integration, *Multicriteria Decision Making*, 2013, Vol. 3, No. 2/3, pp. 101–113. DOI:10.1504/ IJMCDM.2013.053727
6. Afshari A., Vatanparast M., Ćoćkalo D. Application of multi criteria decision making to urban planning – a review, *Journal of Engineering Management and Competitiveness*, 2016, Vol. 6, Issue 03, pp. 46–53.
7. Cegan J., Filion A., Keisler J. Trends and applications of multi-criteria decision analysis in environmental sciences: literature review, *Environment Systems and Decisions*. – 2017, Vol. 37, pp. 1–11. DOI:10.1007/s10669-017-9642-9.
8. Mardani A., Jusoh A., Nor M. D. et al.] Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014, *Economic Research,* 2015, Vol. 28, No. 1, pp. 516–571. DOI: 10.1080/1331677X.2015.1075139
9. Chaoxu L., Renzhi L., Sicheng P. Land-use suitability assessment for urban development using a GIS-based soft computing approach: A case study of Ili Valley, China, *Ecological Indicators,* 2021, Vol. 123, pp. 1–13. DOI:10.1016/j.ecolind.2020.107333
10. Malczewski J. GIS-based land-use suitability analysis: a critical overview, *Progress in Planning,* 2004, Vol. 62, Issue 1, pp. 3–65. DOI:10.1016/ j.progress.2003.09.002
11. Rikalovic A., Cosic I., Lazarevic D. GIS Based Multi-Criteria Analysis for Industrial Site Selection, *Procedia Engineering*, 2014, Vol. 69, No. 12, pp. 1054–1063. DOI: 10.1016/j.proeng.2014.03.090
12. Samani Z. N., Karimi M., Alesheikh A. A. A Novel Approach to Site Selection: Collaborative Multi-Criteria Decision Making through Geo-Social Network (Case Study: Public Parking), *International Journal Geo-Information*, 2018, Vol. 7, Issue 3. DOI:10.3390/ ijgi7030082
13. Lokhande T. I., Mane S. J., Mali S. T. Landfill Site Selection using GIS and MCDA Methods: A Review, *International Journal of Research in Engineering, Science and Technology*, 2017, Vol. 3, No. 3, pp. 25–30.
14. Kuznichenko S., Buchynska I., Kovalenko L. et al. Suitable site selection using two-stage GIS-based fuzzy multi-criteria decision analysis, *Advances in Intelligent Systems and Computing,* 2020, No. 1080, pp. 214–230. DOI:10.1007/978-3-030-33695-0_16
15. Kuznichenko S., Kovalenko L., Buchynska I. et al. Development of a multi-criteria model for making decisions on the location of solid waste landfills, *Eastern-European Journal of Enterprise Technologies,* 2018, Vol. 2, No. 3(92), pp. 21–31. DOI: 10.15587/1729-4061.2018.129287
16. Kuznichenko S., Buchynska I., Kovalenko L. et al. Integrated information system for regional flood monitoring using internet of things, *CEUR Workshop Proceedings*, 2019, Vol. 2683, pp. 1–5.
17. Karpinski M., Kuznichenko S., Kazakova N. et al. Geospatial Assessment of the Territorial Road Network by Fractal Method, *Future Internet,* 2020, Vol. 12, Issue 201. DOI: 10.3390/fi12110201.
18. Kuznichenko S., Buchynska I. A fuzzy approach for determining the cognitive spatial location of an object in geographical information system, *Eastern-European Journal of Enterprise Technologies,* 2021, Vol. 6, No. 9(114), pp. 24–31. DOI: 10.15587/1729-4061.2021.246556
19. Zadeh L. A. Fuzzy sets, *Information and Control,* 1965, Vol. 8, No. 3, pp. 338–353.
20. Malczewski J. On the use of weighted linear combination method in GIS: common and best practice approaches, *Transactions in GIS,* 2002, Vol. 4, No. 1, pp. 5–22. DOI: 10.1111/1467-9671.00035
21. Saaty T. L. The analytic hierarchy process: planning, priority setting, resource allocation. New York, McGraw-Hill, 1980, 287 p.
22. Hwang C. L., Yoon K. Multiple attribute decision making: methods and applications a state-of-the-art survey. New York, Springer-Verlag, 1981, 269 p. DOI:10.1007/978-3-642-48318-9
23. Roy B. Multi-criteria methodology for decision aiding / B. Roy. – Springer Science+Business Media, 1996. – 292 p. DOI:10.1007/978-1-4757-2500-1
24. Vahidnia M. H., Alesheikh A. A., Alimohammadi A. Fuzzy analytical hierarchy process in GIS application, *Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2008, Vol. 37, pp. 593–596.
25. Chen Y., Yu J., Khan S. The spatial framework for weight sensitivity analysis in AHP-based multi-criteria decision making, *Environmental modelling & software*, 2013, Vol. 48, pp. 129–140. DOI: 10.1016/ j.envsoft.2013.06.010
26. Ligmann-Zielinska A., Jankowski P. Spatially-explicit integrated uncertainty and sensitivity analysis of criteria weights in multicriteria land suitability evaluation, *Environmental Modelling & Software,* 2014, Vol. 57, pp. 235–247. DOI: 10.1016/j.envsoft.2014.03.007
27. Malczewski J., Jankowski P. Emerging trends and research frontiers in spatial multicriteria analysis, *International Journal of Geographical Information Science*, 2020, Vol. 34:7, pp. 1257–1282. DOI: 10.1080/ 13658816.2020.1712 403
28. Lloyd C. D. Local models for spatial analysis. Boca Raton, CRC Press, 2010, 352 p.
29. Keller L.R., Simon J. Preference functions for spatial risk analysis, *Risk Analysis*, 2019, Vol. 39 (1), pp. 44–256.
30. Malczewski J., Liu X. Local ordered weighted averaging in GIS-based multicriteria analysis, *Annals of GIS,* 2014, Vol. 20, No. 2, pp. 117–129. DOI: 10.1111/risa.12892
31. Jankowski P. Behavioral decision theory in spatial decision-making models, *Handbook of behavioral and cognitive geography*. U.K.: Edward Elgar Pub, 2018, Ch. 3, pp. 41–55. DOI: 10.4337/9781784717544. 00009

DOI 10.15588/1607-3274-2022-2-14

32. Ligmann-Zielinska A., Jankowski P. Impact of proximity-adjusted preferences on rank-order stability in geographical multicriteria decision analysis, *Journal of Geographical Systems*, 2012, Vol. 14, No. 2, pp. 167–187 DOI: 10.1007/s10109-010-0140-6

Received 15.02.2022.
Accepted 20.03.2022.

УДК 004.942

МОДЕЛЬ ПРОЦЕСУ ГЕОПРОСТОРОВОГО БАГАТОКРИТЕРІАЛЬНОГО АНАЛІЗУ РІШЕНЬ З ТЕРИТОРІАЛЬНОГО ПЛАНУВАННЯ

Кузніченко С. Д. – канд. геогр. наук, доцент, декан факультету комп'ютерних наук, управління та адміністрування Одеського державного екологічного університету, Одеса, Україна.

АНОТАЦІЯ

Актуальність. Розглянуто процес багатокритеріального аналізу рішень з територіального планування та раціонального розміщення просторових об'єктів, заснований на моделюванні властивостей території. Мета роботи – розробка технології багатокритеріального аналізу рішень з територіального планування на основі апарату теорії нечітких множин та функцій геоінформаційного аналізу.

Метод. Запропоновано об'єктно-просторовий підхід до формування множини альтернатив та критеріїв, відповідно до якого процес багатокритеріального аналізу рішень розбивається на два етапи: макро- та мікроаналіз. Етап макроаналізу передбачає оцінювання екологічних та соціально-економічних властивостей території за допомогою функцій геомоделювання. У роботі дано формалізований опис етапу макроаналізу, включаючи методи оцінки якісного та кількісного впливу просторових об'єктів на властивості території та декомпозиції об'єктів на тематичні шари критеріїв. На етапі мікроаналізу виконується ранжування альтернатив з урахуванням обраної стратегії прийняття рішень. Розглянуто метод стандартизації атрибутів критеріїв за допомогою функцій належності до нечіткої множини, а також модифікація методу розрахунку коефіцієнтів відносної важливості (ваг) критеріїв з урахуванням просторової неоднорідності переваг особи, яка приймає рішення. Проведено порівняльний аналіз методів агрегування оцінок альтернатив за різними критеріями. Особливістю представленої технології геопросторового багатокритеріального аналізу рішень з територіального планування є можливість її інтеграції у сучасні геоінформаційні системи.

Результати. Процедура багатокритеріального аналізу рішень реалізована у середовищі геоінформаційної системи ESRI ArcGIS 10.5 та досліджена при вирішенні просторової проблеми раціонального розміщення підприємства.

Висновки. Запропонований об'єктно-просторовий підхід до багатокритеріального аналізу рішень дозволяє явно враховувати просторову неоднорідність географічних даних, яка є результатом впливу на властивості території розміщених на ній географічних об'єктів. Розроблена технологія може бути використана при вирішенні широкого кола проблем, пов'язаних з визначенням раціонального розміщення різних об'єктів капітального будівництва та інфраструктури.

КЛЮЧОВІ СЛОВА: географічні інформаційні системи, просторове моделювання, багатокритеріальний аналіз рішень, нечіткі множини.

УДК 004.942

МОДЕЛЬ ПРОЦЕССА ГЕОПРОСТРАНСТВЕННОГО МНОГОКРИТЕРИАЛЬНОГО АНАЛИЗА РЕШЕНИЙ ПО ТЕРРИТОРИАЛЬНОМУ ПЛАНИРОВАНИЮ

Кузниченко С. Д. – канд. геогр. наук, доцент, декан факультета компьютерных наук, управления и администрирования Одесского государственного экологического университета, Одесса, Украина.

АННОТАЦИЯ

Актуальность. Рассмотрен процесс многокритериального анализа решений по территориальному планированию и рациональному размещению пространственных объектов, основанный на моделировании свойств территории. Цель работы – разработка технологии многокритериального анализа решений по территориальному планированию на основе аппарата теории нечетких множеств и функций геоинформационного анализа.

Метод. Предложен объектно-пространственный подход к формированию множества альтернатив и критериев, в соответствии с которым процесс многокритериального анализа решений разбивается на два этапа: макро- и микроанализ. Этап макроанализа предполагает оценивание экологических и социально-экономических свойств территории с помощью функций геомоделирования. В работе дано формализованное описание этапа макроанализа, включая методы оценки качественного и количественного влияния пространственных объектов на свойства территории и декомпозиции объектов на тематические слои критериев. На этапе микроанализа выполняется ранжирование альтернатив с учетом выбранной стратегии принятия решений. Рассмотрен метод стандартизации атрибутов критериев с помощью функций принадлежности к нечеткому множеству, а также модификация метода расчета коэффициентов относительной важности (весов) критериев, с учетом пространственной неоднородности предпочтений лица, принимающего решения. Проведен сравнительный анализ методов агрегирования с различной формой компромисса между оценками альтернатив по разным критериям. Особенностью преставленной технологии геопространственного многокритериального анализа решений по территориальному планированию является возможность ее интеграции в современные геоинформационные системы.

Результаты. Процедура геопространственного многокритериального анализа решений реализована в среде геоинформационной системы ESRI ArcGIS 10.5 и исследована при решении пространственной проблемы рационального размещения предприятия.

Выводы. Предложенный объектно-пространственный подход к многокритериальному анализу решений позволяет явно учитывать пространственную неоднородность географических данных, которая является результатом влияния на свойства территории расположенных на ней географических объектов. Разработанная технология может быть использована при решении широкого круга проблем, связанных с определением наиболее рационального размещения различных объектов капитального строительства и инфраструктуры.

DOI 10.15588/1607-3274-2022-2-14

КЛЮЧЕВЫЕ СЛОВА: географические информационные системы, пространственное моделирование, многокритериальный анализ решений, нечеткие множества.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Chakhar S. Spatial multicriteria decision making / S. Chakhar, V. Mousseau // Encyclopedia of GIS. – New York : Springer-Verlag, 2008. – P. 747–753. DOI:10.1007/978-3-319-23519-6_839-2
2. Chakhar S. Enhancing geographical information systems capabilities with multicriteria evaluation functions / S. Chakhar, J. M. Martel // Journal of Geographic Information and Decision Analysis. – 2003. – Vol. 7, No. 2. – P. 69–71.
3. Malczewski J. GIS-based multicriteria decision analysis: a survey of the literature / J. Malczewski // International Geographical Information Science. – 2006. – Vol. 20, № 7. – P. 703–726.
4. Malczewski J. Multicriteria Decision Analysis in Geographic Information Science / J. Malczewski, C. Rinner. – New York : Springer, 2015. – 331 p., DOI:10.1007/978-3-540-74757-4
5. Lidouh K. On themotivation behind MCDA and GIS integration / K. Lidouh // Multicriteria Decision Making. – 2013. – Vol. 3, № 2/3. – P. 101–113. DOI:10.1504/ IJMCDM.2013.053727
6. Afshari A. Application of multi criteria decision making to urban planning – a review / A. Afshari, M. Vatanparast, D. Ćoćkalo // Journal of Engineering Management and Competitiveness. – 2016. – Vol. 6, Issue 03. – P. 46–53.
7. Cegan J. Trends and applications of multi-criteria decision analysis in environmental sciences: literature review / J. Cegan, A. Filion, J. Keisler // Environment Systems and Decisions. – 2017. – Vol. 37. – P. 1–11. DOI:10.1007/s10669-017-9642-9.
8. Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014 / [A. Mardani, A. Jusoh, M. D. Nor et al.] // Economic Research. – 2015. Vol. 28, № 1. – P. 516–571. DOI: 10.1080/1331677X.2015.1075139
9. Chaoxu L. Land-use suitability assessment for urban development using a GIS-based soft computing approach: A case study of Ili Valley, China / L. Chaoxu, L. Renzhi, P. Sicheng // Ecological Indicators. – 2021. – Vol. 123. – P. 1–13. DOI:10.1016/j.ecolind.2020.107333
10. Malczewski J. GIS-based land-use suitability analysis: a critical overview / J. Malczewski // Progress in Planning. – 2004. – Vol. 62, Issue 1 – P. 3–65. DOI:10.1016/ j.progress.2003.09.002
11. Rikalovic A. GIS Based Multi-Criteria Analysis for Industrial Site Selection / A. Rikalovic, I. Cosic, D. Lazarevic // Procedia Engineering. – 2014. – Vol. 69, № 12. – P. 1054 – 1063. DOI: 10.1016/j.proeng.2014.03.090
12. Samani Z. N. A Novel Approach to Site Selection: Collaborative Multi-Criteria Decision Making through Geo-Social Network (Case Study: Public Parking) / Z. N. Samani, M. Karimi, A. A. Alesheikh // International Journal Geo–Information – 2018. – Vol. 7, Issue 3. DOI:10.3390/ ijgi7030082
13. Lokhande T. I. Landfill Site Selection using GIS and MCDA Methods: A Review / T. I. Lokhande, S. J. Mane, S. T. Mali // International Journal of Research in Engineering, Science and Technology. – 2017. – Vol. 3, № 3. – P. 25–30.
14. Suitable site selection using two-stage GIS-based fuzzy multi-criteria decision analysis / [S. Kuznichenko, I. Buchynska, L. Kovalenko et al.] // Advances in Intelligent Systems and Computing. – 2020. – № 1080. – P. 214–230. DOI:10.1007/978-3-030-33695-0_16
15. Development of a multi-criteria model for making decisions on the location of solid waste landfills / [S. Kuznichenko, L. Kovalenko, I. Buchynska et al.] // Eastern-European Journal of Enterprise Technologies. – 2018. – Vol. 2, № 3(92). – P. 21–31. DOI: 10.15587/1729-4061.2018.129287
16. Integrated information system for regional flood monitoring using internet of things / [S. Kuznichenko, I. Buchynska, L. Kovalenko et al.] // CEUR Workshop Proceedings. – 2019. – Vol. 2683. – P. 1–5.
17. Geospatial Assessment of the Territorial Road Network by Fractal Method / [M. Karpinski, S. Kuznichenko, N. Kazakova et al.] // Future Internet. – 2020. – Vol. 12, Issue 201. DOI: 10.3390/fi12110201.
18. Kuznichenko, S. A fuzzy approach for determining the cognitive spatial location of an object in geographical information system / S. Kuznichenko, I. Buchynska // Eastern-European Journal of Enterprise Technologies. – 2021. – Vol. 6, № 9(114). – P. 24–31. DOI: 10.15587/1729-4061.2021.246556
19. Zadeh L. A. Fuzzy sets / L. A. Zadeh // Information and Control. – 1965. – Vol. 8, № 3. – P. 338–353.
20. Malczewski J. On the use of weighted linear combination method in GIS: common and best practice approaches / J. Malczewski // Transactions in GIS. – 2002. – Vol. 4, № 1. – P. 5–22. DOI:10.1111/1467-9671.00035
21. Saaty T. L. The analytic hierarchy process: planning, priority setting, resource allocation / T. L. Saaty. – New York: McGraw-Hill, 1980. – 287 p.
22. Hwang C. L. Multiple attribute decision making: methods and applications a state-of-the-art survey / C. L Hwang, K. Yoon. – New York : Springer-Verlag, 1981. – 269 p. DOI:10.1007/978-3-642-48318-9
23. Roy B. Multi-criteria methodology for decision aiding / B. Roy. – Springer Science+Business Media, 1996. – 292 p. DOI:10.1007/978-1-4757-2500-1
24. Vahidnia M. H. Fuzzy analytical hierarchy process in GIS application / M. H Vahidnia, A .A. Alesheikh, A. Alimohammadi // Photogrammetry, Remote Sensing and Spatial Information Sciences. – 2008. – Vol. 37. – P. 593–596.
25. Chen Y. The spatial framework for weight sensitivity analysis in AHP-based multi-criteria decision making / Y. Chen, J. Yu, S. Khan // Environmental modelling & software. – 2013. – Vol. 48. – P. 129–140. DOI: 10.1016/ j.envsoft.2013.06.010
26. Ligmann-Zielinska A. Spatially-explicit integrated uncertainty and sensitivity analysis of criteria weights in multicriteria land suitability evaluation / A. Ligmann-Zielinska, P. Jankowski // Environmental Modelling & Software. – 2014. – Vol. 57. – P. 235–247. DOI: 10.1016/j.envsoft.2014.03.007
27. Malczewski J. Emerging trends and research frontiers in spatial multicriteria analysis / J. Malczewski, P. Jankowski // International Journal of Geographical Information Science. – 2020. – Vol. 34:7. – P. 1257–1282. DOI: 10.1080/ 13658816.2020.1712 403
28. Lloyd C. D. Local models for spatial analysis / C. D. Lloyd. – Boca Raton : CRC Press, 2010. – 352 p.
29. Keller L.R. Preference functions for spatial risk analysis / L.R. Keller, J. Simon // Risk Analysis. – 2019. – Vol. 39 (1). – P. 44–256.
30. Malczewski J. Local ordered weighted averaging in GIS-based multicriteria analysis / J. Malczewski, X. Liu // Annals of GIS. – 2014. – Vol. 20, № 2. – P. 117–129. DOI: 10.1111/risa.12892
31. Jankowski P. Behavioral decision theory in spatial decision-making models / P. Jankowski // Handbook of behavioral and cognitive geography. – U.K.: Edward Elgar Pub, 2018. – Ch. 3. – P. 41–55. DOI: 10.4337/9781784717544. 00009
32. Ligmann-Zielinska A. Impact of proximity-adjusted preferences on rank-order stability in geographical multicriteria decision analysis / A. Ligmann-Zielinska, P. Jankowski // Journal of Geographical Systems. – 2012. – Vol. 14, № 2. – P. 167–187. DOI: 10.1007/s10109-010-0140-6

DOI 10.15588/1607-3274-2022-2-14

UDC 004.925

ALGORITHMS AND ARCHITECTURE OF THE SOFTWARE SYSTEM OF AUTOMATED NATURAL AND ANTHROPOGENIC LANDSCAPE GENERATION

Levus Ye. V. – PhD, Associate Professor of Software Engineering Department, Lviv Polytechnic National University, Lviv, Ukraine.

Morozov M. Yu. – Postgraduate student of the Informatics Department, Technical University of Munich, Munich, Germany.

Moravskyi R. O. – Postgraduate student of the Software Engineering Department, Lviv Polytechnic National University, Lviv, Ukraine.

Pustelnyk P. Ya. – Postgraduate student of the Software Engineering Department, Lviv Polytechnic National University, Lviv, Ukraine.

ABSTRACT

Context. The problem of automation of the generation of natural and anthropogenic landscapes is considered. The subject of the research is methods of procedural generation of landscapes that quickly and realistically visualize natural and anthropogenic objects taking into account different levels of detail.

Objective. The goal of the work is to improve the rendering quality and efficiency of the procedural generation process of landscape surfaces at any level of detail based on the implementation of the developed method.

Method. The proposed method of visualization involves the construction of a natural landscape using Bezier curves and surfaces and manual editing of individual segments; use of software agents that are responsible for individual steps of generating anthropogenic objects; adaptation of anthropogenic objects to the characteristics of natural landscapes; containerization of three-dimensional objects, which is used in various steps to organize the storage and loading of objects efficiently. A generated heightmap based on the Perlin noise algorithm is used to construct surfaces on individual segments of the natural landscape. Landscape processing software agents are used to unify the design of algorithms for creating and processing information about anthropogenic objects. Correct application operation and error resistance is guaranteed due to the inheritance of a specific interface by all implementations of agents. Containerization with two-level caching ensures the efficiency of display detailing.

Results. The developed method is implemented programmatically, and its efficiency is investigated for different variants of input data, which to the greatest extent determine the complexity of visualization objects.

Conclusions. The conducted experiments confirmed the efficiency of the proposed algorithmic software and its viability in practice in solving problems of automated landscape generation. Prospects for further research include improvement and expansion of the algorithms for procedural landscape generation, functionality complication of manual visualized object processing, and division of individual objects into separate hierarchies of containers.

KEYWORDS: object visualization**,** segments, levels of detail, Bezier curves, software agents, containerization.

ABBREVIATIONS

LOD is a level of detail;

PRNG is a pseudorandom number generator;

DDA is a digital differential analyser.

NOMENCLATURE

ch is a number of generated segments;

n is a number of points in a row or a column of the heightmap;

h_{xy} is a surface height at the point *(x, y)*;

step is a step between nodes in the height map (*x* and *y*);

seed is a input parameter for generating pseudo-random numbers;

chunkSize is a segment side size;

curvesPerChunkSize is a number of Bezier curves modelling the surface per landscape segment;

bezierCurveDivisions is a number of pieces to divide the Bezier curve into, used in algorithms for converting to a three-dimensional model or elevation map;

$\tilde{P}_0, \tilde{P}_3$ are start and end points of the third-order Bezier curve, which is used to describe segments of the natural landscape;

C_1, C_2 are checkpoints that do not belong to the third-order Bezier curve used to describe segments of the natural landscape;

B(t) is a parametric Bezier curve;

$\beta_i^3(\tau)$ is a third order Bernstein polynomials;

a is a constant that specifies the "tightness" of the curve;

K is a constant used in the condition of continuity of curves;

d is a maximum allowed distance between cities in the case of laying a road between them;

r is a city range;

C_M is a model visualization complexity.

INTRODUCTION

As a result of constant technical and scientific progress, the tasks of modelling and generation of three-dimensional virtual worlds are gaining popularity not only in the game industry or cinema but also in the fields of education, science, architecture, design, and more. This trend necessitates not only the manual creation of highly realistic models of landscapes, natural and anthropogenic objects through available hardware but also the productive performance of their automatic generation and visu-

DOI 10.15588/1607-3274-2022-2-15

alization with different levels of detail. In addition to performance, other requirements for visualization software systems are essential. In particular: a sufficient level of uniqueness of anthropogenic objects; their automatic adaptation to the characteristics of the landscape on which they are located; high realism of visualization; the ability to supplement the system with new algorithms [1–3].

Automated systems for landscape visualization have become widespread compared to the manual creation of three-dimensional worlds due to their simplicity and speed. The quality of the images used depends on the accuracy of their perception by users of educational or scientific programs, the profitability of the game or movie, as well as the further development of appropriate software systems.

The main problems of the available solutions are their insufficient realism for large scales, limited means for providing details in the results, the price of full versions of the relevant software. Also, these software applications have closed-source, hard-to-extend libraries of landscape generation algorithms, which reduces the flexibility of development. Within projects that require relatively small landscapes, existing solutions can be applied effectively despite existing shortcomings.

This area of research is promising, as, on the one hand, it is necessary to improve the appearance of models, and, on the other hand, it is impossible to go beyond the possible number of calculations, i.e., it is necessary to develop new models and more optimized algorithms. Developing a new, optimized method of landscape generation is an urgent task both from a scientific and practical point of view.

The object of research is the task of generating natural and anthropogenic landscapes. The research subject is landscape generation methods that quickly and realistically visualize objects taking into account different levels of detail. The work aims to improve the quality of reflection and efficiency of the process of landscape surface generation at any level of detail.

1 PROBLEM STATEMENT

According to the purpose of work, the following tasks are solved:

1) determination of functional requirements to the system of landscape visualization based on the analysis of popular software systems of such purpose;

2) modelling of landscape surfaces;

3) modelling of anthropogenic objects according to the landscape;

4) development of a containerization method for objects in three-dimensional scenes with different levels of detail;

5) software implementation of methods for three-dimensional model visualization based on generated object data.

The inputs that directly describe the objects for the visualization system are:

– landscape segment size $chunkSize \in [2; 2^{10}]$;

– the size of the region of landscape segments $regionSize \in [chunkSize; 2^{16}]$;

– the number of curves modeling the surface per landscape segment $curvesPerChunkSize \in [2; 20]$;

– parameter of maximum height (also depth) when using noise functions $\max Height \in [200; 5000]$;

– landscape segment height offset for the noise function $zOffset \in [0;1000]$;

– parameter for the coordinate step in the noise function $noiseStepDivisor \in [500;5000]$;

– the distance to which the city extends its influence to the generation $cityEffectRange \in [chunkSize; regionSize]$;

– the minimum distance between roads in the city $roadMinDistance \in [0; chunkSize]$;

– minimum road width $roadMinWidth \in [0; chunkSize]$;

– maximum road width $roadMaxWidth \in [Min; chunkSize]$;

– maximum distance between cities for construction of long-distance communication $maxNearbyCityDistance \in [chunkSize; 2^{16}]$;

– the minimum width of the architectural element $architectureMinWidth \in [0; chunkSize]$;

– the maximum width of the architectural element $architectureMaxWidth \in [Min; chunkSize]$;

– the minimum area of the architectural element $architectureMinArea \in [0; chunkSize]$.

2 REVIEW OF THE LITERATURE

At the beginning of the researched problem (the 1980s), algorithms of calculation and representation of fixed primitive landscapes were considered. An algorithm for dividing the surface into triangles with its subsequent vertical deformation with the help of fractal noise was created [4], and methods for collecting, storing, and processing landscapes were developed [5].

The intensive advancement of software tools for visualization of natural and anthropogenic landscapes requires the development of visualization methods that provide high-quality images and, at the same time, their cost-effectiveness in terms of computing resources [3, 6–12].

The most common functions of software applications for landscape visualization include:

1) generating a three-dimensional landscape of a specific size based on parameters (e.g., mountain locality based on relief data);

2) loading an existing landscape for processing;

3) processing of the landscape utilizing manual re-editing with available tools and automated systems;

4) generating and processing landscape characteristics, such as water bodies, climate, soils, erosion and more;

5) visualizing the treated landscape, presenting, and preserving the obtained result;

6) generating the scenery of the landscape surface taking into account its characteristics (in particular, trees, hills, ravines, dams, etc. are generated);

DOI 10.15588/1607-3274-2022-2-15

7) generating three-dimensional objects of architecture and infrastructure taking into account the characteristics of the landscape:

7.1) designating anthropogenic areas of the landscape;

7.2) generating infrastructure objects, namely roads, communication lines, power grids, and other connections, taking into account the properties and curvature of the landscape;

7.3) generating architectural objects, in particular buildings for industrial, residential, commercial and cultural purposes, objects of transport and means of communication, taking into account the characteristics of the landscape;

7.4) generating anthropogenic scenery: lamps, greenery, parks;

7.5) visualizing generated three-dimensional objects;

7.6) saving the generated three-dimensional objects.

Generation and visualization of anthropogenic objects is the most extensive and complex process in software systems, which requires the most time and money [13, 14].

Software systems for generating three-dimensional anthropogenic objects have the following advantages:

– Flexibility of application. Objects generated in such systems are not static three-dimensional models but parameterized system objects with additional data that can be modified to achieve the desired result.

– Using templates. After manually changing the generation parameters of architectural and infrastructural objects, they can be saved as templates for later use, which speeds up the work with the system.

– Levels of detail. Generation algorithms support different levels of detail of generated three-dimensional objects, allowing more flexible use of the system.

– Integration into general-purpose software.

Despite the advantages described above, systems for generating three-dimensional objects of architecture and infrastructure have some disadvantages:

– Dependence of the visualization quality and efficiency on the machine's computing power.

– High cost of memory resources to ensure realism.

– Presence of artifacts. Errors occur when generating architectural and infrastructural objects. Generation results require manual verification and adjustment.

The popular main algorithms for containerizing three-dimensional scenes are Object Container Streaming from Cloud Imperium Games, Asset Streaming from Umbra Software, and Partitioned Scene Loading from Unreal Engine. Among their disadvantages is the high probability of data corruption during the transfer of containers; closed software source code, which makes it impossible to use the software in other systems; redundancy of information due to the need for metadata about the components in the files; uneven distribution of objects in sections [15–17].

3 MATERIALS AND METHODS

The proposed method of visualization involves:

1) construction of a natural landscape with the help of curves and Bezier surfaces and manual editing of individual segments;

2) the use of software agents that are responsible for individual steps in the generation of anthropogenic objects;

3) adaptation of anthropogenic objects to the characteristics of natural landscapes;

4) containerization of three-dimensional objects, which is used in various steps to organize the storage and loading of objects effectively.

The advantages of this method are:

– Realistic images due to high-quality consideration of landscape characteristics in the visualization of anthropogenic objects, which involves the use of optimal segmentation and containerization.

– Effective display detail based on containerization with two-level caching.

– Flexibility and ability to develop through the use of software agents.

The algorithm for constructing surfaces for individual parts of a natural landscape segment consists of the following steps:

Step I: Procedural generation of the primary heightmap.

The “chunkSize” parameter determines the size of the generated altitude map. The parameters for generating the heightmap based on the Perlin noise algorithm are set: the input parameter “seed” and the coordinates of the requested segment (x,y).

The height value at points (x, y) is calculated using the following function:

$$h_{xy} = Noise(seed, x, y). \tag{1}$$

Step II: Selection of control points based on the heightmap to specify Bezier curves describing a segment of the natural landscape.

The number of points required to describe one row or column of the heightmap is calculated:

$$n = 3 \cdot curvesPerChunkSize + 1. \tag{2}$$

The step for the heightmap is calculated as follows:

$$step = \frac{chunkSize}{3 \cdot curvesPerChunkSize}. \tag{3}$$

Using formulas (1)–(3) and the points of the segment P_{ij}, which are used to describe the curve, we can define the following statements:

$$P_{ij} = P(x_i, y_j, h_{x_i y_j}),\ i, j=1,\dots,n,\ x_1=0,\ x_i=x_{i-1}+step,$$
$$x_n=chunkSize,\ y_1=0,\ y_j=y_{j-1}+step,\ y_n=chunkSize.$$

It is assumed that the four points used to describe the third-order Bezier curve are taken from the heightmap points P_{ij}, and they pass through this curve. The landscape segments generation algorithm automatically calculates the control points $\{C_1, C_2\}$ for the selected four points

DOI 10.15588/1607-3274-2022-2-15

$\{\tilde{P}_0, \tilde{P}_1, \tilde{P}_2, \tilde{P}_3\}$ from the array of values P_{ij}, through which the curve passes:

$$C_1 = \frac{l_1^2 \tilde{P}_2 - l_2^2 \tilde{P}_0 + (2l_1^2 + 3l_1 l_2 + l_2^2)\tilde{P}_1}{3l_1(l_1 + l_2)}, \quad (4)$$

$$C_2 = \frac{l_3^2 \tilde{P}_1 - l_2^2 \tilde{P}_3 + (2l_3^2 + 3l_3 l_2 + l_2^2)\tilde{P}_2}{3l_3(l_3 + l_2)}, \quad (5)$$

where $l_i = \left|\tilde{P}_i - \tilde{P}_{i-1}\right|^a$, used value a=0.5.

After calculations (4), (5) the curve is described by control points: $\{\tilde{P}_0, C_1, C_2, \tilde{P}_3\}$.

For each pair of curves that have a common point, the control points are modified to ensure the continuity of parametric curves:

$$B_1'(t)=K \cdot B_2'(t). \quad (6)$$

If α*3* is the end point of curve $B_1(t)$, α*2* is the control point of curve $B_1(t)$, β0 is the starting point of curve $B_2(t)$, β1 is the control point of curve $B_2(t)$, then condition (6) is as follows:

$$|\alpha 3 - \alpha 2| = K \cdot |\beta 1 - \beta 0|. \quad (7)$$

All these points form the description basis for the segment in further processing (export or editing). The height values are found using the local coordinates of the calculated control points within the segment, rounding them to integers and using them as indices for the two-dimensional array of the heightmap. The control points are modified for each pair of curves with a common point to ensure the curve continuity.

Step III: Joins with previous segments. If there are adjacent segments to the requested one, the values of the current control points are modified so that there is a smooth interpolation on the boundaries of the segments (7).

Step IV: Formation of the vector polygonal model for the generated segment.

Every four calculated control points on each axis of the plane on individual fragments of the segment (Step II) form a bicubic Bezier surface, the parametric form of which is as follows:

$$\Omega(u,v) = \sum_{i=0}^{3} \sum_{j=0}^{3} \beta_i^3(u) \cdot \beta_i^3(v) \cdot P_{ij} .$$

When converted to a vector polygonal model, each bicubic surface is considered as a set of control points that form Bezier curves in the x direction.

The input data for converting a landscape segment into a vector polygon model are the calculated control points in the Step II. The output data is a set of elementary polygons in the form of an array of vertices and an array of indices of these vertices.

Creating a vector polygonal model consists of the following calculations:

1) The primary Bezier curves are constructed based on the control points of the Bezier surface in the *x*-direction. The number of such curves is equal to *curvesPerChunksSize·n*. For example, the curve Q_1 is built based on points P_{i1}, i=1,…,4. The last control point of each curve constructed in the *x*-direction is the first for the next curve, except the last.

2) Depending on the *bezierCurveDivisions* parameter, the intermediate points L_m of each curve constructed in substep 1) are calculated. These intermediate points are stored in a one-dimensional array M of size N_m, which is calculated by the formula (8):

$$\begin{aligned} &N_M = bezierCurveDivisions^2, \text{ if } curvesPerChunkSize = 1 \\ &N_M = (curvesPerChunkSize \cdot bezierCurveDivisions - 1)^2, \\ &\text{if } curvesPerChunkSize > 1 \end{aligned} \quad (8)$$

3) To determine simple polygons an array of indices I is formed for vertices from array M. The total number of vertices on the segment side is calculated by the formula (9):

$$\begin{aligned} &k = bezierCurveDivisions, \text{ if } curvesPerChunkSize = 1 \\ &k = curvesPerChunkSize \cdot bezierCurveDivisions - 1, \\ &\text{if } curvesPerChunkSize > 1. \end{aligned} \quad (9)$$

The number of polygons is determined by the formula (10):

$$N_T = 2 \cdot curvesPerChunkSize^2 \cdot (bezierCurveDivisions - 1)^2. \quad (10)$$

Passing along the grid of polygons is in the x-direction the indices of the vertices *a, b, c, d* of two triangles are calculated according to formulas (9), (11). These triangles form a square (Fig. 1).

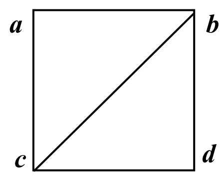


Figure 1 – Indexed polygons that form square

Indices (in the direction x – λ and in the direction y – μ) of the square formed by the triangles of the polygon are used to calculate:

$$\begin{aligned} &a = \lambda + (\mu - 1) \cdot k, \ \lambda = \overline{1, N_T}, \ \mu = \overline{1, N_T} \\ &b = a + k, \\ &c = a + 1, \\ &d = a + k + 1. \end{aligned} \quad (11)$$

The results of the described calculations for the values of *bezierCurveDivisions* = 5 and *curvesPerChunksSize* = 1 are shown in Fig. 2.

DOI 10.15588/1607-3274-2022-2-15

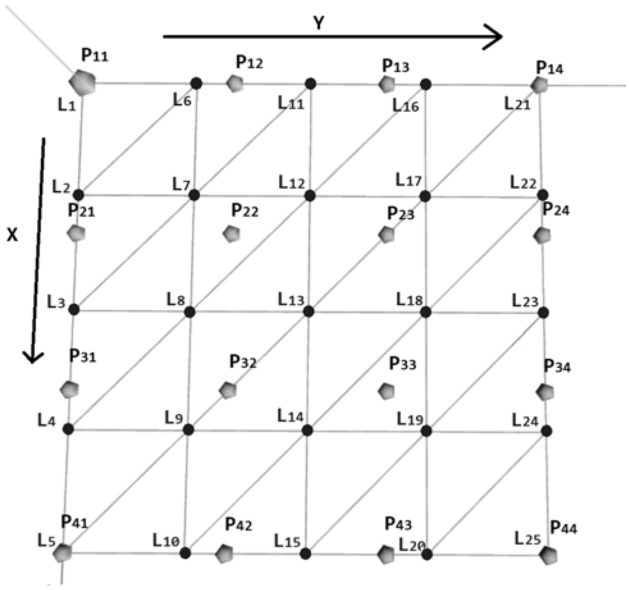


Figure 2 – Example of the vector polygonal model

Information about the fully generated and processed segment is returned to the caller for further processing (visualization or export).

Pre-generated or manually edited landscape segments can be exported to a three-dimensional polygonal model.

For the landscape generation module, it is necessary to retrieve information about the same landscape segment. To not perform generation steps each time, the caching logic for the manually created or edited information is used, which will ensure the processing of repeated queries on landscape segments as a simple search in the cache.

Landscape processing software agents are used to unify the design of algorithms for creating and processing information about anthropogenic objects. Correct application operation and error resistance is guaranteed due to the inheritance of a specific interface by all implementations of agents.

At the user's request, the system prepares the landscape segments to create anthropogenic objects and alternately uses pre-selected agents. After that, the system cache of landscape segments is updated, and the response is returned to the user (Fig. 3).

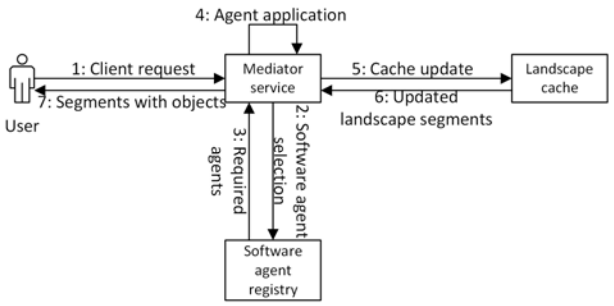


Figure 3 – Communication UML-diagram of the product upon a request from the user

The algorithms and the corresponding software agents that use them are responsible for the following steps:

1) preliminary preparation the landscape segment;

2) determination the city locations;

3) construction of transit roads within cities;

4) construction of roads between cities;

5) determination of road intersections;

6) determination of the boundaries of urban city blocks by crossroads and transit roads;

7) construction of architecture for each city block of the city;

8) algorithms for building three-dimensional models adapting to the landscape based on the received information about objects.

Based on these steps, software agents can create a variety of information about architectural and infrastructural objects and ensure the high performance of the application.

The first step in creating information is to obtain the parameters that are needed for the generation. After that, the user needs to get a prepared landscape segment with the coordinates specified in the request. The preparation includes creating a segment hull, determining its identification number, and obtaining its heightmap. The heightmap is used to adapt to the properties of the landscape when creating three-dimensional models of different levels of detail.

The creation of anthropogenic objects begins with the generation of cities. The essence of this algorithm is the choice of the city location within the region. After execution, the algorithm returns an array of cities belonging to the segment. Each entity of the city has filled in information belonging to the corresponding data structure. The algorithm consists of several sequential steps that use PRNG (Fig. 4).

The algorithm for laying roads in the city depends directly on the type of city generated in the previous step. The work created a type of city with Manhattan markings, i.e., parallel roads and rectangular city blocks. Laying roads for such a city is reduced to determining the distances between parallel streets, creating roads, and cutting roads outside the segment (Fig. 5).

For visual correctness and realism, the generation of long-distance connections requires a preliminary generation of roads in the city. Then intercity roads will join them, correctly continuing their direction.

In order to correctly build long-distance connections, the user needs to have a list of city roads in their boundary segments. This list is acquired by passing the segments in the DDA algorithm towards another city to check whether a particular segment is on the edge. Next, Bezier curves are built to pave a smooth road.

The algorithm for determining intersections searches for road intersections according to the formula for the intersection of two segments. It is key to the next step in defining city blocks, as roads and intersections can quickly identify their boundaries.

An algorithm for building city blocks is needed to determine the boundaries within which architectural objects can be built. City blocks are built between roads and intersections, which ensures the absence of roads and buildings clipping.

DOI 10.15588/1607-3274-2022-2-15

The algorithm for constructing city blocks is somewhat more complex than the previous ones. In the case of expanding the system by other software agents, it must correctly build city blocks at complex intersections and city forms. It is based on the Delaunay triangulation algorithm, which optimally divides a two-dimensional array of vertices into triangles, where the vertices of the city intersection are taken as vertices. From these triangles, city blocks are then formed by merging adjacent ones (Fig. 6).

Since the points-nodes of a nonconvex polygon give the city block boundaries, the algorithm for determining the city block boundaries is reduced to the construction of cyclic paths on the grid of intersections and roads that form a connected graph. Users can use two methods to provide this feature: inspecting intersections along roads and looking for closed loops, or triangulating a graph and then merging triangles into polygons. Since the first option requires the construction of graph edges on roads between different segments, which is computationally more complex, the second option was chosen, namely the Delaunay triangulation. This method of dividing a grid of points into triangles fulfils the task and allows users to quickly calculate adjacent triangles, making it easier to combine them. Once the triangles are combined into polygons, the city block information is stored in the segment.

Unlike previous algorithms, the algorithm for building architecture in a city block works within the boundaries of the city block, not the landscape segment. It arranges architectural elements by selecting their coordinates and type using PRNG.

The last step is to clean up unnecessary information in the landscape segment. Roads that do not border intersections or city blocks are discarded, intersections are merged with roads, and temporary additional information used by a software agent is removed.

To ensure the objects' realism, adaptation to the surrounding landscape takes place, the advantages of which are determined by the division of the landscape into rectangular segments. The algorithms use cubic spline interpolation to determine the height of the terrain from the nearest control points of the simulated surfaces. At the same time, the small size of the segment allows users to make queries and calculations quickly. Caching the heightmap in containers allows the system not to calculate it every time. In addition, taking into account the height values at the points of the segment, the number of the order of 10^8 due to caching allows avoiding display errors (caves under the ground, overhangs in cliffs, etc.). Thus, the speed of adaptation is not limited by the size of the generated landscape, and, accordingly, the memory consumption – by the number of control points.

The developed containerization algorithms provide the following features:

1) creating a hierarchy of containers for a given three-dimensional scene;

2) storing three-dimensional models and other containers inside a container;

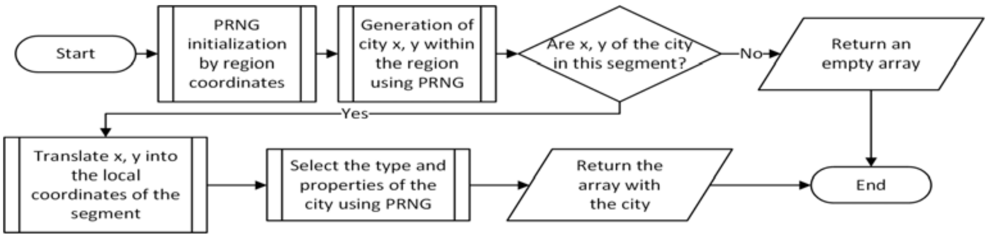


Figure 4 – Block diagram of the city generation algorithm

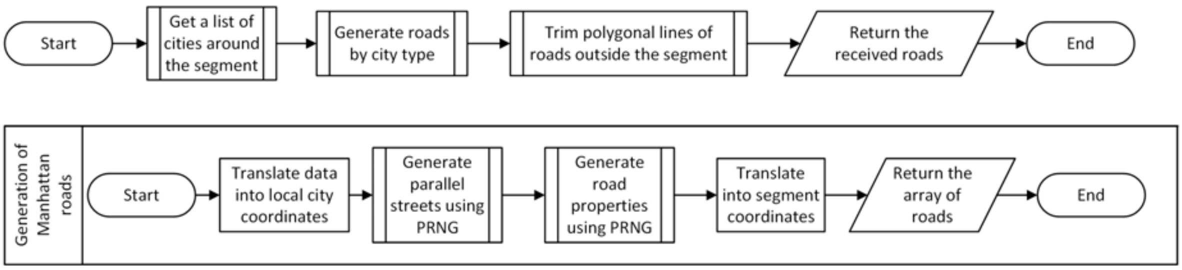


Figure 5 – Block diagram of road construction within a city

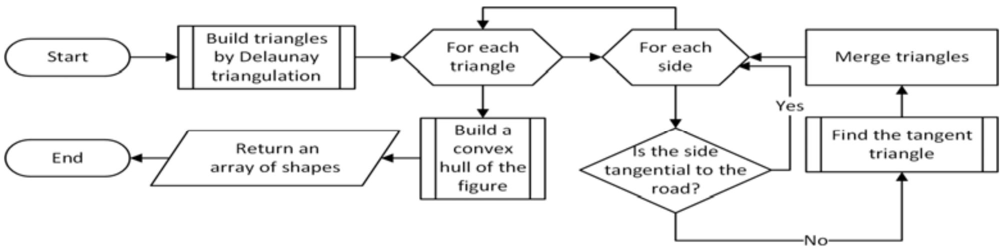


Figure 6 – Block diagram of city block construction

DOI 10.15588/1607-3274-2022-2-15

3) calculating bounding volume for each container, which contains all three-dimensional models of the container;

4) creating a two-tier cache to optimize the process of loading and storing containers (the first tier of the cache stores objects in RAM, the second tier – in the file system);

5) saving containers in a file system in binary format (serialization);

6) saving and loading different levels of detail of objects inside containers.

The container is presented as a data model and contains information about the segment, its three-dimensional model, the current level of detail, the identifier, and other containers (Fig. 7).

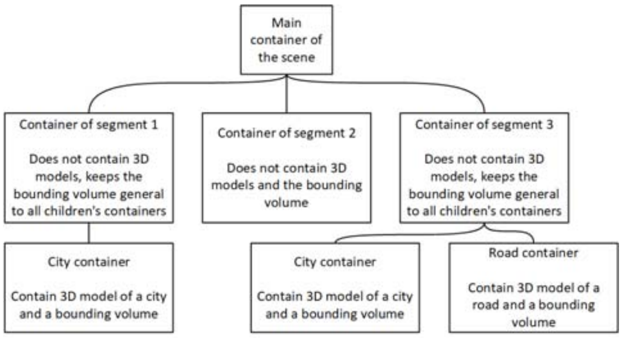


Figure 7 – Container hierarchy example

The architecture of the software system that implements the described algorithms is a session-based client-server. There is a three-tier model based on software agents for creating and editing the properties of anthropogenic objects on the server side. The highest model tier, the service layer, is implemented based on the REST paradigm, which is used at the endpoints handlers of the session server for the software system in which the application is integrated. The business logic tier is at the middle tier with predefined algorithms for creating information about three-dimensional anthropogenic objects and a set of software agents for processing landscape segments. The lowest tier contains the data layer with a description of the data structures used in the application.

The software system supports the construction of bounding volumes and different levels of detail, resulting in a reduction in the data amount that needs to be downloaded. An efficient binary format is used for storing containers. The cache implementation consists of two levels and allows you to optimize the process of saving three-dimensional models. All this allows to speed up the rendering of virtual scenes, which is an essential indicator for the systems of generation and visualization of natural and anthropogenic landscapes.

4 EXPERIMENTS

The developed algorithms are software pieces implemented in the form of the LandscapeGen software system, the server part of which consists of three components (Fig. 8):

– LandscapeGen: Terrain – a component that contains services for generating landscape surfaces using Bezier curves and planes;

– LandscapeGen: Infrastructure – a component that provides services for generating anthropogenic objects of architecture and infrastructure based on ready-made landscape data;

– LandscapeGen: Containerization – a component that provides services for containerization of three-dimensional objects, their storage, and loading.

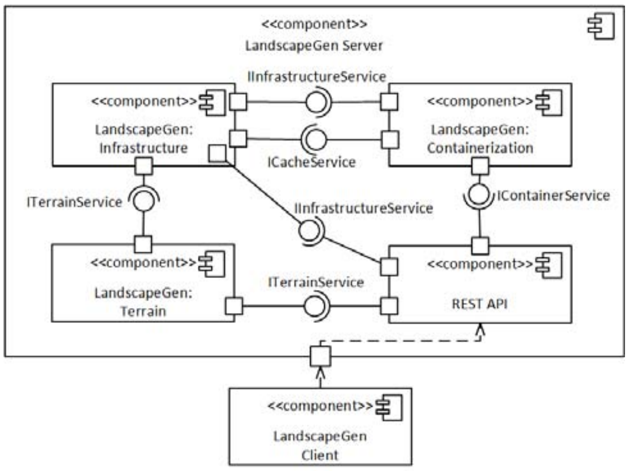


Figure 8 – Component diagram of LandscapeGen software system

The experiments were performed on a computer with the following characteristics: CPU Intel I7 9750H, GPU Nvidia 1660TI, RAM 16GB DDR4, Drive SSD NVME2 1TB. City centres were selected as the locations where the generation takes place in terms of the most significant computing power requirements. Parameters that significantly affect the generation time and do not give only a visual difference were selected for experiments. These include city range (*r*), the maximum allowed distance between cities in case of road construction (*d*), level of detail, and the number of generated segments (*ch*).

The complexity of the visualization model is calculated taking into account the maximum possible level of detail ($lod_{\max}$):

$$C_M = \frac{r \cdot d \cdot ch \cdot \left(lod_{\max} - lod + 1\right)}{256}.$$

A total of about 300 visualization experiments were performed for the following cases: without the containerization cache use, with the use of cache in RAM and hard drive. Used $lod_{\max}$=5, implemented levels of detail– min, low, medium, high, max. The minimum *lod* is for viewing the song from a distance.

The time costs for visualization of one segment for different *d*, *r*, *ch* at their maximum possible values, 4096, 1024, 25, respectively, were recorded (Table 1).

DOI 10.15588/1607-3274-2022-2-15

5 RESULTS

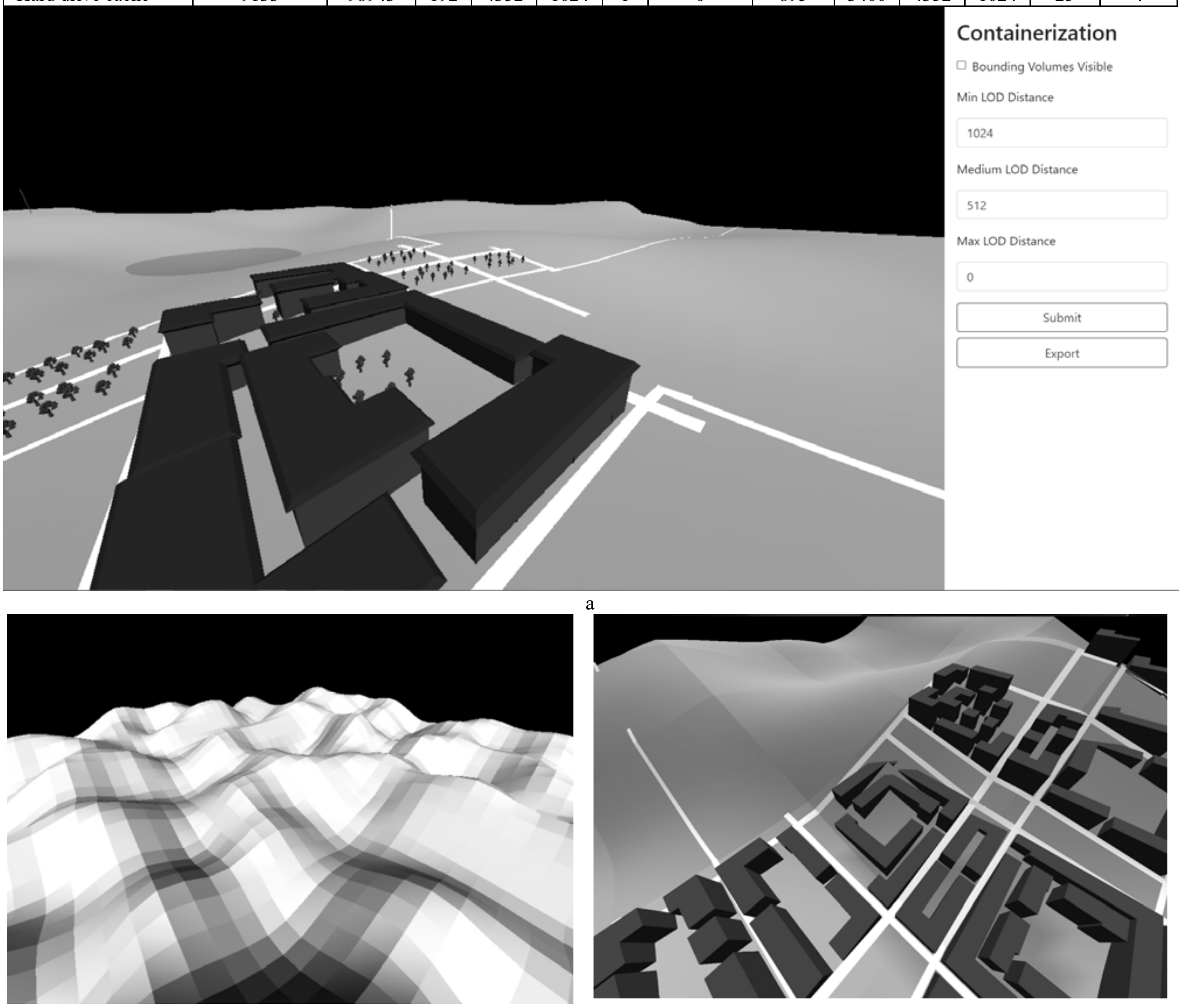
Anthropogenic and natural landscapes visualized by the LandscapeGen system are characterized by the absence of artifacts, adaptation of anthropogenic objects to natural landscapes (Fig. 9). Noise functions, which return the height value at the specified coordinates, are used to ensure the natural landscape automatic generation of the virtual world. A programming interface from the noisejs library is used to work with specific functions implementations: Perlin noise and Simplex noise.

Among the parameters that determine the quality of the obtained images used for modelling natural surfaces are: the number of Bezier curves per side of the segment, the noise reduction factor for landscape generation, the number of control points per segment. The use of these settings is not limited by the amount of memory, as caching methods are used.

The dependence of time costs for visualization of natural and anthropogenic landscapes on the complex characteristics of the complexity of the visualization model is analysed (Fig. 10).

Table 1 – Comparison of time spent for different types of visualization

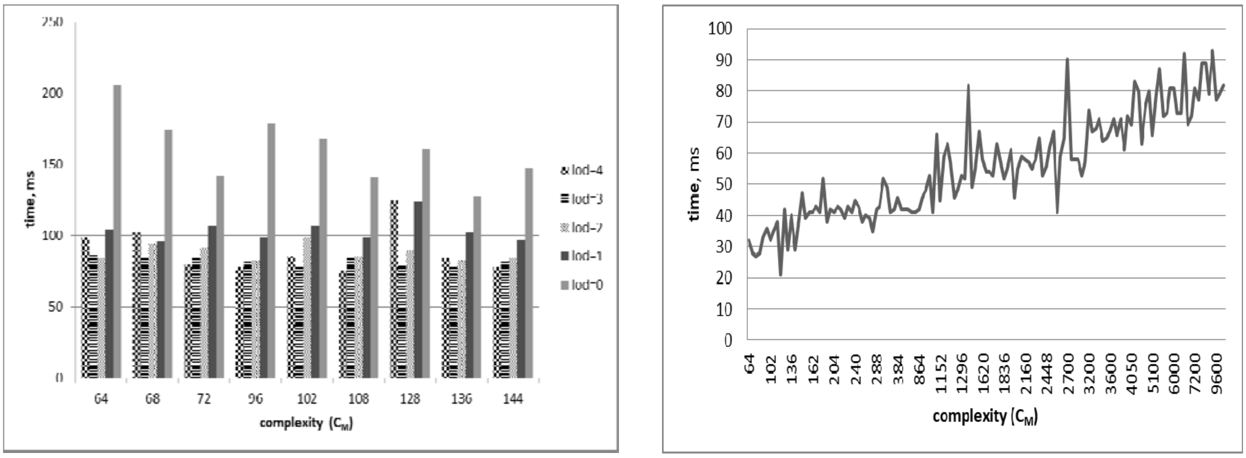
Visualization type	**Average time for segment (µs)**	**Maximum time (µs) for the segment and the corresponding parameters at which it is achieved**						**The minimum time (µs) for the segment and the corresponding parameters at which it is achieved**					
	$time_{avg}$	$time_{max}$	C_M	*d*	*r*	*ch*	*lod*	$time_{min}$	C_M	*d*	*r*	*ch*	*lod*
Without the containerization cache use	68424	205935	192	4096	512	1	0	75084	108	4608	768	1	4
RAM cache	16	52	162	4096	1024	1	3	2	1600	4096	512	25	4
Hard drive cache	9133	98943	192	4352	1024	1	0	895	3400	4352	1024	25	4



a b c

Figure 9 – Examples of visualization:
a – anthropogenic and natural objects in the LandscapeGen program window; b – relief of Bezier surfaces; c – visualization of the urban landscape adapted to a relief (16 curves per segment, Perlin noise smoothing factor 500)

DOI 10.15588/1607-3274-2022-2-15



a b

Figure 10 – Generation time dependency on the complexity of objects:
a – for one segment without the use of caching; b – for one or more segments with RAM caching

6 DISCUSSION

The obtained results of the LandscapeGen software system confirm the effectiveness of the developed method of visualization using containerization.

The average rendering time for hard disk caching experiments is about seven times shorter than the rendering time without caching. At the same time, using cache in RAM reduces rendering time by about 500 times compared to hard disk caching.

Most time is spent on non-caching cases for a minimum level of detail. Moreover, for insignificant values of complexity (up to 144), caching gives an advantage of 4 times the display time (Fig. 7, a, b).

A dramatic increase in the complexity of the visualization model does not significantly affect the visualization time of one segment (Fig. 7, b). In the case of using caching, increasing the complexity of the visualization model by 150 times increases the time only by three. Therefore, the system scales well with different complexity of visualization models.

The proposed method efficiently stores and loads three-dimensional objects, which is especially important to consider the trends of increasing the volume of three-dimensional scenes and growing requirements for detailing objects.

CONCLUSIONS

A unique feature of the developed software system LandscapeGen is the generation of three-dimensional objects with different levels of detail based on software agents, taking into account the characteristics of the landscape. The architecture of the system allows expanding the functionality of the system further.

The scientific novelty of the obtained results lies in developing a method for landscapes surfaces generation, which allows controlling the quantitative and qualitative indicators of modelling, resulting in increased realism of the display result and productivity of the visualization process at different levels of detail.

The practical significance of obtained results lies in developing a software system for the automatic generation of natural and anthropogenic landscapes. The obtained visualizations can be used as a basis for further creation of virtual landscapes, video, photo, and game materials by landscape designers, artists, developers of virtual worlds.

Prospects for further research are the development of algorithms for the procedural generation of natural landscapes, particularly the addition of all ecosystems and appropriate algorithms for adaptation to natural landscapes.

ACKNOWLEDGEMENTS

This paper uses the results obtained by the authors in 2019–2021 at the Department of Software of the National University "Lviv Polytechnic". The authors are grateful to the department's teaching staff for their active participation in the discussion and support of the scientific circle "Algorithms and software of computer graphics systems", understanding of the importance of applied research of geometric modeling theory for computer graphics systems. Practical results of the research are received within the limits of performance of complex bachelor's qualification work by graduates of the department – Morozov M., Pustelnyk P., Moravskyi R. under the direction of the senior lecturer Levus Ye. V. The results of research by Morozov M. Yu. were taken into account for the DAAD Study Scholarship – Master Studies for All Academic Disciplines, 2021/22.

All authors state that they do not receive financial support to conduct research on this topic.

REFERENCES

1. Doran J., Parberry I. Controlled Procedural Terrain Generation Using Software Agents, *IEEE Transactions on Computational Intelligence and AI in Games*, 2010, Vol. 2(2), pp. 111–119. DOI: 10.1109/TCIAIG.2010.2049020
2. Morozov M. Yu., Levus Ye. V., Moravskyj R. O., Pustelnyk P. Ya. Heneruvania landshaftiv dlia cferychnykh poverkhon: analiz zavdannia ta variant vyrishennia, *Naukovui visnyk NLTU Ukraiiny,* 2020, Vol. 30. No. 1, pp. 136–141. DOI: 10.36930/40300124
3. Biljecki F., Kumar K., Nagel C. CityGML Application Domain Extension (ADE): overview of developments, *In: Open Geospatial Data, Software and Standards 3.1* (Dec. 2018), P. 13. DOI: 10.1186/s40965- 018 - 0055 - 6

DOI 10.15588/1607-3274-2022-2-15

4. Gavin S. P. Muller. The definition and rendering of terrain maps/ Gavin S. P. Muller// *ACM SIGGRAPH Computer Graphics*, 1986, Vol. 20, No. 4, pp. 39–48. DOI:10.1145/15886.15890
5. Ebner H., Reinhardt W., and Hobler R. Generation, Management and Utilization of High Fidelity Digital Terrain Models, *XVIth ISPRS Congress Technical Commission III: Mathematical Analysis of Data Supplements*, 1988, Kyoto, Japan, 27(B11), pp. 556–566.
6. Brasebin M. S. Christophe, F. Jacquinod, A. Vinesse, and H. Mahon.3D Geovisualization & Stylization to Manage Comprehensive and Participative Local Urban Plans, *In: ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences IV–2/W1*, October (2016), pp. 83–91. DOI: 10.5194/isprs-annals- IV-2- W1-83-2016.
7. Cherradi G., El Bouziri A., Boulmakoul A., and Zeitouni K. Real-Time HazMat Environmental Information System: A micro-service based architecture, *In: Procedia Computer Science,* 109.June (2017), pp. 982–987. DOI: 10.1016/j.procs.2017.05.457
8. Merino L., Fuchs J., Blumenschein M., Anslow C., Ghafari M., Nierstrasz O., Behrisch M., Keim D.A. On the impact of the medium in the effectiveness of 3D software visualizations, *IEEE Working Conference on Software Visualization (VISSOFT).* Shanghai, China, 2017, pp. 11–21. DOI: 10.1109/VISSOFT.2017.17
9. Teng E., Bidarra R. A semantic approach to patch-based procedural generation of urban road networks, *FDG '17: 12th International Conference on the Foundations of Digital Games, August 2017, proceedings*, pp. 1–10.
10. Burch M., Wallner G., Arends S. T. T. and Beri P. Procedural City Modeling for AR Applications, *24th International Conference Information Visualizations (IV),* 2020, pp. 581–586. DOI: 10.1109/IV51561.2020.00098
11. Zhang X., Zhong M, Liu S, Zheng L, Chen Y., Zhang X, Zhong M, Liu S, Zheng L, Chen Y. Template-Based 3D Road Modeling for Generating Large-Scale Virtual Road Network Environment, *ISPRS International Journal of Geo-Information*, 2019, 8(9):364. DOI: 10.3390/ijgi8090364
12. Kelly G. and McCabe H. Citygen: An interactive system for procedural city generation, *In Fifth International Conference on Game Design and Technology*, 2007, pp. 8–16.
13. Dinkov D., Vatseva R.3D modelling and visualization for landscape simulation, *Proceedings of the 6th International Conference on Cartography and GIS.* Albena, 2016, pp. 320–333.
14. Klimke J. Döllner J. Service-oriented Visualization of Virtual 3D City Models, Directionsmag.com. [Electronic resource]. Access mode: 2012. URL: https://www.directionsmag.com/article/1873
15. Object Container Streaming, *Star Citizen,* 2021. URL: https://starcitizen.tools/Object_Container_Streaming
16. Bushnaief J., Czatrowski P. Solving Visibility and Streaming in The Witcher 3: Wild Hunt with Umbra 3, *GDC Vault.* 2014. URL: www.gdcvault.com (data zvernennja: 22.2.2021).
17. Level Streaming Overview // Unreal Engine. 2021. URL: https://docs.unrealengine.com/en-US/BuildingWorlds/LevelStreaming/Overview/index.html.

Received 01.11.2021.
Accepted 16.02.2022.

УДК 004.925

АЛГОРИТМИ ТА АРХІТЕКТУРА ПРОГРАМНОЇ СИСТЕМИ АВТОМАТИЗОВАНОЇ ГЕНЕРАЦІЇ ПРИРОДНІХ ТА АНТРОПОГЕННИХ ЛАНШАФТІВ

Левус Є. В. – канд. техн. наук, доцент кафедри програмного забезпечення Національного університету «Львівська політехніка», Львів, Україна.

Морозов М. Ю. – магістрант кафедри інформатики Мюнхенського технічного університету, Мюнхен, Німеччина.

Моравський Р. О. – магістрант кафедри програмного забезпечення Національного університету «Львівська політехніка», Львів, Україна.

Пустельник П. Я. – магістрант кафедри програмного забезпечення Національного університету «Львівська політехніка», Львів, Україна.

АНОТАЦІЯ

Актуальність. Розглянуто задачу автоматизації генерування природніх та антропогенних ландшафтів. Предметом дослідження є процедурні методи генерації ландшафту, що швидко та реалістично візуалізують об’єкти з врахуванням різних рівнів деталізації. Мета роботи – підвищення якості відображення та ефективності процесу генерації ландшафту поверхонь при будь-якому рівні деталізації.

Метод. Запропонований метод візуалізації передбачає побудову природнього ландшафту з допомогою кривих та поверхонь Без’є та ручне редагування окремих сегментів; використання програмних агентів, які відповідають за окремі кроки генерації антропогенних об’єктів; адаптацію антропогенних об’єктів до характеристик природніх ландшафтів; контейнеризацію тривимірних об’єктів, що використовується на різних кроках для ефективної організації збереження та завантаження об’єктів. Для побудови поверхонь на окремих сегментах природнього ландшафту використовується згенерована карту висот на основі алгоритму шуму Перлина. Програмні агенти для обробки ландшафту застосовуються для уніфікації побудови алгоритмів створення та обробки інформації про антропогенні об’єкти. Завдяки успадкуванню конкретного інтерфейсу усіма реалізаціями агентів, гарантується коректна робота застосунку та стійкість до помилок. Ефективність деталізації відображення забезпечується контейнеризацією з дворівневим кешуванням.

Результати. Розроблений метод реалізовано програмно і досліджено його ефективність для різних варіантів вхідних даних, що у найбільшій мірі визначають складність об’єктів візуалізації.

Висновки. Проведені експерименти підтвердили працездатність запропонованого алгоритмічного забезпечення і дозволяють рекомендувати його для використання на практиці при вирішенні задач автоматизованої генерації ландшафтів. Перспективи подальших досліджень можуть полягати у вдосконаленні та розширенні алгоритмів процедурного генерування ландшафту, функціоналу ручного опрацювання, розділенні окремих об’єктів на ієрархії контейнерів.

КЛЮЧОВІ СЛОВА: візуалізація об’єктів, сегмент, рівень деталізації, криві Без’є, програмний агент, контейнеризація.

УДК 004.925

АЛГОРИТМЫ И АРХИТЕКТУРА ПРОГРАММНОЙ СИСТЕМЫ АВТОМАТИЗИРОВАННОЙ ГЕНЕРАЦИИ ПРИРОДНЫХ И АНТРОПОГЕННЫХ ЛАНДШАФТОВ

Левус Е. В. – канд. техн. наук, доцент кафедры программного обеспечения Национального университета «Львовская политехника», Львов, Украина.

DOI 10.15588/1607-3274-2022-2-15

Морозов М. Ю. – магистрант кафедры информатики Мюнхенского технического университета, Мюнхен, Германия.

Моравский Р. О. – магистрант кафедры программного обеспечения Национального университета «Львовская политехника», Львов, Украина.

Пустельнык П. Я. – магистрант кафедры программного обеспечения Национального университета «Львовская политехника», Львов, Украина.

АННОТАЦИЯ

Актуальность. Рассмотрена задача автоматизации генерирования природных и антропогенных ландшафтов. Предметом исследования являются процедурные методы генерации ландшафта, быстро и реалистично визуализирующих объекты с учетом разных уровней детализации. Цель работы – повышение качества отражения и эффективности процесса генерации ландшафта поверхностей при любом уровне детализации.

Метод. Предложенный метод визуализации предполагает построение природного ландшафта с помощью кривых и поверхностей Безье и ручное редактирование отдельных сегментов; использование программных агентов, отвечающих за отдельные шаги по генерации антропогенных объектов; адаптацию антропогенных объектов к характеристикам природных ландшафтов; контейнеризацию трехмерных объектов, которая используется на разных шагах для эффективной организации хранения и загрузки объектов. Для построения поверхностей на отдельных сегментах природного ландшафта используется сгенерированная карта высот на основе алгоритма шума Перлина. Программные агенты для обработки ландшафта применяются для унификации построения алгоритмов создания и обработки информации об антропогенных объектах. Благодаря наследованию конкретного интерфейса всеми реализациями агентов гарантируется корректная работа приложения и устойчивость к ошибкам. Эффективность детализации отображения обеспечивается контейнеризацией с двухуровневым кэшированием.

Результаты. Разработанный метод реализован программно, исследовано его эффективность для различных вариантов входных данных, в наибольшей степени определяющих сложность объектов визуализации.

Выводы. Проведенные эксперименты подтвердили работоспособность предлагаемого алгоритмического обеспечения и позволяют рекомендовать его для использования на практике при решении задач автоматизированной генерации ландшафтов. Перспективы дальнейших исследований могут заключаться в совершенствовании и расширении алгоритмов процедурного генерирования ландшафта, функционала ручной проработки, разделении отдельных объектов на иерархии контейнеров.

КЛЮЧЕВЫЕ СЛОВА: визуализация объектов, сегмент, уровень детализации, кривые Безье, программный агент, контейнеризация.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Doran J. Controlled Procedural Terrain Generation Using Software Agents / J. Doran, I. Parberry // IEEE Transactions on Computational Intelligence and AI in Games. – 2010. – Vol. 2 (2). – P. 111–119. DOI: 10.1109/TCIAIG.2010.2049020
2. Heneruvania landshaftiv dlia cferychnykh poverkhon: analiz zavdannia ta variant vyrishennia / M. Yu. Morozov, Ye. V. Levus, R. O. Moravskyj et al.] // Naukovui visnyk NLTU Ukraiiny. – 2020. – Vol. 30, № 1. – P. 136–141. DOI: 10.36930/40300124
3. Biljecki F. CityGML Application Domain Extension (ADE): overview of developments / F. Biljecki, K. Kumar, C. Nagel // In: Open Geospatial Data, Software and Standards 3.1 (Dec. 2018). – P. 13. DOI: 10.1186/s40965- 018 - 0055 - 6
4. Gavin S. P. Muller. The definition and rendering of terrain maps / Gavin S. P. Muller // ACM SIGGRAPH Computer Graphics – 1986. – Vol. 20, № 4. – P. 39–48. DOI:10.1145/15886.15890
5. Ebner H. Generation, Management and Utilization of High Fidelity Digital Terrain Models / H. Ebner, W. Reinhardt, and R. Hobler // XVIth ISPRS Congress Technical Commission III: Mathematical Analysis of Data Supplements. – 1988, Kyoto, Japan. – 27(B11). – P. 556–566.
6. 3D Geovisualization & Stylization to Manage Comprehensive and Participative Local Urban Plans / [M. Brasebin, S. Christophe, F. Jacquinod et al.] // In: ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences IV–2/W1. – October (2016). – P. 83–91. DOI: 10.5194/isprs-annals- IV-2- W1-83-2016.
7. Real-Time HazMat Environmental Information System: A micro-service based architecture / [G. Cherradi, A. El Bouziri, A. Boulmakoul, and K. Zeitouni] // In: Procedia Computer Science. – 2017. – 109.June – P. 982–987. DOI: 10.1016/j.procs.2017.05.457
8. On the impact of the medium in the effectiveness of 3D software visualizations / [L. Merino, J. Fuchs, M. Blumenschein et al.] // IEEE Working Conference on Software Visualization (VISSOFT). – Shanghai, China, 2017. – P. 11–21. DOI: 10.1109/VISSOFT.2017.17
9. Teng E. A semantic approach to patch-based procedural generation of urban road networks / Edward Teng Rafael Bidarra // FDG '17: 12th International Conference on the Foundations of Digital Games, August 2017 : proceedings – P. 1–10.
10. Procedural City Modeling for AR Applications/ [M. Burch, G. Wallner, S. T. T. Arends and P. Beri] // 24th International Conference Information Visualizations (IV). – 2020. – P. 581–586. DOI: 10.1109/IV51561.2020.00098
11. Template-Based 3D Road Modeling for Generating Large-Scale Virtual Road Network Environment / [X. Zhang, M. Zhong, S. Liu et al.] // ISPRS International Journal of Geo-Information. – 2019. – 8(9):364. DOI: 10.3390/ijgi8090364
12. Kelly G. Citygen: An interactive system for procedural city generation / G. Kelly and H. McCabe // In Fifth International Conference on Game Design and Technology. – 2007. – P. 8–16.
13. Dinkov D. 3D modelling and visualization for landscape simulation / D. Dinkov, R. Vatseva // Proceedings of the 6th International Conference on Cartography and GIS. – Albena. – 2016. – P. 320–333.
14. Klimke J. Service-oriented Visualization of Virtual 3D City Models / J. Klimke, J Döllner // Directionsmag.com. [Electronic resource]. – Access mode: 2012. URL: https://www.directionsmag.com/article/1873
15. Object Container Streaming // Star Citizen. 2021. URL: https://starcitizen.tools/Object_Container_Streaming
16. Bushnaief J. Solving Visibility and Streaming in The Witcher 3: Wild Hunt with Umbra 3 / J. Bushnaief, P. Czatrowski // GDC Vault. 2014. URL: www.gdcvault.com (дата звернення: 22.2.2021).
17. Level Streaming Overview // Unreal Engine. 2021. URL: https://docs.unrealengine.com/en-US/BuildingWorlds/LevelStreaming/Overview/index.html.

DOI 10.15588/1607-3274-2022-2-15

UDC 004.056

EFFECTIVENESS OF STEGO IMAGE CALIBRATION VIA FEATURE VECTORS RE-PROJECTION INTO HIGH-DIMENSIONAL SPACES

Progonov D. O. – PhD, Associate Professor, Associate Professor of the Department of Information Security, Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine.

ABSTRACT

Context. The topical problem of sensitive information protection during data transmission in local and global communication systems was considered. The case of detection of stego images formed according to novel steganographic (embedding) methods was analyzed. The object of research is special methods of stego images features pre-processing (calibration) that are used for improving detection accuracy of modern statistical stegdetectors.

Objective. The purpose of the work is performance analysis of applying special types of image calibration methods, namely divergent reference techniques, for revealing stego images formed according to adaptive embedding methods.

Method. The considered divergent reference methods are aimed at search an appropriate transformation for cover and stego images features that allows increasing Euclidean distance between them. This can be achieved by re-projection of estimated features into a high-dimensional space where cover and stego features may have higher inter-cluster distances. The work is devoted to analysis of such methods, namely by applying the inverse Fast Johnson-Lindenstrauss transform for estimation preimages of cover and stego images features. The transform allows considerably decreasing computation complexity of features calibration procedure while providing a fixed level of relative positions changes for cover and stego images features vectors, which is of particular interest in steganalysis.

Results. The dependencies of detection accuracy, namely Matthews correlation coefficient, on cover image payload and dimensionality of estimated preimages for feature vector were obtained. The case of usage state-of-the-art HUGO, S-UNIWARD, MG and MiPOD embedding methods for message hiding into a cover image was considered. Also, the variants of stego image features pre-processing by full access to stego encoder for a steganalytic as well as limited a prior information about used embedding method were analyzed.

Conclusions. The obtained experimental results proved effectiveness of proposed approach in the most difficult case of limited a prior information about used embedding method and low cover image payload (less than 10%). The prospects for further research may include investigation of applying special methods for features preimages estimation in a high-dimensional space for improving detection accuracy for advanced embedding methods.

KEYWORDS: digital image steganalysis, adaptive embedding method, image calibration, dimensionality reduction.

ABBREVIATIONS

ASM is an adaptive steganographic method;
CI is a cover image;
CNN is a convolutional neural network;
DI is a digital image;
DR is the divergent reference calibration method;
FJLT is the Fast Johnson-Lindenstrauss transform;
GMM is the Gaussian Mixture model;
HPF is a high-pass filter;
JLL is the Johnson-Lindenstrauss lemma;
MCC is the Matthews correlation coefficient;
SD is a stegdetector;
SI is sensitive information.

NOMENCLATURE

Δ_p is a cover image payload;

$\rho_{ij}(\cdot)$ is a cost function for estimation CI alteration due to individual stego bit hiding into $(i,j)^{th}$ pixel of CI;

u, v, w are weights;

$C(\cdot)$ is an image calibration operator;

C is the set of three-elements cliques for four-pixels adjacency directions;

D is an array of differences between adjacency pixels values;

$D(X,Y)$ is an empirical distortion estimation function;

$\Im$ represents brightness range for 8-bits grayscale image;

k is the number of parameters for the SPAM model;

M is a binary message to be embedded;

$\mathbf{M}^a$, $\mathbf{M}^b$ are adjacency matrices for Markov model by scanning grayscale image from left-bottom to right-top and from right-top to left-bottom directions respectively;

$\mathbf{M}^c$, $\mathbf{M}^d$ are adjacency matrices for Markov model by scanning grayscale image from left-top to right-bottom and from right-bottom to left-top directions correspondingly;

P_e is the detection error;

P_{FA} is the probability of false alarm during detection (assignment cover image as stego one);

P_{MD} is the probability of missed detection (assignment of stego image as cover one);

T is a threshold;

X is a cover image;

Y is a stego image;

$\Pr(a)$ is the probability of event a.

INTRODUCTION

Ensuring the reliable protection of sensitive information, which is processed in the critical information infrastructure of public institutions and private organizations, is extremely important and urgent task today. Particular attention is paid to counteracting to SI

DOI 10.15588/1607-3274-2022-2-16

leakage during data exchange in communication systems, in particular the detection of latent (steganographic) transmission of SI embedded in multimedia cover files, such as digital images [1, 2]. The solution of this problem is significantly complicated by the widespread usage of attackers the advanced adaptive steganographic methods. The feature of these methods is the minimization of cover image statistical parameters alteration during message embedding, which leads to a significant reduction of modern stegdetectors accuracy.

The object of study is methods for revealing of stego images according to modern ASM. These methods are based on analysis of differences between statistical, spectral and structural parameters of the current DI and available examples of cover or stego images.

Ensuring high accuracy of stego images detection requires usage enormous ensembles of high-pass filters in order to detect weak (anomalous) changes in statistical, spectral and structural parameters of the CI, caused by stegodata embedding. The high complexity of the formation of these ensembles to minimize a stego image detection error in the case of limited a priori data about used ASM determines the urgency of the problem of finding pre-processing (calibration) methods of DI that can reliably detect weak distortions of CI.

The subject of study is methods for DI calibration aimed at detecting weak changes of image's parameters alterations caused by message hiding according to ASM.

Given the mentioned limitations of usage ensembles of HPF to detect stego images formed according to the advanced ASM, it is of interest to investigate the effectiveness of special calibration methods usage. In particular, there is presented limited information in the literature about calibration methods aimed at increasing the distance between the multidimensional vectors (statistical parameters) of cover and stego images [3]. These methods allow increasing the differences between the statistical parameters of the cover and formed stego images without the need to use compute-intensive procedures for high-frequency filtering of a DI in order to extract components that are usually used for message hiding.

The purpose of the work is performance analysis of applying special types of image calibration methods to improve the detection accuracy for stego images formed according to ASM.

1 PROBLEM STATEMENT

For a given set of cover $\mathbf{X}_i$ and stego $\mathbf{Y}_i$ images $(\mathbf{X}_i, \mathbf{Y}_i) \in \Im^{M \cdot N}$, $i \in [1; Q]$ the task of stegdetector training can be presented as the optimization problem [4, 5]:

$$P_e = \min_{P_{FA}} \left(P_{FA} + P_{MD}\left(P_{FA}\right) \right) / 2 . \quad (1)$$

Solving of (1) is done under constrain of applying to images a predefined image calibration transformation $C(\cdot)$: $\Im^{M \cdot N} \to \Im^{M \cdot N}$.

Selection of calibration transformation $C(\cdot)$ should be done according to known a priori information about used embedding method. Nevertheless, this information is limited or even absent in most cases. Therefore, the choice of appropriate transformation $C(\cdot)$ that allows solving problem (1) in case of limited a priori information about steganographic method remains an open question.

The work is devoted to performance analysis of usage special types of image calibration methods that are based on image's vectors (statistical features) preimages estimation into a high-dimensional space in order to emphasize differences between features of cover and stego images.

2 REVIEW OF THE LITERATURE

The feature of advanced methods for message embedding into a cover image is preserving minimal impact on cover's statistical features [4, 5]. This is achieved by carefully selection of cover's pixels to be altered with usage of empirical functions D(**X**,**Y**) for estimation cover image alterations. Detection of these alterations is non-trivial task due to limited information about used functions D(**X**,**Y**). Therefore, special attention is paid on images pre-processing (calibration) methods that allow revealing mentioned alterations for further analysis.

One of most effective methods for image calibration was proposed for SRM statistical model of a cover image [6]. Feature of such methods is usage of redundant set of HPF for image's context suppression. Despite high detection accuracy, practical usage of SRM-based models is limited due to high computation complexity and necessity to update set of HPF for minimization stego image detection error for each embedding method.

Further evolution of SRM-based model is applying of modern convolutional neural networks for learning appropriate filters (convolutional kernels) during SD tuning [7, 8]. Applying of well-known backpropagation method allows considerable reducing time-consuming manual selection of an appropriate HPF for minimization of detection error. In spite of CNN's high detection accuracy, they remain vulnerable to differences between statistical features of training and testing sets of DI (domain adaptation problem). Therefore, applying of computation-intensive transfer learning methods is required for prevention negative impact of this problem.

Given mentioned limitation of modern methods for DI calibration, it is of interest to use special types of image calibration methods, namely the divergent reference methods [3]. These methods are aimed at increasing the distance between the distributions of statistical parameters of cover and stego images by applying of an appropriate transformation for features vectors. Modern approaches to the design of such calibration methods require usage of a priori data about statistical parameters of cover and stego images in order to choose an appropriate transformation method [8, 9]. As a result, the presence of complete / partial overlap of clusters of vectors (statistical features) of cover/stego images leads to a significant reduction in the effectiveness of such calibration methods. To overcome this limitation, we proposed to use methods for image's

DOI 10.15588/1607-3274-2022-2-16

vectors (statistical features) preimages estimation from a high-dimensional space while preserving theirs relative positions. Therefore, the work is devoted to performance analysis of such approach to image calibration for improving performance of modern SD.

3 MATERIALS AND METHODS

The development of effective and computationally cheap image calibration methods requires review and classification of known approaches to solving this problem. This allows establishing the advantages and identifies limitations in the practical application of known calibration methods.

The classification of modern calibration methods for digital images was proposed in the work [3]:

1. Parallel reference – usage of calibration methods leads only to a parallel shift of vectors for cover and stego images, which does not increase the accuracy of the SD;
2. Divergent reference – aimed at enhancing the differences between cover and stego images by increasing distance metric between these vectors;
3. Eraser – as a result of usage of such methods the distance between vectors of cover/stego images considerably decreases, up to their full alignment;
4. Cover estimate – are aimed at estimation features of cover images from the current (noised) image. Correspondingly, applying of such methods preserves minimal changes of cover's images, while leads to considerable changes of stego ones;
5. Stego estimate – are aimed at detection and extraction image's alterations caused by message hiding. Therefore, usage of such methods preserves minimal changes of stego images, while features of cover image are changed significantly.

The schematic representation of the mutual positions of vectors corresponding to cover/stego statistical features by applying of considered calibration methods is shown in Fig. 1.

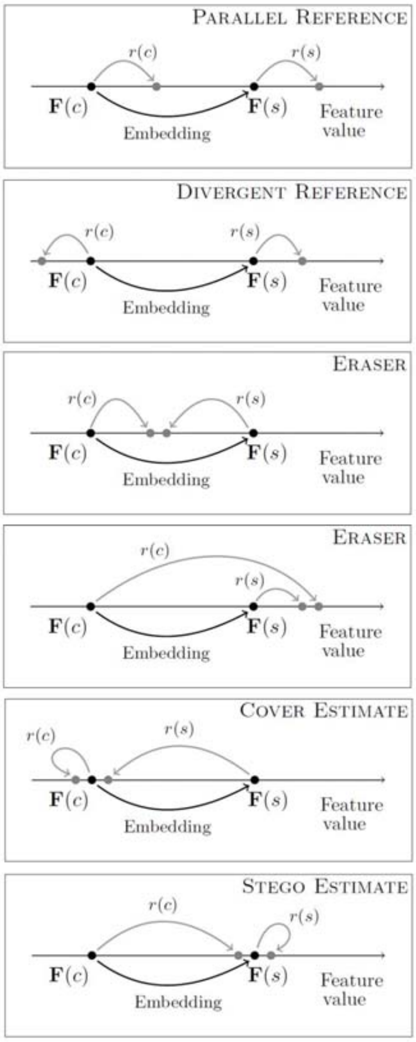


Figure 1 – Schematic representation of cover and stego images features shift caused by calibration methods applying. According to paper [3]

The calibration methods that relates to parallel reference and eraser cases are rarely used today due to considerable decreasing of stegdetector performance. The image calibration methods based on applying of ensembles of HPF are related to the stego estimation case due to detection and extraction of DI alterations caused by message hiding [10–12]. On the other hand, cover estimation calibration methods are not widely adopted in SD today due to theirs "aggressive" characters – removing both internal noise and alterations caused by message hiding [13].

In general, current researches of stego images calibration methods is aimed at finding methods belonging to the DR case (Fig. 1) – the search of methods that enhance the differences between features of cover/stego images, namely to cluster corresponding multidimensional vectors in different parts of the feature space. Therefore, these calibration methods make it possible to use simple (linear) methods of features classification and preserving low detection errors.

The DR-based calibration methods can be implemented by projections of the corresponding vectors from current to a higher dimension space. Thus, despite the relatively small differences between these vectors in the current space, their preimages from a higher dimension space may have significantly greater differences.

Therefore, it is represent the interest to investigate performance of modern methods for vectors re-projection into a higher dimension space. These methods can be represented as "inversion" of the well-known dimensionality reduction techniques that are aimed at preserving relative location of features. One of the most known methods for solving this task is based on Johnson-Lindenstrauss lemma concerning low-distortion embeddings of points from high-dimensional into low-dimensional Euclidean space [14]. The feature of JLL is preservation of projected clusters relevant structure that makes it promising method for wide range of dimensionality reduction technique. Also, the JLL is based on construction the projection matrix that can be

DOI 10.15588/1607-3274-2022-2-16

inverted with usage of Moore-Penrose method [15]. Therefore, the JLL can be adapted for the estimation of cover and stego images feature vectors preimages that take special interest for improving SD performance.

By the Johnson-Lindenstrauss lemma [16], n points in Euclidean space can be projected from the original d dimensions down to lower $k = O(\varepsilon^{-2}\cdot\log n)$ dimensions while just incurring a distortion of at most (±ε) in their pairwise distances, where $0<\varepsilon<1$. Based on the JLL, Alion and Chazelle [17, 18] proposed the Fast Johnson-Lindenstrauss transform for a low-distortion embedding of l_p^d into l_p^k (p equals 1 or 2).

The FJLT is based on preconditioning of a sparse projection matrix with a randomized Fourier transform. Note that we will only consider the l_2 case (p = 2) because of processing two-dimensional matrices of pixels brightness. For the l_1 case, please refer to [17].

The FJLT is denoted as $\mathbf{\Phi}_{JLT}$=FJLT(n, d, ε), that can be obtained as a product of three real-valued matrices:

$$\mathbf{\Phi}_{JLT} = \mathbf{P}_{JLT} \cdot \mathbf{H}_{JLT} \cdot \mathbf{D}_{JLT},$$

where matrices $\mathbf{P}_{JLT}$ and $\mathbf{D}_{JLT}$ are random and matrix $\mathbf{H}_{JLT}$ is deterministic [17, 18], namely:

– Matrix $\mathbf{P}_{JLT}$ is a k-by-d matrix whose elements P_{ij} are drawn independently from Normal distribution $N(0, q^{-1})$ with zero-mean and variance q^{-1} with probability q, and equal zeros with probability (q–1), where

$$q = \min\left\{c \log^2 n/d, 1\right\}$$

for a large enough constant c.

– Matrix $\mathbf{H}_{JLT}$ is d-by-d normalized Hadamard matrix with the elements as

$$H_{ij} = d^{-1/2}(-1)^{\langle i-1, j-1\rangle},$$

where $<i,j>$ is the dot-product of the m-bit vectors of (i,j) expressed in binary format.

– Matrix $\mathbf{D}_{JLT}$ is a d-by-d diagonal matrix, where each diagonal element D_{ii} is drawn independently from {–1, +1} with probability 0.5.

Therefore, the FJLT output is a k-by-d matrix, where d is the original dimension number of the data and k is the lower dimension number, which is set to be ($c'\varepsilon^{-2}\log n$). Here, n is the number of data points, ε is the distortion rate, and c' is a constant. Given any data point $\mathbf{X}$ from a d-dimension space, it is intuitively mapped to the data point $\mathbf{X}'$ at a lower k-dimension space by the FJLT and the distortion of their pairwise distances could be estimated with JLL [17, 18].

We considered usage of standard SPAM statistical model of DI for estimation images statistical features. The SPAM model is based on usage Markov chains theory for estimation cross-correlation of adjacent pixels brightness [19]. The calculation of SPAM-features starts by computation the difference array $\mathbf{D}$ by processing an image in row- and column-wise orders. For example, the array $\mathbf{D}$ for the case of row-wise processing (left-to-right pixels scanning) of the grayscale image $\mathbf{U}$ with size $M{\cdot}N$ pixels can be calculated as [19]:

$$\mathbf{D}^{\rightarrow}_{i,j} = \mathbf{U}_{i,j} - \mathbf{U}_{i,j+1},$$
$$\mathbf{U} \in \Im^{M\cdot N}, i \in [1; M], j \in [1; N-1].$$

Then, the array $\mathbf{D}$ is modelled with usage of first-order and second-order Markov processes that produces $\mathbf{F}_1$ and $\mathbf{F}_2$ features respectively [19]. For the considered example, it leads to:

$$\mathbf{M}^{\rightarrow}_{u,v} = \Pr\left(\mathbf{D}^{\rightarrow}_{i,j+1} = u \mid \mathbf{D}^{\rightarrow}_{i,j} = v\right),$$
$$\mathbf{M}^{\rightarrow}_{u,v,w} = \Pr\left(\mathbf{D}^{\rightarrow}_{i,j+2} = u \mid \mathbf{D}^{\rightarrow}_{i,j+1} = v, \mathbf{D}^{\rightarrow}_{i,j} = w\right),$$
$$u, v, w \in [-T; T], T \in \mathrm{N}.$$

If probabilities $\Pr\left(\mathbf{D}^{\rightarrow}_{i,j} = v\right)$ or $\Pr\left(\mathbf{D}^{\rightarrow}_{i,j+1} = v, \mathbf{D}^{\rightarrow}_{i,j} = w\right)$ are equal to zero, corresponding values $\mathbf{M}^{\rightarrow}_{u,v}$ and $\mathbf{M}^{\rightarrow}_{u,v,w}$ equal to zero as well. The same approach can be used for estimation $\mathbf{F}_1$ and $\mathbf{F}_2$ features for other scanning directions, namely $c \in \{\rightarrow, \leftarrow, \uparrow, \downarrow\}$.

Finally, estimated features $\mathbf{F}_1$ and $\mathbf{F}_2$ are averaged for decreasing dimensionality of SPAM-features. This procedure is based on the standard assumption that statistics in natural images are symmetric with respect to mirroring and flipping [19] is used. Thus, we can separately averaging matrices for horizontal, vertical and diagonal directions to form the final features:

$$\mathbf{F}_{1\ldots k} = \left(\mathbf{M}^{\rightarrow} + \mathbf{M}^{\leftarrow} + \mathbf{M}^{\uparrow} + \mathbf{M}^{\downarrow}\right)/4,$$
$$\mathbf{F}_{(k+1)\ldots 2k} = \left(\mathbf{M}^{a} + \mathbf{M}^{b} + \mathbf{M}^{c} + \mathbf{M}^{d}\right)/4.$$

Number of parameters for the first-order SPAM model is $k=(2T+1)^2$, while for the second-order one – $k=(2T+1)^3$.

4 EXPERIMENTS

Performance analysis of proposed method for images features DR-calibration was performed on ALASKA dataset [20]. The sub-set of 10,000 grayscale images with size 512·512 pixels was pseudo randomly chosen from the dataset. The case of message embedding into CI with usage of advanced adaptive embedding methods HUGO [21], S-UNIWARD [22], MG [23] and MiPOD [24] was considered. The CI payload Δ_p was changed in the following range – 3%, 5%, 10%, 20%, 30%, 40%, 50%.

The feature of considered embedding methods is minimization of total cost by a binary message $\mathbf{M} \in \{0,1\}^K$ hiding into a cover grayscale image X [25]:

$$D(\mathbf{X}, \mathbf{Y}) = \sum\nolimits_{i,j} \rho_{i,j}(\mathbf{X}, \mathbf{Y}) \xrightarrow{|\mathbf{M}|=const} \min. \qquad (2)$$

DOI 10.15588/1607-3274-2022-2-16

Ideally, cost function ρ(·) in (2) can estimate both CI alteration due to changing of individual pixel, and non-linear interaction between these changes [25]. The former estimation can be done with usage of widespread statistical models of CI [1], while the latter one requires compute-intensive analysis of pixels changes combinations that becomes intractable even for short messages **M** (about 100 bits) [25]. Therefore, the simplified function ρ(·) that estimate only CI distortions caused by individual stego bit embedding is used in most real cases.

The HUGO embedding method is based on minimization of CI distortion under constrains of message length by alteration of pixels brightness levels [21]. On the other hand, the S-UNIWARD method uses similar approach by manipulation of CI decomposition coefficients, obtained after two-dimensional discrete wavelet transformation [22]. In contrast, the MG and MiPOD embedding methods use Gaussian Mixture model for estimate statistical features of CI intrinsic noises [23, 24]. Usage of GMM allows both estimation alterations of CI statistical features caused by message hiding, and tracking of expected detection accuracy for formed stego images.

In most cases, selection of cover image pixels to be used during message embedding (2) is performed by heuristic rules. These rules assess noise level in a local neighborhood of $(i,j)^{th}$ pixel [25] that allows achieving close to state-of-the-art security of formed stego images and preserving computation effective optimization methods for cost estimation.

The stegdetector was tested according to cross-validation procedure by minimization of detection error P_e (1) [26]. The dataset was divided 10 times into training (70%) and testing (30%) sub-sets during cross-validation for estimation averaged values of P_e. The SD includes ensemble classifier with Fisher Linear Discriminant base learner [26] trained with second-order SPAM model [19] with threshold parameter T=3, leading to 686 features.

The SD performance significantly depends on fraction F_α of cover-stego images features pairs utilized during training stage [27]:

$$F_\alpha = \frac{\left|\left\{(\mathbf{X},\mathbf{Y}) : (\mathbf{X}_i,\mathbf{Y}_i), i \in S_{train}\right\}\right|}{\left|S_{train}\right|} \cdot 100\%, \qquad (3)$$

where S_{train} – set of images used during training of stegdetector; $\mathbf{Y}_i$ – stego images formed from the i^{th} cover image $\mathbf{X}_i$.

The F_α parameter varies from 0% (absent of cover-stego images pairs in training set) to 100% (training set consists only from cover-stego images pairs). The former case corresponds to the situation when steganalytic does not have access to stego encoder and may use only collected stego images. The latter one relates to the situation when steganalytics have access to stego encoder and they can generate a stego image for any CI.

The Matthews correlation coefficient was used as performance metric for trained SD [28]:

$$MCC = \frac{P_{TP} \cdot P_{TN} - P_{FP} \cdot P_{FN}}{\sqrt{N_{MCC}}}, \qquad (4)$$

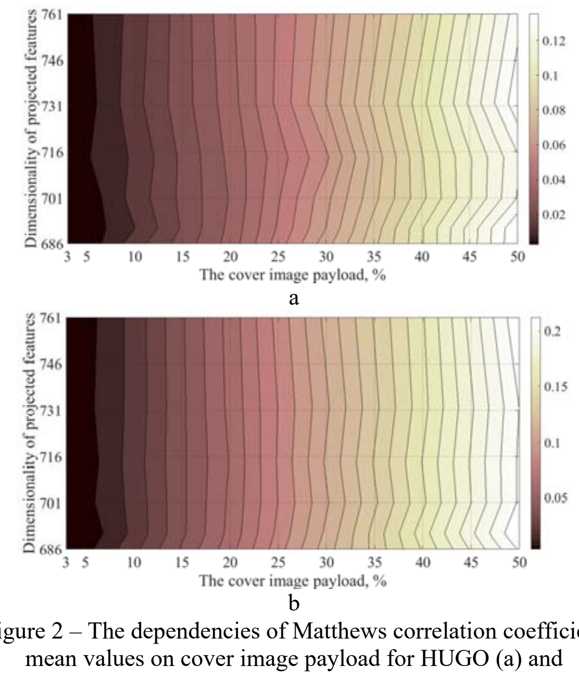
$$N_{MCC} = \left(P_{TP} + P_{FP}\right) \cdot \left(P_{TP} + P_{FN}\right) \times \times \left(P_{TN} + P_{FP}\right) \cdot \left(P_{TN} + P_{FN}\right),$$

where P_{TP}, P_{TN} are probabilities of correct classification of stego and cover images; P_{FP}, P_{FN} are probabilities of false alarm (misclassification of cover image as a stego one) and miss detection (misclassification of stego image as a cover one). The value of MCC index (4) varies from (–1), which corresponds to the case of incorrect classification of cover images as stego ones and vice versa, to (+1), which corresponds to the correct classification of both cover and stego images. The special case is value MCC = 0, which corresponds to the case of assigning the studied image to cover/stego images classes randomly (P_{FP}= P_{FN}).

The estimated features were calibrated with usage of inverse FJLT by increasing of features dimensionality up to 10% in comparison with initial SPAM features – from 686 to 761 with step of 5. The transformation matrix **T** for estimation preimages of features was performed with usage of Moore-Penrose procedure [29]. Due to stochastic nature of FJLT, the SD performance was estimated by 10 times generation of transformation matrix T and using of median values of detection error P_e (1).

5 RESULTS

After testing of stegdetector trained with initial and projected SPAM features the dependencies of MCC values on CI payload were plotted. The dependencies of MCC mean values on cover image payload for considered embedding methods HUGO, S-UNIWARD, MG and MiPOD for the case F_α=100% are presented at Fig. 2–3.

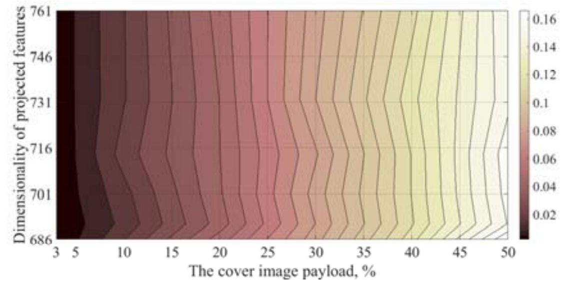


a

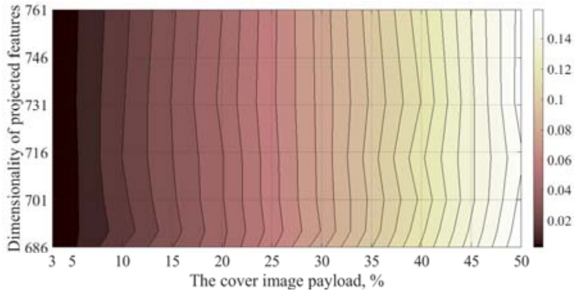
b

Figure 2 – The dependencies of Matthews correlation coefficient mean values on cover image payload for HUGO (a) and S-UNIWARD (b) embedding methods for the case F_α=100% on ALASKA dataset

DOI 10.15588/1607-3274-2022-2-16



a

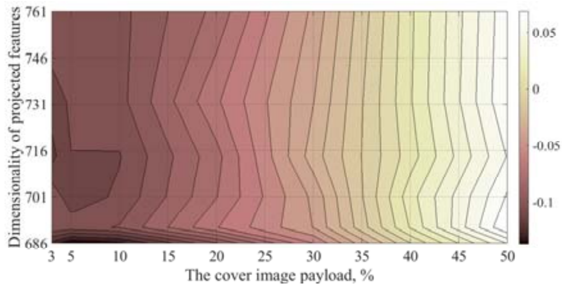


b

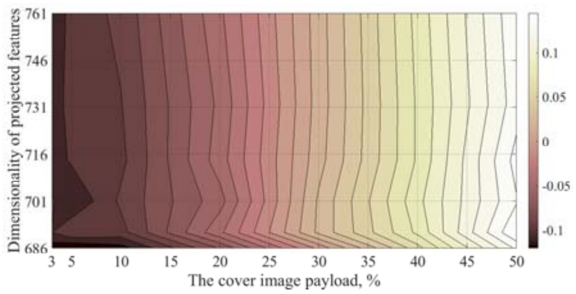
Figure 3 – The dependencies of Matthews correlation coefficient mean values on cover image payload for MG (a) and MiPOD (b) embedding methods for the case F_{α}=100% on ALASKA dataset

Usage of inverse transformation matrix $\mathbf{T}_{inv}$ leads to negligible changes of *MCC* index ($\Delta MCC < 10^{-3}$) for all considered embedding methods (Fig. 2–3). Therefore, we may conclude that usage of DR-features based on features projection into high-dimensional space does not allow improving detection accuracy of SD.

For comparison, the dependencies of MCC mean values on cover image payload for considered embedding methods HUGO, S-UNIWARD, MG and MiPOD for the case F_{α}=0% are presented at Fig. 4–5.

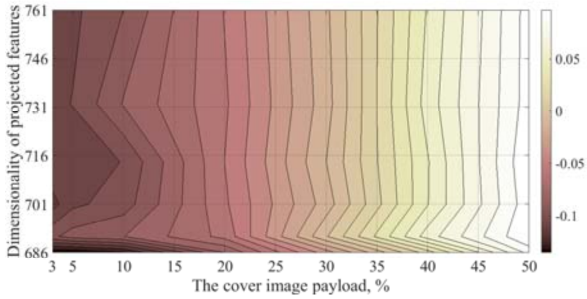


a

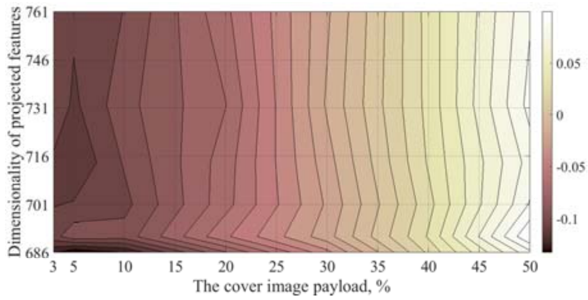


b

Figure 4 – The dependencies of Matthews correlation coeffi cient mean values on cover image payload for HUGO (a) and S-UNIWARD (b) embedding methods for the case F_{α}=0% on ALASKA dataset.



a



b

Figure 5 – The dependencies of Matthews correlation coefficient mean values on cover image payload for MG (a) and MiPOD (b) embedding methods for the case F_{α}=0% on ALASKA dataset.

In contrast to the previous case (Fig. 2–3), projection of SPAM-features into high-dimensional space allows improving values of *MCC* index (Fig. 4–5) even by negligible changes of inverse transformation matrix $\mathbf{T}_{inv}$ size. The biggest impact on *MCC* values was obtain for low (less than 10%) and medium (less than 20%) cover image payload – increasing dimensionality of used features allows increasing *MCC* index up to 0.04 for advanced MG (Fig. 5a) and MiPOD (Fig. 5b) embedding methods. On the other hand, changing of *MCC* for high cover image payload (more than 20%) by usage of inverse transformation matrix $\mathbf{T}_{inv}$ is much smaller ($\Delta MCC \le 2 \cdot 10^{-2}$).

6 DISCUSSION

Providing reliable detection of stego images formed according to advanced ASM requires utilization of huge ensembles of HPS [7]. This complicates tuning of stegdetectors due to necessity to time-consuming preselection of HPS for minimization detection errors. Proposed method of DR-calibration for analyzed images allows improving detection accuracy by search an appropriate transformation for increasing distance between clusters of estimated features for cover and stego images. In general case, the DR-calibration requires utilization of prior information about used embedding method for estimation mutual positions of these clusters. This makes such methods in appropriate candidates for real cases when steganalytics have limited or even no access to stego encoder.

Proposed DR-calibration method is based on inverse FJLT for estimations preimages of cover/stego statistical features from high-dimensional space. Usage of this method allows preserving similar detection accuracy for the case when steganalytics have full access to stego encoder (Fig. 2) and they can embed a payload for an arbi-

DOI 10.15588/1607-3274-2022-2-16

trary cover image. On the other hand, applying of inverse transformation matrix $\mathbf{T}_{inv}$ estimated by inverse FJLT allows improving detection accuracy ($\Delta MCC \leq 4 \cdot 10^{-2}$) in most difficult case of limited a prior information about used embedding method (Fig. 3) – the value F_α=0% (3) corresponds to the case of limited ability of steganalytics to form stego images for an arbitrary cover image.

Despite revealed effectiveness of applying of inverse FJLT, practical application of such method may require compute-intensive pre-processing step. This is connected with stochastic nature of transformation matrix **T** generation by FJLT [18] – the probability of successful generation (matrix T preserves mutual location of features clusters corresponds to cover/stego images) is at least 2/3. This is arisen from the features random projection by JLL and could be amplified to (1–δ) for any δ>0, if we repeat the construction O(log(1/ δ)) times [17].

Additional increasing of detection accuracy by usage of proposed approach can be achieved by preselection of generated inverse transformation matrix $\mathbf{T}_{inv}$ by the criterion of preserving same or increasing inter-distance between clusters of preimages for cover/stego images features. This can be achieved by corresponding increasing of procedure duration that may be critical for some applications, like fast re-tuning of SD.

Therefore, we may conclude that usage of proposed inverse FJLT allows improving detection accuracy for the most difficult cases of limited a prior information about embedding method (F_α=0%) and low cover image payload (less than 10%).

The future research directions may include comparative analysis of other methods for estimation features preimages in high-dimensional space, such as kernel principal component analysis (kernel-PCA) [30], multidimensional scaling [31], matrix completion scheme [32] to name a few. Also, it is represent the interest to estimate performance of proposed DR-calibration method in case of processing real digital images that characterized by high variability of statistical and spectral features.

CONCLUSIONS

The topical problem of improving accuracy for modern stegdetectors in case of processing stego images formed by adaptive embedding methods was considered. The case of applying special types of stego image calibration techniques was investigated.

The scientific novelty of obtained results is performance analysis of special types of digital image calibration, namely divergent reference methods. There is proposed to use inverse Fast Johnson-Lindenstrauss Transform that allows estimating preimages for image's feature from high-dimensional space for increasing Euclidean distances between features clusters correspond to cover/stego images. Proposed approach allows improving detection accuracy for novel embedding methods in the most difficult cases of limited a prior information about embedding method (F_α=0%) and low cover image payload (less than 10%). This allows improving performance of statistical stegdetectors for revealing stego images formed according to advanced embedding methods.

The practical significance of obtained experimental results is estimations of stego images detection error by usage of inverse FJLT. These results allow establishing achievable detection accuracy by usage of DR-based stego image calibration methods for state-of-the-art adaptive embedding methods HUGO, S-UNIWAR, MG and MiPOD.

Prospects for further research are to investigate effectiveness of special methods for features preimages estimation in high-dimensional space as well as performance analysis of DR-based stego image calibration methods by processing of real digital images that characterized by high variability of statistical features.

REFERENCES

1. Yaacoub J.-P. A., Salman O., Noura H. N., Kaaniche N., Chehab A., Malli M. Cyber-physical systems security: Limitations, issues and future trends, *Microprocessors and Microsystems*, 2020, Vol. 77. DOI: 10.1016/j.micpro.2020.103201.
2. Kaspersky Inc. Steganograph in attacks on industrial enterprises. Tech. report. Kaspersky Inc., Moscow, 2020. URL: https://ics-cert.kaspersky.com/publications/stegano-graphy-in-attacks-on-industrial-enterprises/
3. Kodovsky J., Fridrich J. Calibration revisited, *Multimedia and security: 11th ACM workshop, Princeton, 7–8 September, 2009, proceedings*. Princeton, ACM, 2009, pp. 63–74. – DOI: 10.1145/1597817.1597830.
4. Fridrich J. Steganography in Digital Media: Principles, Algorithms, and Applications. Cambridge, Cambridge University Press, 2009, 437 p. ISBN 978–0–521–19019–0. – DOI: 10.1017/CBO9781139192903.
5. Konachovych G., Progonov D., Puzyrenko O. Digital steganography processing and analysis of multimedia files. Kyiv, 'Tsentr uchbovoi literatury' publishing, 2018, 558 p. ISBN 978-617-673-741-4.
6. Fridrich J., Kodovsky J. Rich models for steganalysis of digital images, *IEEE Transactions on Information Forensics Security,* 2012, Vol. 7, pp. 868–882. DOI: 10.1109/TIFS.2012.2190402.
7. Boroumand M., Chen M., Fridrich J. Deep residual network for steganalysis of digital images, *IEEE Transactions on Information Forensics Security*, 2018, Vol. 14, pp. 1181–1193. – DOI: 10.1109/TIFS.2018.2871749.
8. Tabares-Soto R., Arteaga-Arteaga H. B., Bravo-Ortiz M. A., Mora-Rubio A., Arias-Garzón D., Alzate-Grisales J. A., Burbano-Jacome A. B., Orozco-Arias S., Isaza G., Ramos-Pollán R. GBRAS-Net: A Convolutional Neural Network Architecture for Spatial Image Steganalysis, *IEEE Access*, 2021, Vol. 9, pp. 14340–14350. DOI: 10.1109/ACCESS.2021.3052494.
9. Cohen A., Cohen A., Nissim N. ASSAF: Advanced and Slim StegAnalysis Detection Framework for JPEG images based on deep convolutional denoising autoencoder and Siamese networks, *Neural Networks*, 2020, Vol. 131, pp. 64–77. DOI: 10.1016/j.neunet.2020.-07.022.
10. Progonov D. O. Influence of digital images preliminary noising on statistical stegdetectors performance, *Radio Electronics, Computer Science, Control*, Vol. 1(56), 2021, pp. 184–193.

DOI 10.15588/1607-3274-2022-2-16

11. Progonov D. O. Effectiveness of stego images pre-noising with fractional noise for digital image steganalysis, *Applied Aspects of Information Technology*, 2021, Vol. 4, Issue 3, pp. 261–270. DOI: https://doi.org/10.15276/aait.03.2021.5
12. Progonov D. Statistical stegdetectors performance by message re-embedding, *Theoretical and Applied Cybersecurity*, 2021, Vol. 3, No. 1, pp. 5–14.
13. Progonov D.O. Detection Of Stego Images With Adaptively Embedded Data By Component Analysis Methods, *Advances in Cyber-Physical Systems (ACPS),* 2021, Vol. 6, No. 2, pp. 146–154.
14. Achlioptas D. Database-friendly random projections: Johnson–Lindenstrauss with binary coins, *Journal of Computer and System Sciences*, 2003, Vol. 66, Issue 4, pp. 671–687. DOI:10.1016/S0022-0000(03)00025-4.
15. Moore E. H. On the reciprocal of the general algebraic matrix, *Bulletin of the American Mathematical Society*, 1920, Vol. 26, Issue 9, pp. 394–95. DOI:10.1090/S0002-9904-1920-03322-7.
16. Dasgupta S., Gupta A. An elementary proof of a theorem of Johnson and Lindenstrauss, *Random Structures & Algorithms,* 2003, Vol. 22, pp. 60–65. DOI: 10.1002/rsa.10073.
17. Ailon N. B., Chazelle Approximate nearest neighbors and the fast johnson-lindenstrauss transform, *Proceedings of the 38th Annual Symposium on the Theory of Computing (STOC '06),* 2006, Seattle, USA, pp. 557–563. DOI: 10.1145/1132516.1132597.
18. Lv X., Wang Z. An Extended Image Hashing Concept: Content-Based Fingerprinting Using FJLT, *EURASIP Journal on Information Security,* 2009, Vol. 2009, 16 p. DOI: 10.1155/2009/859859.
19. Pevny T., Bas P., Fridrich J. Steganalysis by subtractive pixel adjacency matrix, *IEEE Transactions on Information Forensics Security*, 2010, Vol. 5, pp. 215–224. DOI: 10.1109/TIFS.2010.2045842.
20. Cogranne R., Gilboulot Q., Bas P. The alaska steganalysis challenge: A first step towards steganalysis, *Information Hiding and Multimedia Security, ACM workshop, Paris, 1–3 July, 2019: proceedings*. Paris, ACM Press, 2019, pp. 125–137. – DOI: 10.1145/3335203.3335726.
21. Filler T., Fridrich J. Gibbs construction in steganography, *IEEE Transactions on Information Forensics Security*, 2010. Vol. 5, pp. 705–720. DOI: 10.1109/TIFS.2010.2077629.
22. Holub V., Fridrich J. Designing Steganographic Distortion Using Directional Filters, *Information Forensic and Security, IEEE International Workshop, Tenerife, 2–5 December, 2012, proceedings*. Tenerife, IEEE, 2012. DOI: 10.1109/WIFS.2012.6412655.
23. Sedighi V., Fridrich J., Cogranne R. Content-adaptive pentary steganography using the multivariate generalized gaussian cover model, *Electronic Imaging, Media Watermarking, Security, and Forensics, The International Society for Optical Engineering, San Francisco, 24–26 January, 2015, proceedings*. San Francisco, SPIE, 2015. DOI: 10.1117/12.2080272.
24. Sedighi V., Cogranne R., Fridrich J. Content adaptive steganography by minimizing statistical detectability, *IEEE Transactions on Information Forensics Security,* 2015, Volume 11, pp. 221–234. DOI: 10.1109/TIFS.2015.2486744.
25. Filler T., Fridrich J. Design of adaptive steganographic schemes for digital images, *Electronic Imaging, Media Watermarking, Security, and Forensics: The Interna-tional Society for Optical Engineering, San Francisco, 24–26 January, 2011, proceedings.* San Francisco, SPIE, 2011. DOI: 10.1117/12.872192.
26. Kodovsky J., Fridrich J. Ensemble classifiers for steganalysis of digital media, *IEEE Transactions on Information Forensics Security*, 2012, Vol. 7, pp. 432–444. DOI: 10.1109/TIFS.2011.2175919.
27. Progonov D. Performance of Statistical Stegdetectors in Case of Small Number of Stego Images in Training Set, *IEEE Int. Conf. "Problems of Infocommunications Science and Technology*, 2020. Kharkiv, Ukraine. DOI: https://doi.org/10.1109/PICST51311.20-20.9467901.
28. Chicco D., Jurman G. The advantages of the Matthews correlation coefficient (MCC) over F1 score and accuracy in binary classification evaluation, *BMC Genomics volume*, 2020, Vol. 21, 13 p. DOI: 0.1186/s12864-019-6413-7.
29. Adi B.-I., Greville T. Generalized inverses: Theory and applications, 2nd edition, 2003. New York, NY, Springer. DOI: 10.1007/b97366. – ISBN 978-0-387-00293-4.
30. Honeine P., Richard C. Preimage problem in kernel-based machine learning, *IEEE Signal Processing Magazin,* 2011, Vol. 28, Issue 2, pp. 77–88. DOI: 10.1109/MSP.2010.939747.
31. Cox T. F., Cox M. A. A. Multidimensional Scaling, 2nd edition, ser. Monographs on Statistics and Applied Probability, 2020. London, Chapman and Hall / CRC. DOI: 10.1007/978-3-540-33037-0_14.
32. Yamanishi Y., Vert J.-P. Kernel matrix regression, Tech. Rep., Cornell University library, URL: http://arxiv.org/abs/q-bio/0702054v1, 2007.

Received 22.02.2022.
Accepted 20.03.2022.

УДК 004.056

ЕФЕКТИВНІСТЬ МЕТОДІВ ПОПЕРЕДНЬОЇ ОБРОБКИ СТЕГАНОГРАМ, ЗАСНОВАНИХ НА ВИЗНАЧЕННІ ПРООБРАЗУ ВЕКТОРІВ СТАТИСТИЧНИХ ПАРАМЕТРІВ ЗОБРАЖЕНЬ У ПРОСТОРІ ВИЩОЇ РОЗМІРНОСТІ

Прогонов Д. О. – канд. техн. наук, доцент, доцент кафедри інформаційної безпеки Національного технічного університету України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна.

АНОТАЦІЯ

Актуальність. Розглянуто актуальну проблему захисту конфіденційної інформації під час передачі даних у локальних та глобальних системах зв'язку. Досліджено випадок виявлення стеганограм, сформованих згідно новітніх адаптивних стеганографічних методів. Об'єктом дослідження є спеціальні методи обробки статистичних параметрів стеганограм, що використовуються для підвищення точності роботи сучасних статистичних стегодетекторів. Метою роботи є аналіз ефективності застосування спеціальних методів попередньої обробці цифрових зображень для підвищення точності виявлення стеганограм, сформованих з використанням адаптивних стеганографічних методів.

Метод. Розглянуто використання методів, спрямованих на збільшення евклідової відстані між векторами (статистичними параметрами) зображень-контейнерів та стеганограм шляхом визначення прообразів даних векторів з багатовимірних

DOI 10.15588/1607-3274-2022-2-16

просторів вищої розмірності. Для вирішення даної задачі запропоновано використовувати зворотнє перетворення Джонсона-Лінденштрауса. Запропонований метод дозволяє суттєво зменшити обчислювальну складність процедури попередньої обробки досліджуваних зображень при забезпеченні фіксованого рівня змін взаємного положення векторів, які відповідають зображенням-контейнерам та стеганограмам, що становить особливий інтерес при проведенні стегоаналізу.

Результати. Отримано залежності точності виявлення стеганограм, а саме коефіцієнта кореляції Метьюза, від ступеня заповнення зображення-контейнеру стегоданими при використанні запропонованого методу обробки зображень, а також формування стеганограм згідно новітніх стеганографічних методів HUGO, S-UNIWARD, MG та MiPOD. Визначено досяжні межі точності виявлення стеганограм при застосуванні запропонованого методу у найбільш складному випадку обмеженості апріорних даних щодо використаного стеганографічного методу.

Висновки. Результати проведених експериментальних досліджень підтвердили ефективність запропонованого підходу навіть у найбільш складному випадку проведення стегоаналізу, а саме обмеженості апріорних даних щодо використаного стеганографічного методу та низького ступеня заповнення зображення-контейнеру стегоданими (менше 10%). Подальший інтерес становить порівняльний аналіз ефективності використання спеціалізованих методів визначення прообразів векторів (статистичних параметрів) досліджуваних зображень з метою підвищення точності виявлення стеганограм, сформованих згідно новітніх стеганографічних методів.

КЛЮЧОВІ СЛОВА: стегоаналіз, цифрові зображення, адаптивні стеганографічні методи, методи попередньої обробки зображення, методи зменшення розмірності багатовимірних векторів.

УДК 004.056

ЭФФЕКТИВНОСТЬ МЕТОДОВ ПРЕДВАРИТЕЛЬНОЙ ОБРАБОТКИ СТЕГАНОГРАМ, ОСНОВАННЫХ НА ОПРЕДЕЛЕНИИ ПРООБРАЗОВ ВЕКТОРОВ СТАТИСТИЧЕСКИХ ПАРАМЕТРОВ ИЗОБРАЖЕНИЙ В ПРОСТРАНСТВЕ ВЫСШЕЙ РАЗМЕРНОСТИ

Прогонов Д. А. – канд. техн. наук, доцент, доцент кафедры информационной безопасности Национального технического университета Украины «Киевский политехнический институт имени Игоря Сикорского», Киев, Украина.

АННОТАЦИЯ

Актуальность. Рассмотрена актуальная проблема защиты конфиденциальной информации при передаче данных в локальных и глобальных системах связи. Исследован случай обнаружения стеганограмм, сформированных согласно новейшим адаптивным стеганографическим методам. Объектом исследования являются специальные методы обработки статистических параметров стеганограмм, направленные на повышение точности работы современных стегодетекторов. Целью работы является анализ эффективности применения специальных методов предварительной обработки цифровых изображений для повышения точности обнаружения стеганограмм, сформированных с использованием адаптивных стеганографических методов.

Метод. Рассмотрено использование методов, направленных на увеличение евклидового расстояния между векторами (статистическими параметрами) изображений-контейнеров и стеганограмм, путем определения прообразов данных векторов из пространств более высокой размерности. Для решения данной задачи предложено использовать обратное преобразование Джонсона-Линденштрауса. Предложенный метод позволяет существенно уменьшить вычислительную сложность процедуры предварительной обработки исследуемых изображений при обеспечении фиксированного уровня изменений взаимного положения векторов, соответствующих изображениям-контейнерам и стеганограммам, что представляет особый интерес при проведении стегоанализа.

Результаты. Получены зависимости точности обнаружения стеганограмм, а именно коэффициента корреляции Мэтьюса, от степени заполнения изображения-контейнера стегодаными при использовании предложенного метода обработки изображений, а также формирования стеганограмм согласно новейшим стеганографическим методам HUGO, S-UNIWARD, MG и MiPOD. Определены достижимые границы точности обнаружения стеганограмм при применении предлагаемого метода в наиболее сложном случае ограниченности априорных данных относительно использованного стеганографического метода.

Выводы. Результаты проведенных экспериментальных исследований подтвердили эффективность предлагаемого подхода даже в наиболее сложном случае проведения стегоанализа, а именно ограниченности априорных данных относительного использованного стеганографического метода и низкой степени заполнения изображения-контейнера стегоданными (менее 10%). Дальнейший интерес представляет сравнительный анализ эффективности применения специализированных методов определения прообразов векторов (статистических параметров) изучаемых изображений с целью повышения точности обнаружения стеганограмм, сформированных согласно новейшим стеганографическим методам.

КЛЮЧЕВЫЕ СЛОВА: стегоанализ, цифровые изображения, адаптивные стеганографические методы, методы предварительной обработки изображения, методы уменьшения размерности многомерных векторов.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Cyber-physical systems security: Limitations, issues and future trends / [J.-P. A. Yaacoub, O. Salman, H. N. Noura et al.] // Microprocessors and Microsystems. – 2020. – Vol. 77. DOI: 10.1016/j.micpro.2020.103201.
2. Kaspersky Inc. Steganograph in attacks on industrial enterprises. Tech. report. Kaspersky Inc., Moscow, 2020. – URL: https://ics-cert.kaspersky.com/publications/stegano-graphy-in-attacks-on-industrial-enterprises/
3. Kodovsky J. Calibration revisited / J. Kodovsky, J. Fridrich // Multimedia and security: 11th ACM workshop, Princeton, 7–8 September, 2009: proceedings. – Princeton: ACM, 2009. – P. 63–74. DOI: 10.1145/1597817.1597830.
4. Fridrich J. Steganography in Digital Media: Principles, Algorithms, and Applications / J. Fridrich. – Cambridge : Cambridge University Press, 2009. – 437 p. – ISBN 978–0–521–19019–0. – DOI: 10.1017/CBO9781139192903.
5. Конахович Г. Ф. Комп'ютерна стеганографічна обробка й аналіз мультимедійних даних / Г. Ф. Конахович, Д. О. Прогонов, О. Ю. Пузиренко – Київ : «Центр учбової літератури», 2018. – 558 с. ISBN 978-617-673-741-4.

DOI 10.15588/1607-3274-2022-2-16

6. Fridrich J. Rich models for steganalysis of digital images / J. Fridrich, J. Kodovsky // IEEE Transactions on Information Forensics Security. – 2012. – Vol. 7. – P. 868–882. – DOI: 10.1109/TIFS.2012.2190402.
7. Boroumand M. Deep residual network for steganalysis of digital images / M. Boroumand, M. Chen, J. Fridrich // IEEE Transactions on Information Forensics Security. – 2018. – Vol. 14. – P. 1181–1193. DOI: 10.1109/TIFS.2018.2871749.
8. GBRAS-Net: A Convolutional Neural Network Architecture for Spatial Image Steganalysis / [R. Tabares-Soto, H. B. Arteaga-Arteaga, M. A. Bravo-Ortiz et al.] // IEEE Access. – 2021. – Vol. 9. – pp. 14340–14350. – DOI: 10.1109/ACCESS.2021.3052494.
9. Cohen A. ASSAF: Advanced and Slim StegAnalysis Detection Framework for JPEG images based on deep convolutional denoising autoencoder and Siamese networks / A. Cohen, A. Cohen, N. Nissim // Neural Networks. – 2020. – Vol. 131. – P. 64–77. DOI: 10.1016/j.neunet.2020.-07.022.
10. Progonov D.O. Influence of digital images preliminary noising on statistical stegdetectors performance / D. O. Progonov // Radio Electronics, Computer Science, Control. – 2021. – Vol. 1(56). – P. 184–193.
11. Progonov D. O. Effectiveness of stego images pre-noising with fractional noise for digital image steganalysis / D. O. Progonov // Applied Aspects of Information Technology. – 2021. – Vol. 4, Issue 3. – P. 261–270. DOI: https://doi.org/10.15276/aait.03.2021.5
12. Progonov D. Statistical stegdetectors performance by message re-embedding / D. Progonov // Theoretical and Applied Cybersecurity. – 2021. – Vol. 3, No. 1. – P. 5–14.
13. Progonov D. O. Detection Of Stego Images With Adaptively Embedded Data By Component Analysis Methods / D. O. Progonov // Advances in Cyber-Physical Systems (ACPS). – 2021. – Vol. 6, No. 2. – P. 146–154.
14. Achlioptas D. Database-friendly random projections: Johnson–Lindenstrauss with binary coins / D. Achlioptas // Journal of Computer and System Sciences. – 2003. – Vol. 66, Issue 4. – P. 671–687. DOI:10.1016/S0022-0000(03)00025-4.
15. Moore E. H. On the reciprocal of the general algebraic matrix / E. H. Moore // Bulletin of the American Mathematical Society. – 1920. – Vol. 26, Issue 9. – P. 394–95. – DOI:10.1090/S0002-9904-1920-03322-7.
16. Dasgupta S. An elementary proof of a theorem of Johnson and Lindenstrauss / S. Dasgupta, A. Gupta // Random Structures & Algorithms. – 2003. – Vol. 22. – P. 60–65. DOI: 10.1002/rsa.10073.
17. Ailon N. Approximate nearest neighbors and the fast johnson-lindenstrauss transform / N. Ailon, B. Chazelle // Proceedings of the 38th Annual Symposium on the Theory of Computing (STOC '06). – 2006, Seattle, USA. – P. 557–563. DOI: 10.1145/1132516.1132597.
18. Lv X. An Extended Image Hashing Concept: Content-Based Fingerprinting Using FJLT / X. Lv, Z. Wang // EURASIP Journal on Information Security. – 2009. – Vol. 2009. – 16 p. DOI: 10.1155/2009/859859.
19. Pevny T. Steganalysis by subtractive pixel adjacency matrix / T. Pevny, P. Bas, J. Fridrich // IEEE Transactions on Information Forensics Security. – 2010. – Vol. 5. – P. 215–224. DOI: 10.1109/TIFS.2010.2045842.
20. Cogranne R. The alaska steganalysis challenge: A first step towards steganalysis / R. Cogranne, Q. Gilboulot, P. Bas // Information Hiding and Multimedia Security: ACM workshop, Paris, 1–3 July, 2019: proceedings. – Paris : ACM Press. – 2019. – P. 125–137. DOI: 10.1145/3335203.3335726.
21. Filler T. Gibbs construction in steganography / T. Filler, J. Fridrich // IEEE Transactions on Information Forensics Security. – 2010. – Volume 5. – P. 705–720. – DOI: 10.1109/TIFS.2010.2077629.
22. Holub V. Designing Steganographic Distortion Using Directional Filters / V. Holub, J. Fridrich // Information Forensic and Security: IEEE International Workshop, Tenerife, 2–5 December, 2012: proceedings. – Tenerife : IEEE, 2012. – DOI: 10.1109/WIFS.2012.6412655.
23. Sedighi V. Content-adaptive pentary steganography using the multivariate generalized gaussian cover model / V. Sedighi, J. Fridrich, R. Cogranne // Electronic Imaging, Media Watermarking, Security, and Forensics: The International Society for Optical Engineering, San Francisco, 24–26 January, 2015 : proceedings. – San Francisco : SPIE, 2015. DOI: 10.1117/12.2080272.
24. Sedighi V. Content adaptive steganography by minimizing statistical detectability / V. Sedighi, R. Cogranne, J. Fridrich // IEEE Transactions on Information Forensics Security. – 2015. – Vol. 11. – P. 221–234. DOI: 10.1109/TIFS.2015.2486744.
25. Filler T. Design of adaptive steganographic schemes for digital images / T. Filler, J. Fridrich // Electronic Imaging, Media Watermarking, Security, and Forensics: The International Society for Optical Engineering, San Francisco, 24–26 January, 2011 : proceedings – San Francisco : SPIE, 2011. DOI: 10.1117/12.872192.
26. Kodovsky J. Ensemble classifiers for steganalysis of digital media / J. Kodovsky, J. Fridrich // IEEE Transactions on Information Forensics Security. – 2012. – Vol. 7. – P. 432–444. DOI: 10.1109/TIFS.2011.2175919.
27. Progonov D. Performance of Statistical Stegdetectors in Case of Small Number of Stego Images in Training Set / D. Progonov // IEEE Int. Conf. "Problems of Infocommunications Science and Technology. – 2020. – Kharkiv, Ukraine. DOI: https://doi.org/10.1109/PICST51311.20-20.9467901.
28. Chicco D. The advantages of the Matthews correlation coefficient (MCC) over F1 score and accuracy in binary classification evaluation / D. Chicco, G. Jurman // BMC Genomics volume. – 2020. – Vol. 21. – 13 p. DOI: 0.1186/s12864-019-6413-7.
29. Adi B.-I. Generalized inverses: Theory and applications / B.-I. Adi, T. Greville – 2nd edition. – 2003. – New York, NY: Springer. DOI:10.1007/b97366. ISBN 978-0-387-00293-4.
30. Honeine P. Preimage problem in kernel-based machine learning / P. Honeine, C. Richard // IEEE Signal Processing Magazin. – 2011. – Vol. 28, Issue 2. – P. 77–88. DOI: 10.1109/MSP.2010.939747.
31. Cox T. F. Multidimensional Scaling / T. F. Cox, M. A. A. Cox – 2nd edition. – ser. Monographs on Statistics and Applied Probability. – 2020. – London : Chapman and Hall / CRC. – DOI: 10.1007/978-3-540-33037-0_14.
32. Yamanishi Y. Kernel matrix regression. / Y. Yamanishi, J.-P. Vert – Tech. Rep., Cornell University library. URL: http://arxiv.org/abs/q-bio/0702054v1, 2007.

DOI 10.15588/1607-3274-2022-2-16

e-ISSN 1607-3274 Радіоелектроніка, інформатика, управління. 2022. № 2
p-ISSN 2313-688X Radio Electronics, Computer Science, Control. 2022. № 2

UDC 004.05; 004.4

TOOLS FOR SELECTING A SOFTWARE DEVELOPMENT METHODOLOGY TAKING INTO ACCOUNT PROJECT CHARACTERISTICS

Seniv M. M. – PhD, Associate Professor of Software Department, Lviv Polytechnic National University, Lviv, Ukraine.

Kovtoniuk A. M. – Ms. Sc., Lviv Polytechnic National University, Lviv, Ukraine.

Yakovyna V. S. – Dr. Sc., Full Professor of Artificial Intelligence Department, Lviv Polytechnic National University, Lviv, Ukraine; Faculty of Mathematics and Computer Science, University of Warmia and Mazury in Olsztyn, Poland.

ABSTRACT

Context. In the software development process, the choice of a software development methodology is one of the important stages that significantly affects the success/failure of the project. The choice of the optimal development methodology depends on many factors and is a time-consuming and nontrivial task.

Objective. Therefore, there is a need to develop an effective and flexible software tool for selecting the best software development methodology that would automate this process and take into account the key characteristics of the project.

Method. This article presents an algorithm for selecting a software development methodology using methods of multi-criteria analysis and expert evaluation, which provides for gathering of the expert evaluation and implements the process of selecting the methodology using such methods as AHP, TOPSIS and Weighted Sum.

Results. Using the above-mentioned algorithm, a software system was developed for selecting the best software development methodology depending on the characteristics of the project, where the criteria weights provided by experts were taken into account and the AHP method was applied to determine user priorities regarding the criteria for the methodology comparison. The TOPSIS and Weighted Sum method were chosen to calculate the estimates of the methodology selection. The software tool provides for the output of useful details of the selection results, namely, an expert evaluation of the specified parameter values in relation to all methodologies, and it can be used to improve the efficiency of the software development process in terms of automating the provision of recommendations to IT project managers.

Conclusions. The algorithm for selecting a software development methodology was developed, which, unlike the existing ones, provided for gathering of expert evaluation, taking into account the values of the criteria set by a user independently, and implemented the process of selecting the methodologies using such methods of multi-criteria analysis as AHP, TOPSIS and weighted sum. Using the above algorithm, a software system was developed for selecting the best software development methodology, depending on the characteristics of the project, where the criteria weights provided by experts were taken into account, and the AHP method was applied to determine user priorities for methodology comparison criteria. TOPSIS and weighted sum methods and were chosen to calculate the scores of methodology choice. The software tool provides for the output of useful details about the selection results, namely, an expert evaluation of the set parameter values regarding all methodologies.

KEYWORDS: software, software development methodologies, software engineering.

ABBREVIATIONS

TOPSIS is a Technique for Order of Preference by Similarity to Ideal Solution;

AHP is a Analytic Hierarchy Process;

CASE is a computer-aided software engineering;

PAPRIKA is a Potentially All Pairwise Rankings of all possible Alternatives;

XP is a Extreme Programming;

DSDM is a Dynamic Systems Development Method;

RAD is a Rapid Application Development;

ROC is a Rank Order Centroid;

SDLC is a Software Development life cycle;

DBMS is a Database Management System;

SWEBOK is a Software Engineering Body of Knowledge;

PRINCE is a PRojects IN Controlled Environments;

PMBOK is a Project Management Body of Knowledge;

SMARTER is a Specific, Measurable, Achievable, Realistic, Time bound, Evaluate, and Reviewed;

PIS is a positive ideal solution;

NIS is a negative ideal solution.

NOMENCLATURE

p_a – priority evaluation of alternative a;

x_{ai} – evaluation of alternative a by criterion i;

w_i – weight of criterion i;

n – number of criteria;

x_{ij} – evaluation of alternative (methodology) i by criterion j;

m – number of alternatives;

n_{ij} – normalised value of evaluation of alternative i by criterion j;

Y – set of alternatives;

N – set of criteria.

INTRODUCTION

With every passing year, the software development process becomes more complex, requiring deeper knowledge and experience from developers and project managers. The software creation is a series of processes result-

DOI 10.15588/1607-3274-2022-2-17

ing in the development of a software product. These processes are based mainly on software engineering technologies. The software development process can begin with the development of a software system from scratch, or new software is developed based on existing software systems by modifying them. The software development process, like any other intellectual activity, is based on such human factors as judgements and conclusions, i.e., is creative. As a result, the attempts to automate this process have met with only limited success. CASE tools can help in the implementation of some stages of the software development process, but they do not help much at those stages where the factor of a creative approach to development is essential [1]. The procedure for selecting a specific software development methodology also plays a significant role in the above-mentioned process. The success of the software product implementation depends on it, making this stage very important. However, due to a large number of existing methodologies, it really becomes a challenge for managers and developers to determine the one that would best suit the project task and development team. The reason is that different types of software projects require different approaches, since each category of projects has different priorities and goals; in addition, clear and standardized criteria for selecting a software development methodology have not yet been specified [2–4]. Therefore, the algorithmic support and software development for the selection of the most suitable software development methodology depending on the characteristics of the project and for various types of projects is an urgent scientific task.

Based on this, the **object of the research** is the process of selecting the methodology of software development, **the subject of the research** are algorithms, methods and tools for selecting the methodology of software development, taking into account the characteristics of the project; the **aim of the research** is to develop an effective and flexible tool for selecting the optimal methodology for software development, taking into account the characteristics of the project.

2 PROBLEM STATEMENT

Given: the set $Y = \{Y_1, Y_2, \ldots, Y_7\}$ of alternatives (software development methodologies) and the set of $N = \{N_1, N_2, \ldots, N_{23}\}$ criteria (project characteristics) with the weight of the i-th criterion w_i.

The task is to build a hierarchy in the form of a multitree and calculate the global priorities of alternatives – the priorities of alternatives for the whole hierarchy. The input data are the results of a survey of experts in the form of matrices of pairwise comparisons at all nodes of the hierarchy. Hierarchical synthesis is used to weigh the own vectors of matrices of pairwise comparisons, as well as to calculate the general priorities of alternatives. As a result of constructing a hierarchy and implementing paired comparisons, matrices of paired comparisons should be constructed for all vertices of the hierarchy except leaves. The pairwise comparison method to calculate the aggregate evaluation (global priority) of alternatives (development methodologies) should be applied.

3 REVIEW OF THE LITERATURE

Currently, various approaches are used to automate and optimize the choice of a software development methodology. One of them is rule-based expert systems [5]. Such criteria as application size, risks, project complexity, reliability, time, team size and expertise are taken into account, and a cascade model, spiral model, incremental model, XP, Scrum or RAD model can be proposed based on these characteristics. The expert system [5] uses a modular rule-based architecture. The questionnaire consists of different questions about the characteristics of the project: system type, system size, level of possible risks, complexity, reliability, etc. The experts can update or add any question from this repository. The "rule repository" is maintained as a set of "if...then" rules, it provides recommendations according to the characteristics of the project. The "set of facts" contains facts about recommendations for different possible values in rules. The answers provided by a user are placed in the relevant rules of the "rule repository", which are used by the "rule engine" for comparing the "set of facts", structuring and displaying recommendations to a user through the display module ("SDLC recommendation display module") [5]. The main disadvantage of this type of system is the difficulty of filling a knowledge base. Upon the selection, as many existing software development methodologies as possible should be considered, and also many different criteria should be taken into consideration depending on the characteristics of the project. When trying to make the knowledge base as complete as possible, it is extremely difficult to predict all the details, especially considering that expert opinions often differ. Besides, users cannot change the priority of criteria in this type of system.

Another approach is described in the work [2], where an approach to solving the problem of choosing the agile methodology for small and medium-sized projects is proposed, using the multi-criteria method based on SMARTER. The proposed method for the methodology selection consists of the following stages [2]:

1. Determining a set of criteria: 13 criteria are proposed related to the setting up of work on the project, the complexity of the project and change management;
2. Developing alternative solutions: the choice is limited to four agile methodologies: DSDM, Scrum, XP and Crystal;
3. Creating an evaluation matrix: the evaluation of methodologies in relation to criteria is based on the number of scientific papers, which indicate that a certain value of the criterion is suitable for a certain software development methodology;
4. The relative importance of criteria is determined, and values of criteria weights are calculated using the ROC method;
5. The multi-attribute value of the function of each of the alternatives is set by the aggregation of functions;

DOI 10.15588/1607-3274-2022-2-17

As a result, the alternatives are ranked from best to worst [2].

Also, in [6], for the selection of practices for organizing the software development process, it is proposed to use the PAPRIKA method. 31 practices are evaluated in pairs against 11 criteria. The tool interviews users and, based on the answers, forms a list of practices that it recommends using in project development. The PAPRIKA method is based on users expressing their preferences with respect to the relative importance of the criteria or attributes of interest for the made decision or choice, by pairwise comparison (ranking) of alternatives [6].

In [7], a method for selecting a project testing technique is described, using the AHP hierarchy analysis technique and TOPSIS method. TOPSIS is based on the concept that the ideal alternative has the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution. AHP is used to calculate the criteria weights. AHP uses the relative consistency ratio to verify the consistency of the criteria weights.

In turn, a tool that uses the method of selecting a project management methodology based on fuzzy representations is described in the work [7]. The method uses a questionnaire with questions related to the number of people involved in the project, the customer's experience of working with the team, evaluation of the project team's competence by the project manager, project reporting and likelihood of risk events. For each situation specified in the questionnaire, using a survey of expert opinion, the membership functions of all project management methodologies considered are determined, i.e., their applicability to a particular situation. In accordance with the answers to the questions of the questionnaire for the project, the membership functions of the project evaluation for each of its parameters are formed. For all the methodologies considered, their total weighted distances from the project evaluation according to the questionnaire are calculated using the Euclidean and Hamming distances. The approach with the calculated minimum distances is selected [8].

M. Despa in his work [9] conducted a comparative analysis of software development methodologies with an emphasis on the features of project management. The author presented and compared the stages of the development process for such methodologies as waterfall, prototyping, iterative and incremental, spiral, rapid application development, extreme programming, V-model, scrum, cleanroom, dynamic systems development methodology, rational unified process, lean software development, test-driven development, behavior-driven development, feature-driven development, model-driven engineering, crystal methods, joint application development, adaptive software development, open source software development and Microsoft Solutions Framework. Such factors affecting the software development process as frequent software requirements changes, high dynamics of the technology stack and development standards, qualifications of the development team and the team globalization and dispersion were considered in the study [9]. The author describes in detail the characteristics, advantages, and disadvantages of each of the investigated methodologies. The advantages of traditional methodologies [9] include ease of understanding and implementation, availability of substantial documentation and ease of tracking, evaluation, and reporting. The agile methodologies, in turn, provide greater flexibility and can easily adapt to changes, contributing to earlier release of working code, better self-organization of teams and adaptive planning.

G.S. Matharu with co-authors [10] explore the issue of choosing between such agile software development methodologies as Scrum, Kanban, and extreme programming. The paper presents a detailed comparison of these methodologies in terms of such parameters as design approaches, customer cooperation, project complexity, team roles, team interaction, approach to workflow organization, requirements management, coding, and testing approaches, etc. The authors [10] indicate and analyse companies that use the above software development approaches. The authors showed that currently the most widespread in the industry are the approaches based on the Scrum methodology.

L. R. Vijayasarathy and C.W. Butler [11] study the factors influencing the selection of the best software development methodology. The authors investigated the problems of the influence of a software project organizational structure and characteristics of the team and the project itself on determining the best software development methodology. The study was conducted by interviewing project managers and members of the development team on the choice of methodologies. The results [11] show that although the agile methodologies such as the Agile Unified Process or Scrum have become increasingly popular in the last decade, traditional methodologies, including the waterfall model, are still popular in the software development industry. The companies also often adopt a hybrid approach using different methodologies in the same project. Besides, the choice of methodology is associated with certain organizational, project and team characteristics and remains an urgent task of software engineering [11].

The work [12] is dedicated to the issues of modelling the software development methodologies. The authors note that although modern modelling approaches must have a strong theoretical foundation, they do contain many vague concepts or even contradictions. C. Gonzalez-Perez and B. Henderson-Sellers present an approach that analyses the basic concepts of structural models and modelling in software engineering using representation theory. The authors investigated different types of interpretive reflections needed to track model entities with the entities they represent. The paper also explains the difference between forward- and backward-looking models and considers the need to integrate products and processes into methodologies.

The article [13] analyses the software development methodologies and their main stages. The authors compare international approaches, standards, and practices for software development with the standards and practices

DOI 10.15588/1607-3274-2022-2-17

used in Pakistan. The comparative analysis shows the gaps and shortcomings of the practices adopted in Pakistan and the ways to improve them.

Another aspect of research in the field of software development methodologies is considered in the article [14], which examines the issue of ensuring that the skills and competencies of students of higher education institutions meet the requirements and expectations of the labour market. K. Saeedi and A. Visvizi emphasize the key role of teaching the software development processes and technologies for industry, economics, students, and universities. The paper points out the importance and relevance of agile development methodologies scrum, at the present stage. By analysing the problems and challenges of switching to agile software development methodologies in software projects, the article [14] concludes that software development and methodology for its development form the thrust of a multi-stakeholder ecosystem that defines today's digital economy and society.

Based on the foregoing, a conclusion can be made that high activity in the field of software development has led to the emergence of a large number of methodologies, and now the choice of a suitable approach remains a problem [15], because it usually requires quite extensive experience in software development. It is also worth noting that the problem of choosing a software development methodology is the reason for the studies, the purpose of which is to create a universal method for selecting the software development methodology. They can be divided into two types: rule-based expert systems and tools using multi-criteria analysis methods. The disadvantage of using classical expert systems is the complexity of filling them with a large amount of data and inability of users to influence the priority of criteria. In contrast to them, the existing approaches to the choice of software development methodologies, which use the methods of multi-criteria analysis, provide for the possibility of establishing criteria weights, but most of them still rely on the opinion of only one expert and a fixed set of criteria. Since there are many methodologies, the expert opinions may differ regarding the optimal values of criteria for a particular methodology. Besides, the criteria, possible values for which cannot be easily expressed in numbers, may also be considered. Therefore, there is a need to create a flexible tool that would be free of these limitations and allow automating the selection of the software development methodology, which is the most favourable for a certain project.

4 MATERIALS AND METHODS

It was decided to use the following methods of multi-criteria analysis for the process of selecting the best methodology: analytic hierarchy process, weighted sum method, TOPSIS and methods for expert evaluation. The AHP, developed by Thomas L. Saaty, is a well-known technique for multi-criteria decision making [16]. One of the distinguishing features of the AHP is the creation of a pairwise comparison matrix using a verbal scale. In the standard version of the method, the normalised eigenvector of this matrix allows calculating the score of each alternative and weight of each criterion.

The weighted sum method is the most popular method of multi-criteria analysis due to its simplicity. As the name suggests, this is simply the sum of the weighted scores:

$$p_a = \sum_{i=1}^{n} x_{ai} w_i , \tag{1}$$

We assume that the goal is to maximize all criteria.

The TOPSIS method is focused on evaluating the alternative in terms of the best and worst points [6].

1. The normalization of evaluation by criteria is carried out:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} , \tag{2}$$

2. The weighted normalised decision matrix is calculated considering criteria weights:

$$u_{ij}=w_j n_{ij} \text{ where } i=1,\ldots,m;\ j=1,\ldots,n. \tag{3}$$

3. The PIS and NIS are determined:

$$A^+ = \frac{\max}{iu_{ij}}, A^- = \frac{\min}{iu_{ij}}.$$

4. The distance of alternatives to PIS and NIS is calculated:

$$d_i^+ = \sqrt{\sum_{i=1}^{n} (u_{ij} - A_j^+)^2} , j = 1,..., m. \tag{4}$$

$$d_i^- = \sqrt{\sum_{i=1}^{n} (u_{ij} - A_j^-)^2} , j = 1,..., m. \tag{5}$$

5. The integral index (proximity index) is determined for each compared alternative:

$$R_i = \frac{d_i^-}{d_i^- + d_i^+}. \tag{6}$$

The proximity index is between 0 and 1, where 1 is the best alternative.

5 EXPERIMENTS

Experts evaluate the extent to which it is permissible to use a certain methodology for each characteristic of the project, i.e., each possible value of the criterion.

The test data presented in the work [8] were used as the baseline, namely: 7 methodologies, a list of 23 criteria and their possible values, criteria weights, evaluation of values of criteria in relation to methodologies. A detailed list of project characteristics according to which the methodology is selected, is given in Table 1. Each of

DOI 10.15588/1607-3274-2022-2-17

them has four stages of gradation presented in the table. The weights of expert opinion may vary. Given these weights, the expert evaluation is aggregated.

It was decided to use the AHP to calculate the weights of criteria used to evaluate alternatives. The user makes a pairwise comparison of the criteria, and the absolute weights of criteria are calculated using the AHP. The pairwise comparison is made on a scale from 1 to 9. The AHP uses a consistency ratio as a measure to check the consistency of the weights obtained. This ensures that the weights are consistent.

Based on the user-defined values of criteria, their weights and expert evaluation, the system calculates the score for each methodology using the weighted sum and TOPSIS methods. The higher the score, the better the applicability of the methodology to the project.

Table 1 – Parameter values

N	**Parameter**	**Possible values**			
1.	Project cost	< 100,000	100,000–300,000	300,000 – 1,000,000	> 1,000,000
2.	Requirements change percent/month	< 7%	7%–25%	25%–45%	> 45%
3.	Number of people involved in the project	< 10 per	10–30 per	30–100 per	> 100 per
4.	Consequences in case of unsatisfactory project outcome	loss of comfort in work	Loss of insignificant sum of money	Loss of irreplaceable sum of money	Loss of life
5.	Work experience in the given field	No work experience	Experience of working in the field for less than 2 years	Experience of working in the field from 2 to 5 years	Experience of working in the field from 2 to 5 years
6.	Requirements to the realization period of the project	The period is unlimited	Not very urgent	Urgent	Very urgent
7.	Teams ability to work effectively in freedom or order	Able to work effectively in full order	Able to work effectively in middle order	Able to work effectively in partial order	Able to work effectively in full freedom
8.	Understanding of requirements, adapting ability, initiative	Almost do not understand the requirements; require frequent explanations and constant control	Understand the requirements, can follow them, but require regular control	Understand the requirements, can follow them, do not require regular control	Have good understanding of the requirements; can follow them without regular control; can suggest better alternatives
9.	Probability of occurrence of managerial risks (inefficient planning, controlling, communication problems, etc.)	Risk is not likely to occur (10%)	Probability of risk occurrence is equal (50%)	Risk is highly likely to occur (75%)	Risk will most probably occur (>95%)
10.	Knowledge of applied tools and methods	Tools and methods, applied in the given project, have never been used before and are unknown to the team	Tools and methods, applied in the project, are known to the team but have never been used before	Tools and methods, used in the project, are known to the team but are rarely used	Tools and methods, are known to the team and have been widely used before
11.	Means of communication	Written reports. Formal record-keeping	Voice communication	Online text communication	Direct communication
12.	Frequency of reporting to the Customer	Reports on every operation	Reports on completing the blocks of work	Reports on the readiness of a component of projects product	Reports about project finish
13.	Understanding the scope of works	There is a full list of works; further alternation is impossible	There is a detailed list of works, further alternation is possible	There is an approximate list of project works	The team understands the project goal and several ways for its achievement
14.	Requirements to the project quality	Highest international requirements	International requirements	National requirements	Local requirements
15.	Probability of occurrence of technical, manufacturing or qualitative risks	Risk is not likely to occur (10%)	Probability of risk occurrence is equal (50%)	Risk is highly likely to occur (75%)	Risk will most probably occur >95%)
16.	Probability of occurrence of external risks (disruption of work by contractors, unfavourable political, etc.)	Risk is not likely to occur (10%)	Probability of risk occurrence is equal (50%)	Risk is highly likely to occur (75%)	Risk will most probably occur >95%)
17.	Probability of occurrence of organizational risks (disruption of funding, delivery of resources, inaccurate prioritizing, etc.)	Risk is not likely to occur (10%)	Probability of risk occurrence is equal (50%)	Risk is highly likely to occur (75%)	Risk will most probably occur >95%)

DOI 10.15588/1607-3274-2022-2-17

Table 1 – Parameter values (continuation)

N	Parameter	Possible values			
18.	Requirements to the precise compliance with a deadline	The deadline should be strictly met	Insignificant deviation from the deadline is allowed	Considerable deviation from the deadline is allowed	Compliance with the deadline is now strictly required
19.	Ability to admit mistakes	Do not admit makings mistakes and cannot learn from them	Rarely admit their mistakes but try t never make them again	Openly admit making mistakes and try to never make them again	Openly admin making mistakes and always learn from them
20.	Learning ability	It is hard for the team to learn new knowledge and technologies, and to adjust to changes	For some members of the team, it is hard to learns new information and technologies, but the team can adjust to changes	Easily absorb new knowledge, can adjust to changes	The team can easily absorb information, always tries to learn something new; can well adjust to the changes
21.	Experience of cooperation	Have never worked together	Worked together on the creation of a product but in the different field	Worked together on the creation of one product in a field of interest	Worked together on the creation of several projects in the field of interest
22.	Teams ability to clearly formulate and openly express ideas	Cannot clearly formulate ideas and rarely express them	Can clearly formulate their ideas but rarely express them	Can clearly formulate their ideas and openly express them	Can clearly formulate, openly express and justify their ideas
23.	Customers experience of working with this project team	Has never worked with this team	Worked with some members of the team	Worked with the project team leader	One or more common projects with the whole project team

6 RESULTS

To create a tool to automate the selection of the best software development methodology for the project, an appropriate algorithm was developed, which provided for the gathering of expert evaluation and implemented the process of selecting methodologies using such multi-criteria analysis methods as AHP and weighted sum. It consists of 11 steps; its block diagram is shown in Fig. 1.

1. Filling the database with description of software development methodologies.

2. Filling the database with a set of necessary criteria, by which the characteristics of projects will be determined, with the relevant setting of initial values.

3. Setting the default weights for the criteria and, if required, the weights for individual possible values of criteria.

4. Gathering the expert evaluation of all possible values of criteria in relation to all methodologies available in the database.

5. A user must set the values of criteria in accordance with the characteristics of the project; if required, a user can omit some of the criteria.

6. If required, a user can determine the weights of criteria independently, using the AHP method. If a user refuses, then the weight of criteria takes on the default values.

7. If a user agrees to determine the weights of criteria independently:

a) A user must compare in pairs the importance of all specified criteria with each other.

b) The relative consistency of the weights is determined, if it is > 0.2, then the weights are not consistent, and a user should start the process of comparison from the beginning or allow the default values of the weights to be set.

8. The decision matrix with $m \times n$ dimension is determined, where m is the number of methodologies, n is the number of criteria, the values of which are set by a user. The matrix consists of evaluation of the established values of criteria in relation to methodologies.

9. The scores for methodologies are determined using the weighted sum method.

10. The scores for the methodology are determined using the TOPSIS method:

a) A weighted normalised matrix is determined.

b) The positive and negative ideal solution is determined.

c) The Euclidean distance and relative proximity of each of the alternatives (methodologies) to ideal solutions are calculated.

11. The methodologies are sorted from the best (with the highest scores) to the worst (with the lowest scores), and details on the scores of the established values of criteria are provided.

For the purpose of the software implementation of the above algorithm, a software system was developed in the form of a web application with a client-server architecture, therefore, any modern web browser with the Internet access can be its operating environment. For technical implementation, the Ruby programming language version 2.6.5 was chosen with the Ruby on Rails framework version 6.0.3.3. PostgreSQL version 13.1 was used as a DBMS.

The main features of the software product are the introduction by experts of membership functions for each known criterion regarding each methodology in the system; adding new methodologies and criteria; determining the criteria weights by default; determining the criteria weights based on comparison of criteria by a user; input of criteria values by a user; selection and output of the results of the methodology selection. The form for creating a new project is presented in Fig. 2.

DOI 10.15588/1607-3274-2022-2-17

By clicking on a specific project, a user will be redirected to the stage corresponding to the status of the project. This can be:

– filling out a questionnaire about the project (Fig. 3);

– comparison of the importance of parameters (Fig. 4);

– page with results (Fig. 5).

The questionnaire for setting the parameter values is displayed as shown in Fig. 3. The name of the project is indicated at the top of the page, below it there is a progress bar displaying the percentage of questions (parameters) answered by a user, below it there is the name of a parameter and available answer choices, as well as the submit and skip buttons.

Figure 4 shows the interface for the pairwise comparison of parameters. It contains the names of parameters and their set values, as well as a slider to estimate the degree of importance of one parameter with respect to the other one.

Figure 5 shows the results page. The left pane displays a list of methodologies, sorted from best to worst. After clicking on one of them, the right panel displays their values and scores of the set parameter values in relation to this methodology.

The questionnaire for establishing expert evaluation is shown in Fig. 6.

The developed algorithm for selecting a software development methodology uses the weighted sum and TOPSIS methods to find the best alternative, i.e., methodology. To determine the weights of criteria by a user, the AHP method is used. The decision matrix is formed of the estimates of the criteria values in relation to the methodologies determined with the help of experts.

To check the accuracy of the recommendations provided by the software tool, the extent to which it meets the expectations of users - managers and project developers, and its reaction to data changes, the test data presented in the work [8] were used, namely: 7 methodologies, a list of 23 criteria and their possible values, criteria weights, evaluation of criteria values in relation to methodologies.

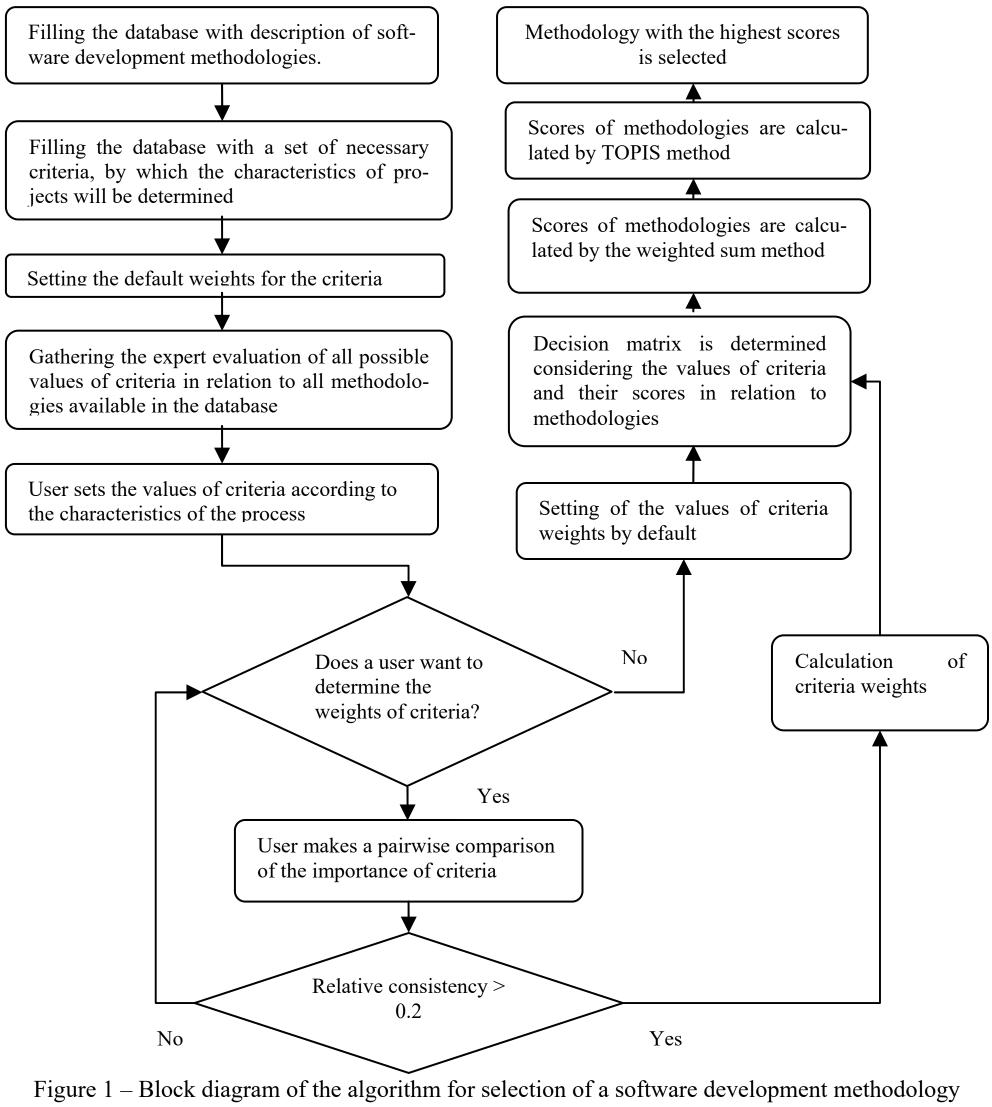


Figure 1 – Block diagram of the algorithm for selection of a software development methodology

DOI 10.15588/1607-3274-2022-2-17

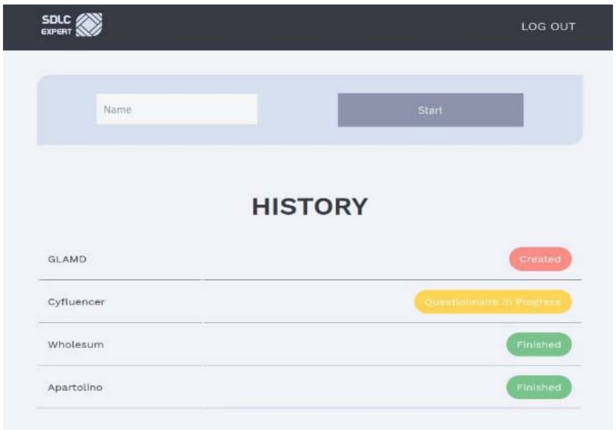


Figure 2 – List of projects

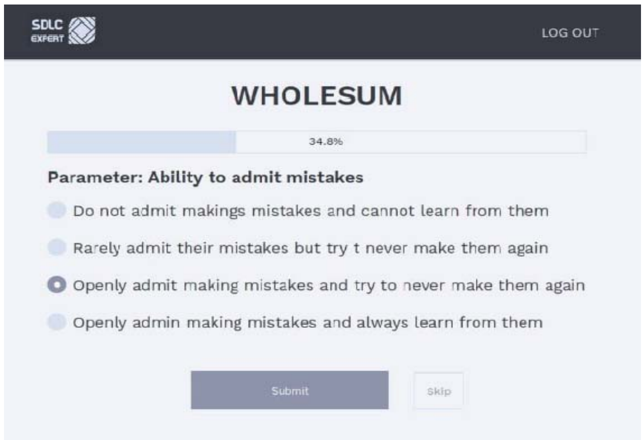


Figure 3 – Setting of parameter values

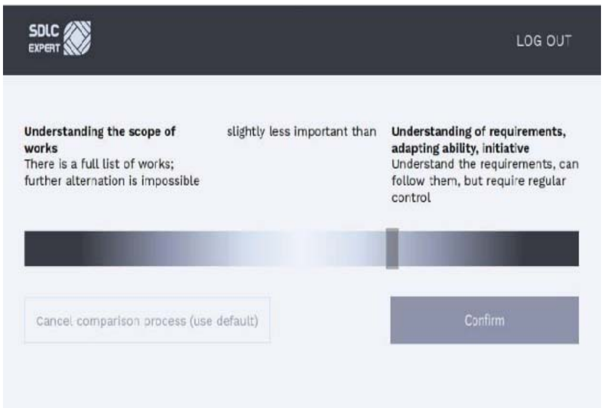


Figure 4 – Comparison of parameter importance

Figure 5 – Page of the methodology selection results

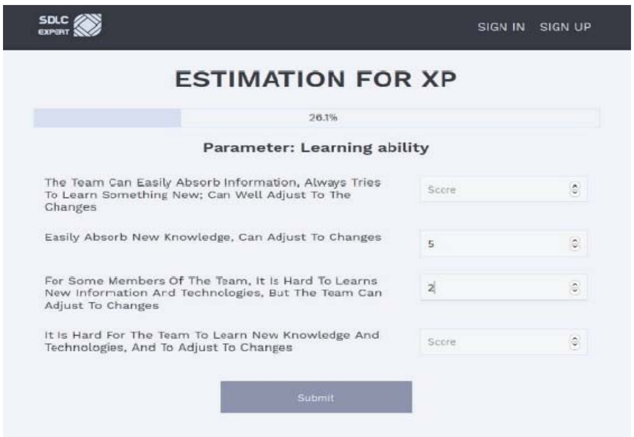


Figure 6 – Filling in the scores by an expert

Table 2 shows the results of calculating the scores using the approach described in [8] and a tool developed by us using the weighted sum and TOPSIS methods.

Table – 2 Table of comparison of methodology scores

Methodology	Results in the work [9]	A developed software tool		
		Weighted Sum	TOPSIS	Average
PMBOK	0.341	0.165	0.347	0.256
ISO21500	0.341	0.165	0.347	0.256
PRINCE2	0.276	0.143	0.314	0.228
SWEBOK	0.361	0.193	0.376	0.285
Scrum	0.900	0.371	0.764	0.567
XP	0.732	0.190	0.404	0.297
Kanban	0.663	0.233	0.514	0.373

The comparison table shows that the recommended methodology is the same in all cases. For clarity, this data is presented in Fig. 7–9 by means of diagrams.

It is also worth comparing the order of ranked methodologies (Table 3).

Table.3 Comparison of the order of ranked methodologies

No.	From the work [9]	A developed software tool		
		Weighted Sum	TOPSIS	Average
1	Scrum	Scrum	Scrum	Scrum
2	XP	Kanban	Kanban	Kanban
3	Kanban	SWEBOK	XP	XP
4	SWEBOK	XP	SWEBOK	SWEBOK
5	PMBOK	PMBOK	PMBOK	PMBOK
6	ISO21500	ISO21500	ISO21500	ISO21500
7	PRINCE2	PRINCE2	PRINCE2	PRINCE2

DOI 10.15588/1607-3274-2022-2-17

It can be seen from the comparison that the methodology recommended by both approaches is the same, but the following two positions differ: in the work [8], the second position is occupied by XP, and the third – by Kanban; in the result of the selection made by our system, on the contrary: Kanban – ranks second and XP ranks third. We can conclude from this research that the system works correctly regarding the results of the work [9].

Also, to verify the operation of the system, its operation was tested using the data of real projects, three anonymized commercial projects from LinkUp company (https://linkupst.com/).

Project No. 1. Web platform for planning meals for groups of people. Main characteristics of the project:

– no experience of work with the customer;
– domain knowledge;
– the team has already worked, having the same composition, with the same tools;
– clear and almost completely known requirements;
– project is not very urgent and does not require strict adherence to deadlines;
– existing risks associated with third-party service;
– communication in the form of correspondence;
– reporting after the implementation of individual components of the product.

Criteria weights: By default. Expected result: Scrum. Results – (Table 4)

Table 4 – The result of selection of methodology for the project No. 1

№	Weighted Sum		TOPSIS		Average	
1.	SWEBOK	0.2913	Scrum	0.5526	Scrum	0.4106
2.	ISO21500	0.2696	SWEBOK	0.5204	SWEBOK	0.4059
3.	PMBOK	0.2696	PMBOK	0.4894	PMBOK	0.3795
4.	Scrum	0.2685	ISO21500	0.4894	ISO21500	0.3795
5.	PRINCE2	0.2619	Kanban	0.4885	PRINCE2	0.3723
6.	Kanban	0.2141	PRINCE2	0.4826	Kanban	0.3513
7.	XP	0.2059	XP	0.4633	XP	0.3346

Project No. 2. Web-based rental platform. Main characteristics of the project:

– no experience of work with the customer;
– minimum domain knowledge;
– a large team;
– requirements are known in large part;
– urgent;
– expensive;
– no significant risks;
– weekly calls;
– reporting every two weeks.

Criteria weights: By default. Expected result: SWEBOK. Results – (Table 5)

Table 5 – The result of selection of methodology for the project No. 2

№	Weighted Sum		TOPSIS	
1.	SWEBOK	0.3565	SWEBOK	0.6810
2.	PRINCE2	0.3424	PRINCE2	0.6612
3.	ISO21500	0.3304	ISO21500	0.6251
4.	PMBOK	0.3304	PMBOK	0.4347
5.	Scrum	0.2087	Scrum	0.4346
6.	Kanban	0.1467	Kanban	0.2962
7.	XP	0.1441	XP	0.2900

Project No. 3. Mobile game. Main characteristics of the project:

– customer's experience of work with the team;
– good domain knowledge;
– a small team consisting of the developers who have already worked together on games;
– most requirements are known;
– not very urgent, but adherence to deadlines is required;
– no significant risks;
– communication in the form of correspondence and weekly calls;
– reporting every week.

Criteria weights: By default. Expected result: Kanban. Results – (Table 6).

Table 6 – The result of selection of methodology for the project No. 3

№	Weighted Sum		TOPSIS	
1.	Scrum	0.3185	Scrum	0.6837
2.	Kanban	0.2543	Kanban	0.5067
3.	SWEBOK	0.2489	SWEBOK	0.3974
4.	PRINCE2	0.2250	XP	0.3935
5.	XP	0.2250	PRINCE2	0.3697
6.	PMBOK	0.2228	PMBOK	0.3639
7.	ISO21500	0.2228	ISO21500	0.3639

7 DISCUSSION

Thus, for the first project, the expected result showed only the selection by means of the TOPSIS method, whereas the weighted sum method produced fundamentally different results. This can be explained by the fact that some criteria compensate for the others in the weighted sum method.

As for the second project, users obtained the expected result. However, on the page with the results, users can see that SWEBOK may not meet some of their requirements (Fig. 10). It can be seen that SWEBOK is a bad option for urgent projects, and it does not require the team to be able to quickly learn new things. The users should consider these details when making the final decision on the selection of a software development methodology.

In the third case, a person who was making decisions expected that the recommended methodology would be Kanban, but in the selection with TOPSIS and weighted sum methods, the scrum methodology ranked first. In this case, a user can check why this happened, what values of criteria and to what extent satisfy the methodology by Kanban (Fig. 11).

Thus, a user sees from the results that the following criteria were unsatisfactory for Kanban:

– ability of the team to work without control – Kanban requires the team to work independently and be self-organized without the need of being monitored;
– reporting frequency – Kanban provides for the reporting to be carried out at the end of the project or a large part of the project, but not after every operation;
– understanding of the scope of work – it makes sense to use Kanban if there is a lot of uncertainty about how to implement the product;

DOI 10.15588/1607-3274-2022-2-17

– ability to learn – Kanban is usually used in cases when all team members are able to quickly learn new things;

– adherence to deadlines – Kanban is used in cases when it is not required to strictly adhere to the deadlines, including the intermediate ones;

– frequency of requirements changes – Kanban is an effective solution in cases when frequent changes in requirements are expected. If during the project the requirements remain mostly unchanged, then one of the main advantages of Kanban will not be demonstrated.

The system was tested for the same project but with different criteria weights (Table 7).

In this case, most of the criteria were suitable for the Scrum methodology, therefore, irrespective of the way the criteria weights were arranged, in all cases the Scrum methodology ranked first. The XP methodology was the least suitable in all cases. The weights of criteria influenced all other positions in the ranked list of methodologies.

The critical characteristics for a respective methodology were also determined for each of the projects (Table 8).

Thus, the results of the verification allow us to ensure that in more than 50% of cases the expectations matched the results, namely: for the first project the results met the expectations, for the second – the expected methodology took the second place, for the third one – the expected methodology of the project was recommended by the selection using the TOPSIS method, but not the Weighted Sum – this is justified by the fact that the Weighted Sum method is characterized by compensation between the criteria, therefore we can draw a conclusion, that the results calculated by means of TOPSIS method provide more adequate recommendations. Besides that, the experiment was held, which identified the same values of the criteria, but different weights, and which revealed that the system responds to such changes, but if a certain methodology has a very large advantage over others, the weights do not have much effect on the "victory" of this methodology.

An experiment was also conducted with the change of weights of the criteria while their values remained unchanged, the result of which suggests that the weights of the criteria significantly affect the selection result, especially when the values of the criteria satisfy and do not satisfy each of the methodologies almost equally.

CONCLUSIONS

This paper solves the problem of developing an effective and flexible tool for selecting of the most appropriate methodology for software development considering the characteristics of the project. To solve this problem the analysis of the existing approaches to the selection of software development methodology was carried out, as a reslt of which it was determined that most of these approaches are focused on the selection of a certain methodology out of the fixed set, and they consider a limited range of criteria. We have also developed the algorithm and software system for the selection of the best methodology of software development depending on the characteristics of the project, where the criteria weights provided by the experts were considered and the AHP method was applied to determine user priorities for methodology comparison criteria. TOPSIS and weighted sum methods were chosen to calculate the scores of methodology choice. The software tool provides for the output of useful details about the selection results, namely, an expert evaluation of the set parameter values regarding all methodologies. The verification of the developed software system was performed based on the test data of the paper [8], which showed almost an exact match of recommendations of the best methodologies for this project and on the real projects by the comparison of expected results of the user with the results the user received with the help of the developed software tool. The results of the verification were the following: more than in 50% of cases, the expectation matched the results.

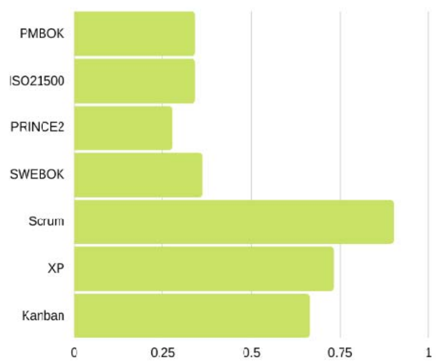


Figure 7 – Scores of methodologies in the work [8]

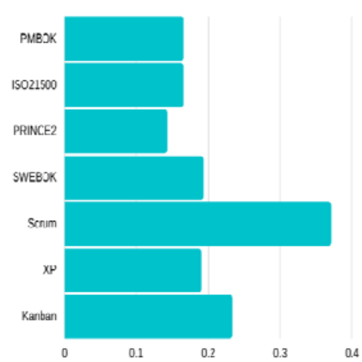


Figure 8 – Scores of methodologies using the weighted sum method

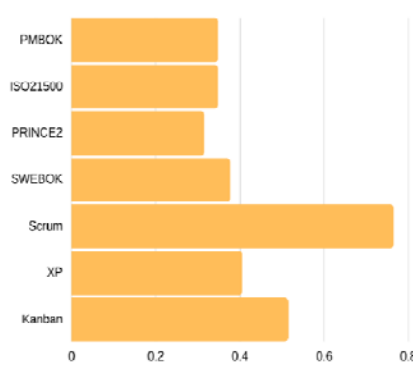
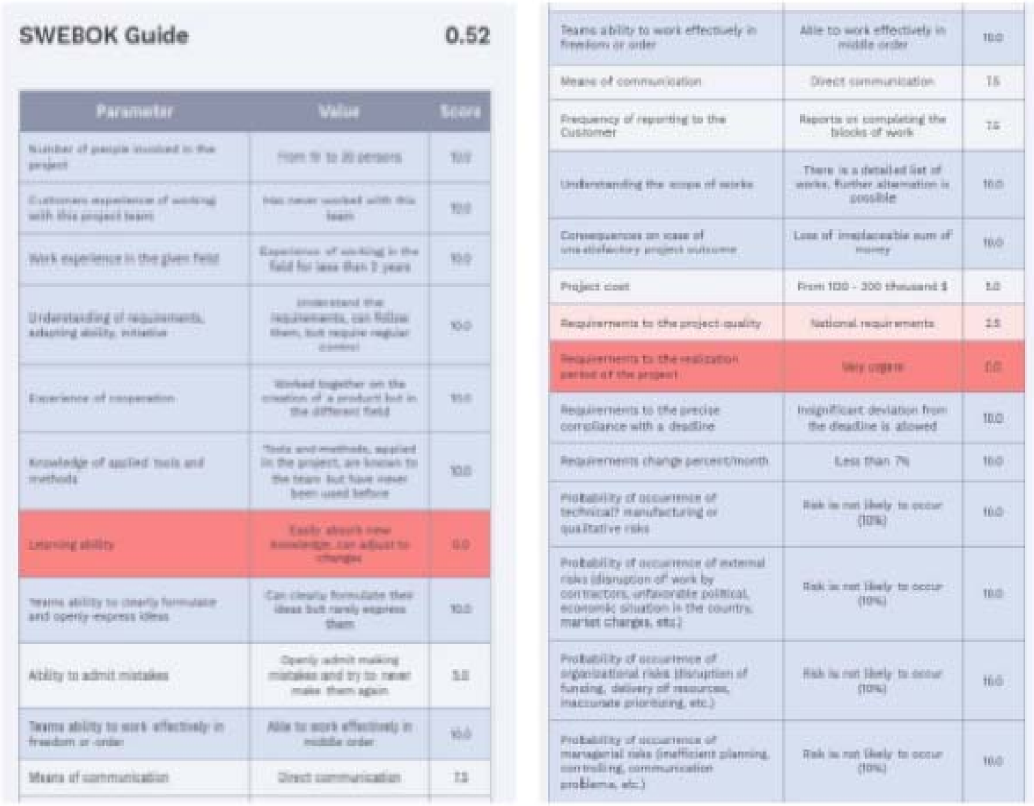


Figure 9 – Scores of methodologies using the TOPSIS method

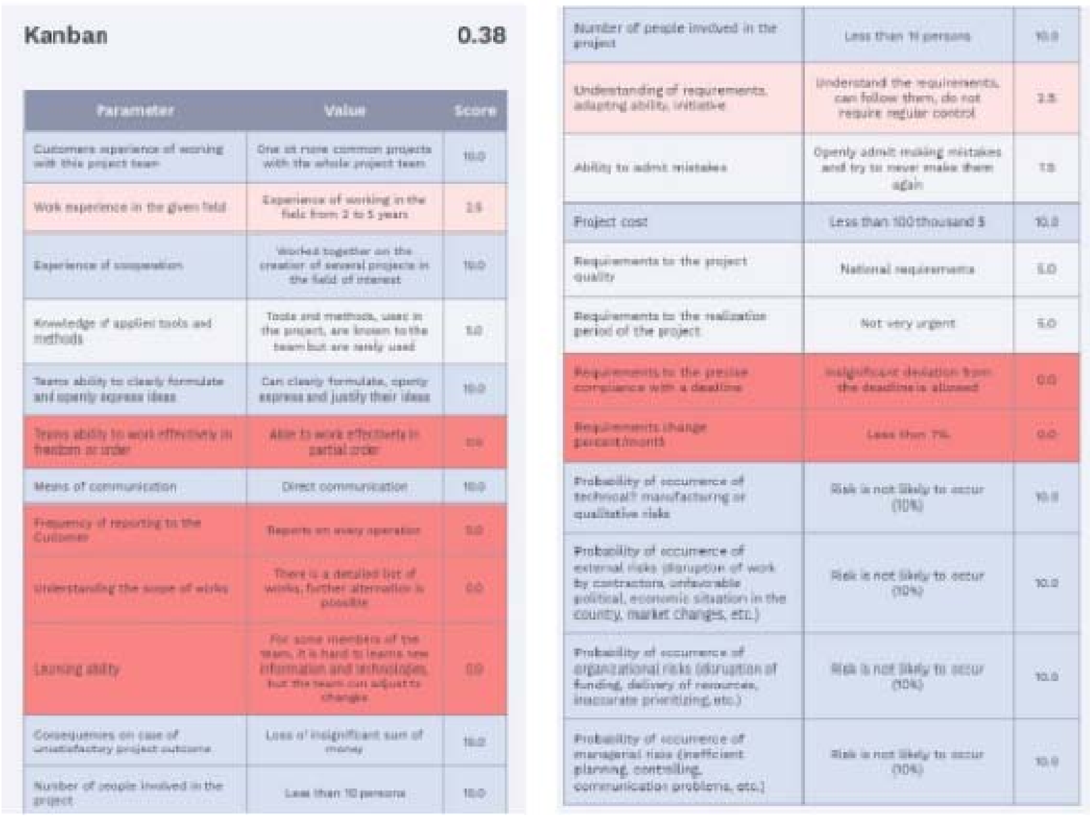
DOI 10.15588/1607-3274-2022-2-17



SWEBOK Guide 0.52

Parameter	Value	Score
Number of people involved in the project	From 11 to 20 persons	10.0
Customers experience of working with this project team	Has never worked with this team	10.0
Work experience in the given field	Experience of working in the field for less than 2 years	10.0
Understanding of requirements, adapting ability, initiative	Understand the requirements, can follow them, but require regular control	10.0
Experience of cooperation	Worked together on the creation of a product but in the different field	10.0
Knowledge of applied tools and methods	Tools and methods, applied in the project, are known to the team but have never been used before	10.0
Learning ability	Easily absorb new knowledge, can adjust to changes	0.0
Teams ability to clearly formulate and openly express ideas	Can clearly formulate their ideas but rarely express them	10.0
Ability to admit mistakes	Openly admit making mistakes and try to never make them again	5.0
Teams ability to work effectively in freedom or order	Able to work effectively in middle order	10.0
Means of communication	Direct communication	7.5
Frequency of reporting to the Customer	Reports on completing the blocks of work	7.5
Understanding the scope of works	There is a detailed list of works, further alternation is possible	10.0
Consequences on case of unsatisfactory project outcome	Loss of irreplaceable sum of money	10.0
Project cost	From 100 – 300 thousand $	5.0
Requirements to the project quality	National requirements	2.5
Requirements to the realization period of the project	Very urgent	0.0
Requirements to the precise compliance with a deadline	Insignificant deviation from the deadline is allowed	10.0
Requirements change percent/month	Less than 7%	10.0
Probability of occurrence of technical? manufacturing or qualitative risks	Risk is not likely to occur (10%)	10.0
Probability of occurrence of external risks (disruption of work by contractors, unfavorable political, economic situation in the country, market changes, etc.)	Risk is not likely to occur (10%)	10.0
Probability of occurrence of organizational risks (disruption of funding, delivery of resources, inaccurate prioritizing, etc.)	Risk is not likely to occur (10%)	10.0
Probability of occurrence of managerial risks (inefficient planning, controlling, communication problems, etc.)	Risk is not likely to occur (10%)	10.0

Figure 10 – Details of the scores of SWEBOK methodology for the project No. 2



Kanban 0.38

Parameter	Value	Score
Customers experience of working with this project team	One or more common projects with the whole project team	10.0
Work experience in the given field	Experience of working in the field from 2 to 5 years	2.5
Experience of cooperation	Worked together on the creation of several projects in the field of interest	10.0
Knowledge of applied tools and methods	Tools and methods, used in the project, are known to the team but are rarely used	5.0
Teams ability to clearly formulate and openly express ideas	Can clearly formulate, openly express and justify their ideas	10.0
Teams ability to work effectively in freedom or order	Able to work effectively in partial order	0.0
Means of communication	Direct communication	10.0
Frequency of reporting to the Customer	Reports on every operation	0.0
Understanding the scope of works	There is a detailed list of works, further alternation is possible	0.0
Learning ability	For some members of the team, it is hard to learn new information and technologies, but the team can adjust to changes	0.0
Consequences on case of unsatisfactory project outcome	Loss of insignificant sum of money	10.0
Number of people involved in the project	Less than 10 persons	10.0
Number of people involved in the project	Less than 11 persons	10.0
Understanding of requirements, adapting ability, initiative	Understand the requirements, can follow them, do not require regular control	2.5
Ability to admit mistakes	Openly admit making mistakes and try to never make them again	7.5
Project cost	Less than 100 thousand $	10.0
Requirements to the project quality	National requirements	5.0
Requirements to the realization period of the project	Not very urgent	5.0
Requirements to the precise compliance with a deadline	Insignificant deviation from the deadline is allowed	0.0
Requirements change percent/month	Less than 7%	0.0
Probability of occurrence of technical? manufacturing or qualitative risks	Risk is not likely to occur (10%)	10.0
Probability of occurrence of external risks (disruption of work by contractors, unfavorable political, economic situation in the country, market changes, etc.)	Risk is not likely to occur (10%)	10.0
Probability of occurrence of organizational risks (disruption of funding, delivery of resources, inaccurate prioritizing, etc.)	Risk is not likely to occur (10%)	10.0
Probability of occurrence of managerial risks (inefficient planning, controlling, communication problems, etc.)	Risk is not likely to occur (10%)	10.0

Figure 11 – Details of the scores of Kanban methodology for the project No. 3

DOI 10.15588/1607-3274-2022-2-17

Table 7 – Comparison of results with different versions of criterion weights

No.	Weights by default		Same weight (= 1)		User weights	
1	Scrum	0.5782	Scrum	0.6018	Scrum	0.5562
2	Kanban	0.5193	SWEBOK	0.4838	PMBOK	0.5167
3	SWEBOK	0.4796	Kanban	0.4824	ISO21500	0.5167
4	PRINCE2	0.4562	PMBOK	0.4771	SWEBOK	0.5154
5	PMBOK	0.4458	ISO21500	0.4771	PRINCE2	0.4874
6	ISO21500	0.44588	PRINCE2	0.4536	Kanban	0.4302
7	XP	0.3843	XP	0.4126	XP	0.3880

Table 8 – The critical characteristics for a respective methodology for each of the projects

Project No. 1 (Scrum)	**Project No. 2 (SWEBOK)**	**Project No. 3 (Kanban)**
Requirements change percent/month	Requirements change percent/month	Teams ability to work effectively in freedom or order
Work experience in the given field	Teams ability to work effectively in freedom or order	Frequency of reporting to the Customer
Understanding of the scope of works	Understanding of requirements, adapting ability, initiative	Understanding of the scope of works
Experience of cooperation	Frequency of reporting to the Customer	Learning ability
Customers experience of working with this project team	Customers experience of working with this project team	Requirements to the precise compliance with a deadline
		Requirements change percent/month

The **scientific novelty** of the received results lies in the fact that it is for the first time when the algorithm for the selecting a methodology of software development was designed, and unlike other existing algorithms this one provides for collecting of expert evaluation, yet considering the values of criteria, specified by the user independently, and implements the process of selecting methodologies using the methods of multi-criteria analysis AHP, TOPSIS and Weighted Sum.

Practical value of the results of this paper lies in the fact, that we suggested an approach, which helps software engineers to choose a methodology of software development, which meets their requirements and expectations. The approach is based on the developed algorithm, which uses 7 methodologies and 23 criteria of the projects and provides for collecting of expert evaluation as well as implements the process of selecting methodologies my means of methods of multi-criteria analysis AHP and Weighted Sum and allows us to determine "unsatisfactory" criteria for a particular methodology. The practical application of the suggested approach allows us to reduce the time spent on the process of selecting the methodology for a particular project by 2–3% of the total project cost, as well as increase the adequacy of the methodology selection, especially for the teams with little experience, which generally confirms the feasibility of its use when choosing the best software development methodology.

The developed software tool for multi-criteria decision-making regarding the selection of development methodology, depending on the characteristics of the project and organization of business processes in an IT company, allows for systematic investigating the problem of the methodology selection, prioritization and evaluation of the goals and alternatives of the selection.

REFERENCES

1. Sommerville, Ian. Software engineering. Boston, Pearson, 2011, 773 p.
2. V. B. S. Silva, F. Schramm and A. C. Damasceno, A multicriteria approach for selection of agile methodologies in software development projects, *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC).* Budapest, Hungary, 2016, pp. 2056–2060. DOI: 10.1109/SMC.2016.7844542.
3. Preeti Rai Impact of Different Methodologies in Software Development Process, (IJCSIT), *International Journal of Computer Science and Information Technologies*, 2014, Vol. 5 (2), pp. 1112–1116.
4. Harb Y. A., Noteboom C. Evaluating Project Characteristics for Selecting the Best-fit Agile Software Development Methodology: A Teaching Case Evaluating Project Characteristics for Selecting the Bestfit, *Journal of the Midwest Association for Information Systems*, 2015, Vol. 1 (1), pp. 33–52.
5. Kumar K., Kumar S. A Rule-based Recommendation System for Selection of Software Development Life Cycle Models, *ACM SIGSOFT Software Engineering Notes*, 2013, Vol. 38, Issue 4, pp. 1–6. DOI: 10.1145 / 2492248.2492269
6. Gil Hernández-Ledesma, Erik G. Ramos, Carlos A. Fernández-y-Fernández et al. Selection of Best Software Engineering Practices: A Multi-Criteria Decision Making Approach, *Research in Computing Science*, 2017, No. 136, pp. 47–60. DOI: 10.13053/rcs-136-1-4
7. Victor M., Upadhyay N. Selection of Software Testing Technique: A Multi Criteria Decision Making Approach, *Trends in Computer Science, Engineering and Information Technology. CCSEIT 2011. Communications in Computer and Information Science, Goa-403726, India 2011, proceedings.* Springer, Berlin, Heidelberg, Vol. 204, pp. 453–462 https://doi.org/10.1007/978-3-642-24043-0_46
8. Kononenko I. V., Lutsenko S. Yu. Method for selection of project management approach based on fuzzy concepts, *Bulletin of NTU "KhPI". Series: Strategic management, portfolio, program and project management*, 2017, Vol. 2 (1224). pp. 8–17. DOI: https://doi.org/10.20998/2413-3000.2017.1224.2
9. Despa M. L. Comparative study on software development methodologies, *Database Systems Journal*, 2014, Vol. V, № 3/2014, pp. 37–56.

DOI 10.15588/1607-3274-2022-2-17

10. Matharu G. S., Mishra A., Singh H. et al. Empirical Study of Agile Software Development Methodologies: A Comparative Analysis, *ACM SIGSOFT Software Engineering Notes,* 2015, Vol. 40, No. 1, pp. 1–6. https://doi.org/10.1145/2693208.2693233
11. Vijayasarathy L. R., Butler C. W. Choice of Software Development Methodologies: Do Organizational, Project, and Team Characteristics Matter? *IEEE Software*, 2016, Vol. 33, No. 5, pp. 86–94. DOI: 10.1109/MS.2015.26.
12. Gonzalez-Perez C., Henderson-Sellers B. Modelling software development methodologies: A conceptual foundation, *Journal of Systems and Software*, 2007, Vol. 80, No. 11, pp. 1778–1796. https://doi.org/10.1016/j.jss.2007.02.048
13. Saeed S., Jhanjhi NZ, Naqvi M. et al. Analysis of Software Development Methodologies, *International Journal of Computing and Digital Systems*, 2019, Vol. 8, No. 5, pp. 445–460. http://dx.doi.org/10.12785/ijcds/080502
14. Saeedi K., Visvizi A. Software Development Methodologies, HEIs, and the Digital Economy, *Education Sciences,* 2021, Vol. 11, No. 2, P. 73. https://doi.org/10.3390/educsci11020073
15. Symets I., Yakovyna V., Seniv M. The Relation between Software Development Methodologies and Factors Affecting Software Reliability, *Computer Sciences and Information Technologies (CSIT), 15th IEEE International Conference*. Lviv-Zbarazh, 23–26 September 2020, pp. 377–381. doi: 10.1109/CSIT49958.2020.9321937
16. Saaty T., Greco S., Ehrgott M., Figueira J. (eds). The analytic hierarchy and analytic network processes for the measurement of intangible criteria and for decision-making, *Multiple Criteria Decision Analysis. International Series in Operations Research & Management Science*. Springer, NY 2016, Vol. 233, pp. 363–419.

Received 30.01.2022.
Accepted 16.02.2022.

УДК 004.05; 004.4

ЗАСОБИ ПІДБОРУ МЕТОДОЛОГІЇ РОЗРОБЛЕННЯ ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ З УРАХУВАННЯМ ХАРАКТЕРИСТИК ПРОЕКТУ

Сенів М. М. – канд. техн. наук, доцент, доцент кафедри Програмного забезпечення, Національний університет «Львівська політехніка», Львів, Україна.

Ковтонюк А. М. – магістр інженерії програмного забезпечення, Національний університет «Львівська політехніка», Львів, Україна.

Яковина В. С. – д-р техн. наук, професор, професор кафедри Систем штучного інтелекту, Національний університет «Львівська політехніка», Львів, Україна; Факультет математики та комп’ютерних наук, Вармінсько-Мазурський Університет в Ольштині, Польща.

АНОТАЦІЯ

Актуальність. В процесі розробки програмного забезпечення вибір методології його розроблення є одним з важливих етапів, який суттєво впливає на успіх/провал проекту. Вибір оптимальної методології розробки залежить від багатьох факторів та є трудомісткою і нетривіальною задачею.

Мета. Відповідно, існує потреба у розробленні ефективного та гнучкого програмного засобу для підбору оптимальної методології розроблення програмного забезпечення, який би автоматизував даний процес а також враховував ключові характеристики проєкту.

Метод. В даній роботі представлено алгоритм підбору методології розроблення програмного забезпечення з використанням методів багатокритеріального аналізу та експертних оцінок, який передбачає збір оцінок експертів та реалізує процес підбору методології за допомогою методів AHP, TOPSIS та Weighted Sum.

Результати. З використанням вищезазначеного алгоритму було розроблено програмну систему для підбору оптимальної методології розроблення програмного забезпечення в залежності від характеристик проєкту, де враховано ваги критеріїв, надані експертами, а також застосовано метод AHP для визначення користувацьких пріоритетів критеріїв порівняння методологій. Для обчислення оцінок вибору методологій було обрано метод зваженої суми та TOPSIS. Програмний засіб передбачає виведення корисних деталей про результати підбору, а саме експертну оцінку заданих значень параметрів відносно всіх методологій, та може бути використаний для підвищення ефективності процесу розроблення програмного забезпечення в частині автоматизації надання рекомендацій керівникам IT-проектів.

Висновки. Розроблено алгоритм для вибору методології розроблення програмного забезпечення, який, на відміну від існуючих, передбачає збір оцінок експертів, враховуючи при цьому значення критеріїв, заданих користувачем самостійно, і реалізує процес підбору методологій використовуючи методи багатокритеріального аналізу AHP, TOPSIS та Weighted Sum. З використанням вищеописаного алгоритму було розроблено програмну систему для підбору оптимальної методології розроблення програмного забезпечення в залежності від характеристик проєкту, де враховано ваги критеріїв, надані експертами, а також застосовано метод AHP для визначення користувацьких пріоритетів критеріїв порівняння методологій. Для обчислення оцінок вибору методологій було обрано метод зваженої суми та TOPSIS. Програмний засіб передбачає виведення корисних деталей про результати підбору, а саме експертну оцінку заданих значень параметрів відносно всіх методологій.

КЛЮЧОВІ СЛОВА: програмне забезпечення; методології розробки програмного забезпечення; інженерія програмного забезпечення.

УДК 004.05; 004.4

СРЕДСТВА ПОДБОРА МЕТОДОЛОГИИ РАЗРАБОТКИ ПРОГРАММНОГО ОБЕСПЕЧЕНИЯ С УЧЕТОМ ХАРАКТЕРИСТИК ПРОЕКТА

Сенив М. М. – канд. техн. наук, доцент, доцент кафедры Программного обеспечения, Национальный университет «Львовская политехника», Львов, Украина.

Ковтонюк А. М. – магистр инженерии программного обеспечения, Национальный университет «Львовская политехника», Львов, Украина.

Яковина В. С. – д-р техн. наук, профессор, профессор кафедры Систем искусственного интеллекта, Национальный университет «Львовская политехника», Львов, Украина; Факультет математики и компьютерных наук, Варминско-Мазурский Университет в Ольштыне, Польша.

DOI 10.15588/1607-3274-2022-2-17

АННОТАЦИЯ

Актуальность. В процессе разработки программного обеспечения выбор методологии его разработки является одним из важных этапов, существенно влияющих на успех/провал проекта. Выбор оптимальной методологии разработки зависит от многих факторов и является трудоемкой и нетривиальной задачей.

Цель. Соответственно, существует потребность в разработке эффективного и гибкого программного средства для подбора оптимальной методологии разработки программного обеспечения, которое бы автоматизировало данный процесс а также учитывало ключевые характеристики проекта.

Метод. В данной работе представлен алгоритм подбора методологии разработки программного обеспечения с использованием методов многокри-териального анализа и экспертных оценок, предусматривающий сбор оценок экспертов и реализующий процесс подбора методологии с помощью методов AHP, TOPSIS и Weighted Sum.

Результаты. С использованием вышеупомянутого алгоритма была разработана программная система для подбора оптимальной методологии разработки программного обеспечения в зависимости от характеристик проекта, где учтены весы критериев, предоставленные экспертами, а также применен метод AHP для определения пользовательских приоритетов критериев сравнения методологий. Для вычисления оценок выбора методологии был выбран метод взвешенной суммы и TOPSIS. Программное средство предполагает вывод полезных деталей о результатах подбора, а именно экспертную оценку заданных значений параметров относительно всех методологий, и может быть использован для повышения эффективности процесса разработки программного обеспечения в части автоматизации предоставления рекомендаций руководителям ИТ-проектов.

Выводы Разработан алгоритм выбора методологии разработки проограммного обеспечения, который, в отличие от существующих, предусматривает сбор оценок экспертов, учитывая при этом значение критериев, заданных пользователем самостоятельно, и реализует процесс подбора методологий используя методы многокритериального анализа AHP, TOPSIS и Weighted Sum. С использованием вышеописанного алгоритма была разработана программная система для подбора оптимальной методологии разработки программного обеспечения в зависимости от характеристик проекта, где учтены весы критериев, предоставленные экспертами, а также применен метод AHP для определения пользовательских приоритетов критериев сравнения методологий. Для вычисления оценок выбора методологии был выбран метод взвешенной суммы и TOPSIS. Программное средство предусматривает вывод полезных деталей о результатах подбора, а именно экспертную оценку заданных значений параметров в отношении всех методологий.

КЛЮЧЕВЫЕ СЛОВА: программное обеспечение; методологии разработки программного обеспечения; инженерия программного обеспечения.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Sommerville, Ian. Software engineering. / I. Sommerville. – Boston : Pearson, 2011. – 773 p.
2. Silva V. B. S. A multicriteria approach for selection of agile methodologies in software development projects / V. B. S. Silva, F. Schramm and A. C. Damasceno //2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC). – Budapest, Hungary. – 2016. – P. 2056–2060. DOI: 10.1109/SMC.2016.7844542.
3. Preeti Rai Impact of Different Methodologies in Software Development Process, (IJCSIT) / R. Preeti// International Journal of Computer Science and Information Technologies. – 2014. – Vol. 5 (2). – P. 1112–1116.
4. Harb Y.A. Evaluating Project Characteristics for Selecting the Best-fit Agile Software Development Methodology: A Teaching Case Evaluating Project Characteristics for Selecting the Bestfit / Y. A. Harb., C. Noteboom // Journal of the Midwest Association for Information Systems. – 2015. – Vol. 1 (1). – P. 33–52.
5. Kumar K. A Rule-based Recommendation System for Selection of Software Development Life Cycle Models / K. Kumar, S. Kumar // ACM SIGSOFT Software Engineering Notes. – 2013. – Vol. 38, Issue 4. – P. 1–6. DOI: 10.1145 / 2492248.2492269
6. Selection of Best Software Engineering Practices: A Multi-Criteria Decision Making Approach / Gil Hernández-Ledesma, Erik G. Ramos, Carlos A. Fernández-y-Fernández et al. // Research in Computing Science. – 2017. – № 136. – P. 47–60. DOI: 10.13053/rcs-136-1-4
7. Victor M. Selection of Software Testing Technique: A Multi Criteria Decision Making Approach / M. Victor, N. Upadhyay // Trends in Computer Science, Engineering and Information Technology. CCSEIT 2011. Communications in Computer and Information Science, Goa-403726, India 2011: proceedings. – Springer, Berlin, Heidelberg. – Vol. 204. – P. 453–462. https://doi.org/10.1007/978-3-642-24043-0_46
8. Kononenko I. V. Method for selection of project management approach based on fuzzy concepts / I. V. Kononenko S. Yu. Lutsenko // Bulletin of NTU "KhPI". Series: Strategic management, portfolio, program and project management. – 2017. – Vol. 2 (1224). – P. 8–17. DOI: https://doi.org/10.20998/2413-3000.2017.1224.2
9. Despa M. L. Comparative study on software development methodologies / M. L. Despa // Database Systems Journal. – 2014. – Vol. V, № 3/2014. – P. 37–56.
10. Empirical Study of Agile Software Development Methodologies: A Comparative Analysis / G. S. Matharu. A. Mishra, H. Singh et al. // ACM SIGSOFT Software Engineering Notes. – 2015. – Vol. 40, № 1. – P. 1–6. https://doi.org/10.1145/2693208.2693233
11. Vijayasarathy L.R. Choice of Software Development Methodologies: Do Organizational, Project, and Team Characteristics Matter? / L. R. Vijayasarathy. C. W. Butler // IEEE Software. – 2016. – Vol. 33, № 5. – P. 86–94. DOI: 10.1109/MS.2015.26.
12. Gonzalez-Perez C. Modelling software development methodologies: A conceptual foundation / C. Gonzalez-Perez, B. Henderson-Sellers // Journal of Systems and Software. – 2007. – Vol. 80, № 11, – P. 1778–1796. https://doi.org/10.1016/j.jss.2007.02.048
13. Analysis of Software Development Methodologies / S. Saeed, NZ Jhanjhi, M. Naqvi et al. // International Journal of Computing and Digital Systems. – 2019. – Vol. 8, № 5. – P. 445–460. http://dx.doi.org/10.12785/ijcds/080502
14. Saeedi K. Software Development Methodologies, HEIs, and the Digital Economy / K. Saeedi, A. Visvizi. // Education Sciences. – 2021. – Vol. 11, № 2. – P. 73. https://doi.org/10.3390/educsci11020073
15. Symets I. The Relation between Software Development Methodologies and Factors Affecting Software Reliability / I. Symets, V. Yakovyna, M. Seniv // Computer Sciences and Information Technologies (CSIT) : 15th IEEE International Conference, Lviv-Zbarazh, 23–26 September. – 2020. – P. 377–381. DOI: 10.1109/CSIT49958.2020.9321937
16. Saaty T. The analytic hierarchy and analytic network processes for the measurement of intangible criteria and for decision-making / T. Saaty // Multiple Criteria Decision Analysis. International Series in Operations Research & Management Science / Greco S., Ehrgott M., Figueira J. (eds). – Springer, NY. – 2016. – Vol. 233. – P. 363–419.

DOI 10.15588/1607-3274-2022-2-17

UDC 681.518:004.93

INFORMATION-EXTREME MACHINE TRAINING SYSTEM OF FUNCTIONAL DIAGNOSIS SYSTEM WITH HIERARCHICAL DATA STRUCTURE

Shelehov I. V. – PhD, Associate Professor, Associate Professor of the Department of Computer Science, Sumy State University, Sumy, Ukraine; DrS-student at the Department of Computer Systems, Networks and Cybersecurity, National Aerospace University M.E. Zhukovsky "Kharkiv Aviation Institute", Kharkiv, Ukraine.

Barchenko N. L. – PhD, Associate Professor of the Department of Computer Science, Sumy State University, Sumy, Ukraine.

Prylepa D. V. – Assistant Professor, Department of Computer Science, Sumy State University, Sumy, Ukraine.

Bibyk M. V. – Assistant of the Konotop Institute of Sumy State University, Konotop, Ukraine.

ABSTRACT

Context. The problem of information-extreme machine learning of the functional diagnosis system is considered by the example of recognizing the technical state of a laser printer by typical defects of the printed material. The object of the research is the process of hierarchical machine learning of the functional diagnosis system of an electromechanical device.

Objective. The main objective is to improve the functional efficiency of machine learning during functional diagnostics system retraining using automatically forming a new hierarchical data structure for an expanded alphabet of recognition classes.

Method. A method of information-extreme hierarchical machine learning of the system of functional diagnosis of a laser printer based on typical defects of the printed material is proposed. The method was developed with functional approach of modeling the cognitive processes of natural intelligence, which makes it possible to give the diagnostic system the properties of adaptability under arbitrary initial conditions for the formation of images of printing defects and flexibility during retraining of the system due to an increase in the power of the alphabet of recognition classes. The method is based on the principle of maximizing the amount of information in the process of machine learning. The process of information-extreme machine learning is considered as an iterative procedure for optimizing the parameters of the functioning of the functional diagnostics system according to the information criterion. As a criterion for optimizing machine learning parameters, a modified Kullback's information measure is considered, which is a functional of the exact characteristics of classification solutions. According to the proposed categorical functional model, an information-extreme machine learning algorithm has been developed based on a hierarchical data structure in the form of a binary decomposition tree. The use of such a data structure makes it possible to split a large number of recognition classes into pairs of nearest neighbors, for which the optimization of machine learning parameters is carried out according to a linear algorithm of the required depth.

Results. Information, algorithmic software for the system of functional diagnostics of a laser printer based on images of typical defects in printed material has been developed. The influence of machine learning parameters on the functional efficiency of the system of functional diagnostics of a laser printer based on images of defects in printed material has been investigated.

Conclusions. The results of physical modeling have confirmed the efficiency of the proposed method of information-extreme machine learning of the system of functional diagnosis of a laser printer based on typical defects in printed material and can be recommended for practical use. The prospect of increasing the functional efficiency of information-extremal learning of the functional diagnostics system is to increase the depth of machine learning by optimizing additional parameters of the system's functions, including the parameters of the formation of the input training matrix.

KEYWORDS: information-extreme machine learning, categorical functional model, information criterion, control tolerance system, functional diagnostics, laser printer.

ABBREVIATIONS

IEI-technology is an information-extreme intellectual technology;

SCD ia s system of control tolerances;

SFD is a system of functional diagnostics.

NOMENCLATURE

M is a set of recognition classes;

m is a number of the recognition class;

N is a set of recognition features in the structured vector;

i is a number of the recognition feature;

J is a set of structured vectors of recognition features;

j is a number of the structured vector;

H is a set of tiers of decursive tree;

h is a number of the tier of decursive tree;

S is a set of strata of decursive tree;

s is a number of the stratum of decursive tree;

m_s is a serial number of the recognition class in the s-th stratum;

$X^{|S|}$ is an averaged vector of recognition class features $X^{|S|}$;

d_{h,s,m_s} is a radius of the hyperspherical container of the recognition class x_{h,s,m_s};

$\delta_{h,s}$ is a parameter equal to half of the control field of tolerances on the characteristics of the recognition classes of the s-th stratum of the h-th tier;

δ_H is a parameter equal to half the normalized field of tolerances for recognition features;

DOI 10.15588/1607-3274-2022-18

E_{h,s,m_s} is an information criterion for optimizing machine learning parameters for the recognition class X^{o}_{h,s,m_s};

G_E is a working (permissible) area for determining the function of the information criterion of optimization;

G_d is an allowable range of values of the radius of the containers of the recognition classes;

G is a set of input factors;

T is a set of moments of time reading information;

Ω is a space of recognition signs;

Z is a set of technical conditions of the object of diagnosis;

Y is an input training matrix;

X is a working binary training matrix;

g is a decursive tree construction operator;

f_1 is a training matrix formation operator;

f_2 is an operator of binary training matrix formation X;

$I^{|C|}$ is a set C of statistical hypotheses;

$\Im^{|Q|}$ is a set Q of exact characteristics;

$G_{\delta,h,s}$ is a valid range of parameter values $\delta_{h,s}$;

d is a parameter that characterizes in code units the value of the radius of the containers of the recognition classes;

$\alpha^{(k)}_{h,s,m_s}$ is an error of the first kind, calculated in the k-th step of machine learning;

$\beta^{(k)}_{h,s,m_s}$ is an error of the second kind, calculated in the k-th step of machine learning;

p is a small enough number that is entered to avoid division by zero;

$x^{(j)}$ is a recognizable vector of signs;

μ_{m_s} is an membership function of the vector $x^{(j)}$ of the recognition class X^{o}_{h,s,m_s};

d^{*}_{h,s,m_s} is are optimal values of the recognition class container X^{o}_{h,s,m_s};

L is a set of steps of the machine algorithm for sequential optimization of control tolerances;

l is a number of the step of machine algorithm;

$\otimes$ is a repeat operation symbol;

D_1^{*} is an extreme value of the first reliability;

β^{*} is an extreme value of the error of the second kind;

$M_{h,s}$ is a set of recognition classes in the s-th stratum of the h-th tier;

$m_{h,s}$ is a number of the recognition class in the s-th stratum of the h-th tier;

$\{k\}$ is a set of steps of machine learning;

$\tilde{\Re}^{|M|}$ is a fuzzy division of the feature space into M recognition classes;

$Y^{|S|}$ is an input training matrix of recognition classes S strata of decursive tree;

$X^{|S|}$ is a binary training matrix of recognition classes S of decursive tree strata;

E is a term set of values of the information criterion;

R is an operator of construction of division $\tilde{\Re}^{|2|}$ of space of signs on recognition classes;

Ψ is an operator for testing the basic statistical hypothesis about the affiliation of the vector x_{h,s,m_s} of the recognition class $X^{o}_{h,s,\Bbbk\Bbbk m_s}$;

γ is an operator of formation of a set of exact characteristics for the set system of estimations of decisions;

φ is an operator for calculating the information criterion for optimizing the parameters of machine learning;

$y_{m,i}$ is a value of the i-th diagnostic feature of the average of the educational matrix vector y_m of the recognition class X^{o}_m;

U is an operator that regulates the process of machine learning;

$M_{h,s}$ is a number of recognition classes of the s-th stratum of the h-th tier.

INTRODUCTION

No matter how reliable a laser printer is, over time it loses its initial stability. Defects can be caused by individual pieces of equipment, consumables, printing materials, internal or external software, and environmental conditions. Therefore, the creation of SFD laser printer by analyzing the image of the printed material is an urgent task. The main way to solve this problem is to apply ideas and methods of data mining based on machine learning and pattern recognition.

A method of hierarchical information-extreme machine learning for task of information synthesis of SFD laser printer by defects in printed material is proposed.

The object of research is the process of SFD hierarchical machine learning.

The recognition classes alphabet expansion leads to increase the degree of their intersection in the fixed diagnostic features space and to reduce the full probability of correct diagnosis. One of the ways to increase the functional efficiency of SFD machine learning is a transforming a linear data structures to hierarchical ones. However, the existing methods of data mining, including artificial neural networks, have a problem of retraining the system. The solution of this problem requires reprogramming of the intelligent system by changing its structure or functional model.

The subject of research is the method of SFD information-extreme hierarchical machine learning.

DOI 10.15588/1607-3274-2022-18

The known divisive or agglomerative hierarchical machine learning methods have functional efficiency that significantly depends on the power of the recognition classes alphabet. Therefore, important tasks are to reduce the impact of the alphabet's power for high efficiency and rapidity of diagnostic solutions.

The purpose of the work is to increase the functional efficiency of SFD machine learning during its retraining after expanding the recognition classes alphabet by automatically forming a new hierarchical data structure.

1 PROBLEM STATEMENT

Consider the formalized formulation of the problem of information synthesis capable of learning the SFD of a laser printer based on images of defects in printed material.

Let the alphabet $\{X_m^o \mid m = \overline{1,M}\}$, of recognition classes, which characterize the different technical states of the laser printer be given. Based on the results of scanning the images of defects in the printed material of the laser printer, the input training matrix of brightness is formed $\| y_{m,i}^{(j)} \mid i = \overline{1,N}; j = \overline{1,J} \|$, in which i-th column of the matrix is a training sample, and j-th row is a structured vector of features of the recognition class X_m^{o}.

By constructing a decursive hierarchical structure, it is necessary to divide the alphabet $\{X_m^{\text{o}}\}$ into pairs of the nearest neighboring recognition classes.

According to the concept of IEI-technology, the input training matrix is transformed into a working binary matrix, which in the process of machine learning is adapted to the maximum reliability of diagnostic solutions. Let the depth of machine learning be equal to two levels. At the first level, the optimal (hereinafter in the informational sense) geometric parameters of hyperspherical containers of recognition classes are determined, and at the second level, the system of control tolerances for recognition features is determined. In this case, the vector of operating parameters that affect the functional efficiency of machine learning system to recognize the vectors of class features X_{h,s,m_s}^{o}, has the form

$$g_{h,s} = < x_{h,s,m_s}, d_{h,s,m_s}, \delta_{h,s} > . \quad (1)$$

The restrictions are imposed on the parameters of the system, which will be called machine learning parameters:

– the radius d_{h,s,m_s} of the recognition class container X_{h,s,m_s}^{o} must be less than the center-to-center distance to its nearest neighbor of the corresponding stratum;

– the range of parameter values $\delta_{h,s}$ is given by the inequality

$$\delta_{h,s} < \delta_H / 2.$$

DOI 10.15588/1607-3274-2022-18

In the process of machine learning SFD is necessary:

1) optimize the parameters of vector (1) according to the alphabetical average of recognition $\{X_{h,s,m_s}^{\text{o}}\}$ information criteria

$$\overline{E}_{h,s} = \frac{1}{2} \sum_{m=1}^{2} \max_{G_E \cap G_{d,s}} E_{h,s,m_s}(d_{h,s,m_s}); \quad (2)$$

2) according to the optimal geometric parameters of the containers of recognition classes obtained in the process of machine learning to build decisive rules for each stratum of the hierarchical structure, which guarantee a high total probability of making the correct diagnostic decisions.

3) at the stage of examination it is necessary to make a classification decision on the belonging of the recognized recognition to one of the classes of the formed alphabet of the corresponding final stratum;

4) automatically form a decursive hierarchical data structure that contains the learning matrix of the new recognition class and retrain the SFD.

Thus, the task of information-extreme synthesis of learnable SFD is to optimize the parameters of its machine learning by approaching the global maximum of the information criterion (2) to its maximum limit value.

2 REVIEW OF THE LITERATURE

A detailed analysis of the causes of possible defects of the material printed on a typical laser printer is considered in [1, 2]. In practice, diagnosing a laser printer for defects in printed material requires a high level of professionalism and experience from the person performing the repair. However, the search for the cause of the defect is usually associated with the need to study the technical condition of the components and devices of the laser printer and test the system software. At the current level of development of information technology, increasing the efficiency of troubleshooting machines and complex devices is achieved through computer-integrated systems of functional diagnostics (SFD) [3, 4]. As the main way of information synthesis of SFD is the use of intelligent information technologies of data analysis [5–7]. At the same time, the most widespread methods of machine learning and pattern recognition [8, 9]. Algorithms of machine learning based on neural networks [10–12] and the method of reference vectors [13, 14] are known, but due to the many dimensions of the feature dictionary and significant intersection of recognition classes, they do not allow to achieve high enough image recognition reliability. In [15–17], the application of fuzzy neural networks for functional diagnostics is considered, but there is also the problem of multidimensionality, which significantly limits the capability of fuzzy logic.

In [18, 19] to reduce the impact of multidimensionality, it is proposed to use input data extractors built on artificial networks, but this approach can lead to loss of information. The use of ideas and methods of the so-called IEI-data analysis technology, which is based on maximizing the information capacity of the system in the process of its machine learning [20–22], should be considered as a promising area. The main paradigm of information-extreme machine learning, as in neuro-like structures, is the adaptation of the input mathematical description of the system to the maximum reliability of pattern recognition. But in contrast to neuro-like structures, the decision-making rules constructed within the framework of the geometric approach are practically invariant to the multidimensionality of the dictionary of features. Since the use of functional diagnostics is expedient at high power of the alphabet of recognition classes, which characterize the possible technical conditions of the device, it is necessary to retrain the SFD in automatic mode. To this end, [23–25] considers the functioning of the SFD in the mode of information-extreme hierarchical machine learning, which allows you to automatically retrain the system when expanding the alphabet of recognition classes. But these works do not explore the problem of building a new hierarchical data structure, which inevitably arises when retraining SFD.

The article considers the problem of increasing the functional efficiency of information-extreme machine learning by automatically forming a new hierarchical data structure when retraining SFD through the expansion of the alphabet of recognition classes.

3 MATERIALS AND METHODS

The method of information synthesis of SFD will be considered as part of IEI-technology based on maximizing the information capacity of the system in the process of information-extreme machine learning. It is known that with increasing the power of the alphabet of recognition classes and the constant space of diagnostic features increases the degree of intersection of recognition classes. Since in [21] the degree of intersection of recognition classes is characterized by the ratio of the total probability P_f of making erroneous diagnostic decisions to the total probability P_t of making correct diagnostic decisions, the reliability of diagnosis, respectively, due to increasing probability P_f will decrease. A recognized way to reduce the impact of the multidimensionality of the recognition alphabet on the functional efficiency of machine learning is the transition from a linear data structure to a hierarchical.

Consider the possibility of automating the formation of the input learning matrix by expanding the alphabet of recognition classes by implementing the method of information-extreme machine learning using a hierarchical data structure in the form of a binary decursive information tree. The data structure in the form of a binary tree will be called decursive, in which, in contrast to the recursive attribute from the top of the upper tier is transferred to the top of its stratum of the lower tier. In our case, the learning matrices of the corresponding recognition classes are considered as attributes of the vertices. Final executions from which attributes are not transferred will be called final. Thus, as the power of the recognition class alphabet increases, the decursive hierarchical structure is divided into strata, each of which consists of the two closest in binary space Hamming features of the recognition classes. This allows for their classification to use a linear algorithm of information-extreme machine learning of the required depth. In contrast to neuro-like structures, the depth of information-extreme machine learning is determined not by the number of hidden layers, but by the number of machine learning parameters that are optimized by the information criterion.

The incidence matrix $A=\{a_{\pi,\varsigma}\}$ of a decursive tree will be determined as follows:

$a_{\pi,\varsigma} = 1$, if the beginning of the edge ς connects to the vertex π and has a direction from the vertex π;

$a_{\pi,\varsigma} = -1$, if the end (arrow) of the rib ς connects to another vertex and has a direction from the vertex π;

$a_{\pi,\varsigma} = 0$, if the beginning of the edge ς does not connect to the vertex π;

$a_{\pi,\varsigma} = *$, if the beginning of the edge ς connects with the vertex π and has a direction from the vertex π to the vertex of the stratum of the lower tier with the same attribute.

For the incident matrix of a decursive tree the specific difference from the oriented graph establishes the following lemma.

Lemma. For a decursive graph with ς edges, the number of columns of the incident matrix that have zero sum of elements is equal to $\varsigma - \pi^*$, where π^* – the number of vertices that pass their attributes.

The functional categorical model of information-extreme machine learning according to the hierarchical data structure will be presented in the form of an oriented graph of mappings by machine learning operators of the corresponding sets one on top of the other

$$I_B = \langle G, T, \Omega, Z, H, Y^{|S|}, X^{|S|}, g, f_1, f_2 \rangle.$$

The categorical model of information-extreme machine learning of SFD according to the decursive hierarchical structure of data is shown in Fig. 1.

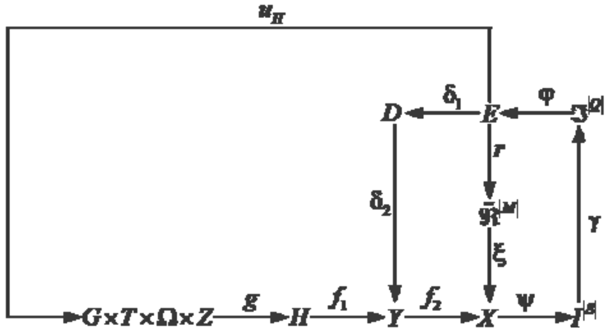


Figure 1 – Categorical model of SFD machine learning

Shown in Fig. 1 the operator g from the source of information, which is given by the Cartesian product of sets $T \times G \times \Omega \times Z$, forms a decursive binary tree H,

DOI 10.15588/1607-3274-2022-18

and the operator f_1 forms the input fuzzy learning matrices of the corresponding strata $Y^{|S|}$. The operator f_2 by comparing the recognition features with their specified control tolerances forms a set of $X^{|S|}$ binary working matrices, which in the process of machine learning through allowable transformations are adapted to the maximum possible probability of making the correct classification decisions. The term set E, the elements of which are calculated at each step of machine learning values of the information criterion, according to the principle of complete composition is common to all contours of optimization of learning parameters. The operator $r: E \rightarrow \tilde{\Re}^{|M|}$ At each step of machine learning restores in the radial basis of the binary space of Hamming signs containers of recognition classes, which form a partition $\tilde{\Re}^{|M|}$. The operator ξ displays the partition $\tilde{\Re}^{|M|}$ on the fuzzy distribution of binary vectors of recognition classes $\{X^{o}_{h,s,m_s}\}$. Next, the operator $\psi: X_{h,\ s} \rightarrow I^{|C|}$ tests the basic statistical hypothesis $\gamma: x^{(j)}_{h,s,m_s} \in X^{o}_{h,s,m_s}$. The operator γ determines the set of accuracy characteristics $\Im^{|Q|}$, where $Q=C^2$, and the operator φ calculates the set E of values of the information criterion of optimization, which is a functional of the accuracy characteristics. The control tolerance optimization loop is closed by a term set D, the elements of which are the values of the control tolerances on the recognition features. The operator u_H regulates the process of machine learning.

Thus, the proposed categorical model of information-extreme machine learning allows directly in the operating mode to automatically retrain SFD when expanding the alphabet of recognition classes.

Information-extreme machine learning according to the hierarchical data structure in the form of a binary decursive tree is carried out according to the scheme:

1) the average vectors $\{y_m \mid m = \overline{1, M}\}$ of structured diagnostic features are determined by the input training matrices of the initial alphabet recognition classes;

2) for a given parameter δ of the field of control tolerances are calculated for each i-th feature of the vector y_m lower $A_{HKm,\ i}$ and upper $A_{BKm,\ i}$ control tolerances for diagnostic features according to the formulas

$$A_{HKm,\,i} = y_{m,\ i} - \delta;\ A_{BKm,\,i} = y_{m,\ i} + \delta;$$

a set of $\{x_m\}$ binary averaged vectors of diagnostic features is formed as a rule

$$x_{m,i} = \begin{cases} 1, \text{if } A_{HKm,i} < y_{m,i} < A_{BKm,i}; \\ 0, \text{if otherwise}; \end{cases}$$

3) the vectors of the set $\{x_m\}$ are ordered by increasing the code distance from the zero binary vector;

4) binary ordered vectors of diagnostic features are divided into two approximately equal groups, which determine the two branches of the binary decursive tree;

5) as attributes of vertices of the first (upper according to dendrographic classification) tier of a decursive tree containing one stratum, educational matrices of recognition classes are selected, the averaged vectors of features of which are adjacent for each group;

6) strata of the lower tiers of each branch of the tree contain in addition to the transported from the upper tier of the training matrix also the training matrix of the nearest neighboring in its group recognition class;

7) the construction of the tree continues until the final strata are formed, which contain training matrices of all recognition classes from the initial complete alphabet $\{X^{o}_{m}\}$.

Thus, the binary decursive tree constructed according to the above scheme divides the given alphabet of high power into strata, each of which contains the two nearest neighboring classes. As a result, the necessary condition is created for the construction of highly reliable decision rules for each stratum by information-extreme machine learning according to a linear algorithm.

According to the categorical model (Fig. 1), the information-extreme algorithm of SFD machine learning according to the hierarchical data structure will be presented in the form of a procedure for finding the global maximum averaged alphabetically $\{X^{o}_{h,s,m_s}\}$ classes of recognition of the corresponding stratum criterion (2):

$$\delta^{*}_{K,\,h,\,s} = \arg \max_{G_{\delta,\ h,\ s}} \{ \max_{G_E \cap G_d} \overline{E}_{h,\ s}(d) \}. \tag{3}$$

Thus, in contrast to the linear algorithm, in which the optimal value of the parameter δ is determined for the entire alphabet of recognition classes, in information-extreme machine learning on a hierarchical decursive data structure, the parameter δ is determined for each stratum separately.

The internal cycle of procedure (3) implements the basic algorithm, the functions of which are the calculation at each step of machine learning criterion (2), finding its global maximum and determining the optimal geometric parameters of the containers of recognition classes.

The input data of the basic algorithm are an array of implementations $\{y^{(j)}_{m,\ i} \mid m = \overline{1, M}; i = \overline{1, N}, j = \overline{1, n}\}$, a system of control tolerances $\{\delta_{K,\ i}\}$ for diagnostic features and levels of selection $\{\rho_{m,\ i}\}$ of coordinates of binary averaged feature vectors, which in our case by default are equal to $\rho_{m,\ i} = 0{,}5$.

Optimization of geometric parameters of containers of recognition classes takes place according to the following main stages of the basic algorithm of machine learning:

1) formation of the input structured learning matrix;

2) determination of average implementations of recognition classes;

3) the formation of a binary training matrix with a given system of control tolerances for diagnostic signs;

DOI 10.15588/1607-3274-2022-18

4) determination of averaged binary feature vectors, the coordinates of which are calculated by statistical averaging of the corresponding binary training samples;

5) determining the center-to-center distances for a given alphabet of recognition classes by calculating the code distances between the averaged vectors of features of recognition classes.

6) calculation at each step of learning the average information criterion for optimizing the parameters of machine learning;

7) search for the global maximum of the average information criterion for optimizing the parameters of machine learning, which is in the working (permissible) area of determining the function of the criterion;

8) determination of optimal radius of containers of recognition classes, which at each step of machine learning are restored in the radial basis of the space of diagnostic features by iterative procedure

$$d^*_{h,s,m} = \arg \max_{G_E \cap G_d} \overline{E}_{h,s}(d_{h,s,m}),\ m = \overline{1, M}_{h,s}, \tag{4}$$

9) STOP.

In the external cycle of procedure (3) the operator of change of the parameter $\delta_{h,\ s}$ of the field of control tolerances is realized until the value of the information criterion of optimization of parameters of machine learning does not reach the maximum value.

As a criterion for optimizing the parameters of machine learning SFD for each stratum of the decursive hierarchical data structure was used a modified Kulback's information measure, which for equally probable two alternative hypotheses has the form

$$E^{(k)}_{h,s,m} = \frac{1}{2}\{2 - [\alpha^{(k)}_{h,s,m}(d) + \beta^{(k)}_{h,s,m}(d)]\} \times \\ \times \log_2 \frac{2 - [\alpha^{(k)}_{h,s,m}(d) + \beta^{(k)}_{h,s,m}(d)] + 10^{-p}}{\alpha^{(k)}_{h,s,m}(d) + \beta^{(k)}_{h,s,m}(d)] + 10^{-p}}. \tag{5}$$

When calculating the information criterion of optimization (5) in the process of implementing the machine learning algorithm due to the limited random samples in the training matrix instead of the exact characteristics used their estimates.

According to the optimal geometric parameters of hyperspherical containers of recognition classes, decisive rules in the form of implication are constructed

$$(\forall X^o_{m,h,s} \in \Re^{|M|})(\forall x^{(j)} \in \Re^{|M|})\{if\ [(\mu_{m_s} > 0)\ \& \\ \&\ (\mu_m = \max_{\{m\}}\{\mu_{m_s} \mid m_s = \overline{1,2}\}]\ then\ x^{(j)} \in X^o_{h,s,m_s} \\ else\ x^{(j)} \notin X^o_{h,s,m_s}\}. \tag{6}$$

In expression (6) function μ_m the affiliation of the vector $x^{(j)}$ to the hyperspherical container of the recognition class X^{o}_{h,s,m_s} is determined by the formula

$$\mu_m = 1 - \frac{d(x^{(j)} \oplus x^*_{h,s,m})}{d^*_{h,s,m}}. \tag{7}$$

Thus, the vector of features $x^{(j)}$ belongs to the class from the given alphabet of the corresponding stratum, for which the membership function (6) is positive and maximal. In addition, built on the geometric approach of the decision rules (6) allow you to make diagnostic decisions in real time, which is relevant in functional diagnosis.

4 EXPERIMENTS

As an example of the implementation of information-extreme machine learning SFD images of seven printing defects were considered, which characterized the corresponding recognition classes, arranged according to the above scheme of construction of the variation series and shown in Fig. 2.

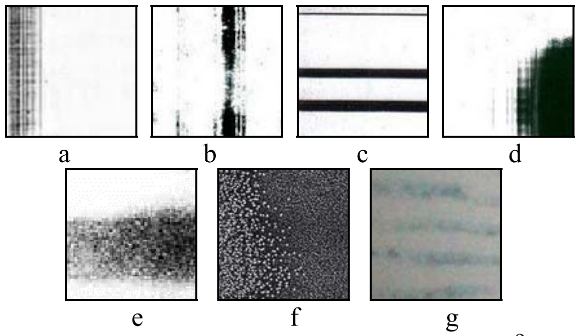


Figure 2 – Image of printing defects: a – class X^o_1 ; b – class X^o_2 ; c – class X^o_3 ; d – class X^o_4 ; e – class X^o_5 ; f – class X^o_6 ; g – class X^o_7

The following are the factors that determine the causes of defects in printed material:

1) damaged coating of the photoconductor, which causes a defect on the edge of the printed image in the form of repeating black stripes (recognition class X^o_1);

2) amaged corotron (charge roller), in which repeated vertical stripes are visible in the middle of the printed image (recognition class X^o_2);

3) damage to the thermal film, in the case of which horizontal black lines appear on the printed image (recognition class X^o_3);

4) worn drum coating, which causes the appearance of wide repeating black stripes on the edge of the printed image (recognition class X^o_4);

5) worn corotron, which leads to the appearance of repeating spots on the printed image (recognition class X^o_5);

DOI 10.15588/1607-3274-2022-18

6) incorrectly installed bushing on the corotron, which leads to the black color of part of the printed image (recognition class X_6^o);

7) poor quality toner cartridge, which causes the appearance of wavy lines and blurs on the printed image (recognition class X_7^o).

The input training matrix was formed by reading the brightness of the pixels of parts of the images of the printed material with the dimension of 100×100 pixels that contained defects, shown in Fig. 2. Since the images are considered stationary in brightness, their scanning was carried out in the Cartesian coordinate system. In addition, its transposed matrix was attached to the input training matrix, which allowed to double the space of diagnostic features and thus, in accordance with the maximum-distance principle of recognition theory, create the necessary conditions to increase the average interclass code distance.

In order to test the functional efficiency of the proposed method, information-extreme machine learning of the SFD was first implemented according to the hierarchical decursive structure of the first five and seventh shown in Fig. 2 recognition classes. In Fig. 3 shows the initial decursive data structure, built according to the above algorithm.

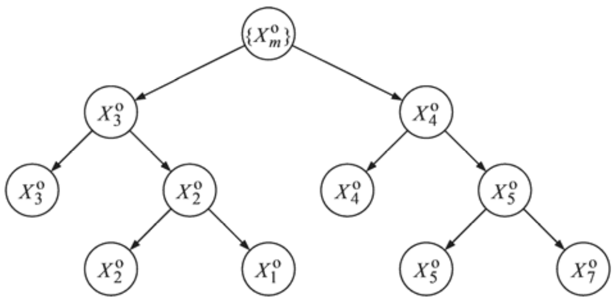


Figure 3 – Hierarchical data structure for the six classes

Analysis of fig. 3 shows that the alphabet of the six recognition classes was divided into four final strata, each consisting of the two nearest neighboring classes. If one class is included in the two final stratas, then when constructing the decision rules (6) the membership function (7) is chosen with the optimal geometric parameters of the class for which the radius determined by procedure (4) is minimal.

In order to test the algorithm of information-extreme machine learning of the SFD of the printer, the sixth class of recognition was added to the alphabet. (Fig. 2f). Since the fifth class was the nearest neighbor for the new recognition class in the variation series, they formed a new final stratum. Figure 4 shows the decursive tree of the new hierarchical data structure.

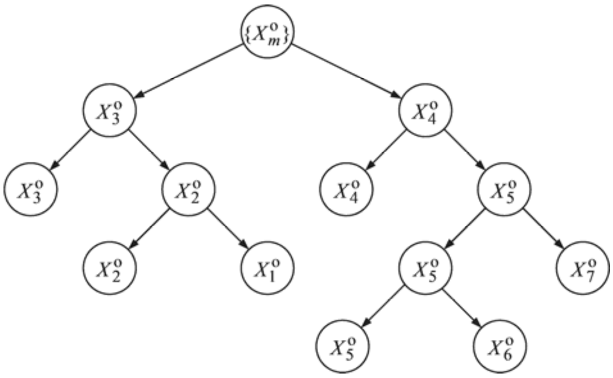


Figure 4 – Hierarchical data structure for seven recognition classes

As a result of SFD retraining, new decision rules were built for the extended alphabet of recognition classes. In the operating mode, diagnosing the printer according to the image of the defect of the printed material is carried out by consistent implementation of the decisive rules built at the stage of machine learning (6).

5 RESULTS

Information-extreme machine learning of the SFD of a laser printer for defects in printed material was initially carried out for six classes of recognition according to the hierarchical structure shown in Fig. 3. As an example, consider the results of the implementation of the machine learning algorithm for the execution of the first tier (according to the dendrographic classification, the tiers are counted from above) and the first execution of the second tier. In fig. 5 shows a graph of the dependence of the average information criterion (5) on the parameter of the field of control tolerances for recognition features, obtained by procedure (3) with parallel optimization of control tolerances for recognition features for the execution of the first tier of the decursive tree.

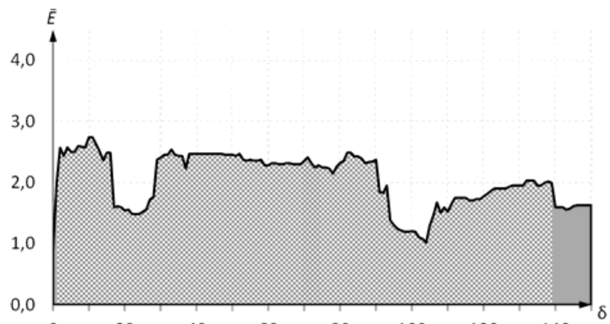


Figure 5 – Graph of the dependence of the information criterion on the parameter of the field of control tolerances for the execution of the first tier

In Fig. 5 and further, double hatching indicates the working area for determining the function of criterion (5), in which the first reliability is greater than 0.5, and the error of the second kind is less than 0.5. Analysis of Fig. 5 shows that the optimal value of the parameter of the field of control tolerances is $\delta_{1,1}^* = 10$ (hereinafter in the

DOI 10.15588/1607-3274-2022-18

gradations of brightness) at the maximum value of the information criterion $\overline{E}^*_{1,1} = 2.78$ ·

To build the decision rules (6) it is necessary to know the optimal geometric parameters of the containers of recognition classes. Figure 6 shows graphs of the dependence of the information criterion (5) on the radius of hyperspherical containers of the strata recognition classes of the first tier of the decursive tree.

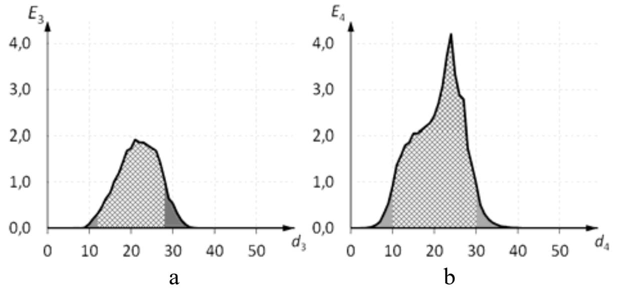


Figure 6 – Graph of the dependence of the information criterion on the radius of the containers of the classes of recognition of the strata of the first tier: a – class X^o_3 ; b – class X^o_4

The analysis of Fig. 6 shows that the optimal radius of the containers of the recognition classes are: $d^*_3 = 21$ (hereinafter in code units) for the recognition class X^o_3 and $d^*_4 = 25$ for the recognition class X^o_4 .

In Fig. 7 shows a graph of the dependence of the average information criterion (5) on the parameter of the field of control tolerances on the recognition features for the first stratum of the second tier of the decursive tree.

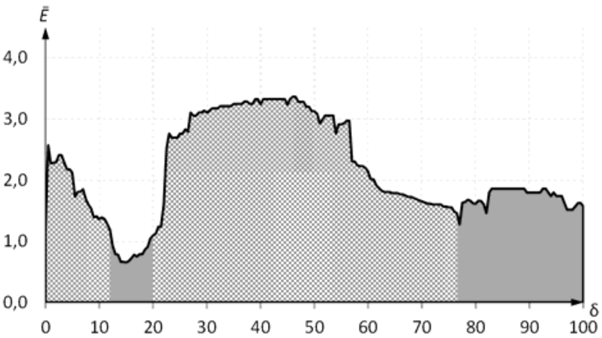


Figure 7 – Graph of the dependence of the information criterion on the parameter of the field of control tolerances for the first stratum of the second tier

Analysis of Fig. 7 shows that the optimal value of the parameter of the field of control tolerances is equal $\delta^*_{2,1} = 47$ to the maximum value of the information criterion $\overline{E}^*_{1,1} = 3{,}48$.

The result of optimization by criterion (5) of the geometric parameters of the the recognition classes containers of the first stratum of the second tier is shown in Fig. 8.

Analysis of Figure 8 shows that the optimal radius of the containers of the recognition classes are: $d^*_2 = 65$ for the recognition class X^o_2 and $d^*_3 = 46$ for the recognition class X^o_3 . Since the class X^o_3 belongs to the stratum of the first tier and the first stratum of the second tier, the optimal radius of its container according to the minimum-distance principle of recognition theory should be equal to $d^*_3 = 21$, that corresponding to the Fig. 6a.

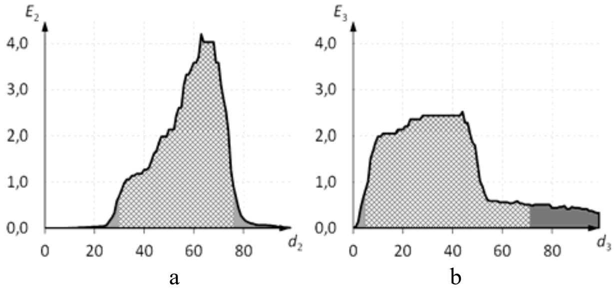


Figure 8 – Graph of the dependence of the information criterion on the radius of the containers of the recognition classes of the first stratum of the second tier: a – class X^o_2 ; b – class X^o_3

Similarly, in the process of machine learning, the geometric parameters of hyperspherical containers of other recognition classes, which are part of the hierarchical structure shown in Figure 4, were optimized.

After optimizing the geometric parameters of the containers of all seven classes of recognition, the average value of the information criterion was equal to $\overline{E}^* = 3.28$. Since the maximum limit value of criterion (5) for the given parameters $n = 30$ and $p = 2$ is equal to $E_{\max} = 4.35$, the algorithm of parallel-sequential optimization of control tolerances in the form of a procedure was used to increase the functional efficiency of SFD machine learning

$$\delta^*_{K,i} = \arg\left[\bigotimes_{l=1}^{L} \max_{G_{\delta,h,s}} \{ \max_{G_E \cap G_d} \overline{E}_{h,s}(d) \} \right], i = \overline{1,N}. \quad (8)$$

The control tolerances defined at the parallel optimization stage are accepted as starting points for the sequential optimization algorithm. Since the optimization of the i -th diagnostic feature other subsequent features have suboptimal control tolerances, the sequential optimization in this case requires iterative runs until the value of the information criterion of optimization will not change.

Table 1 shows the results of parallel-sequential optimization of machine learning parameters for recognition classes of all strata of the decursive tree (Fig. 4).

DOI 10.15588/1607-3274-2022-18

Table 1 – The results of machine learning

Classes	E_m^*	d_m^*	Exact characteristics	
			D_1^*	β^*
X_1^o	4.35	19	1.00	0
X_2^o	3.89	31	0.89	0.03
X_3^o	4.35	48	1.00	0
X_4^o	3.89	28	0.88	0.05
X_5^o	4.35	24	1.00	0
X_6^o	2.19	25	0.55	0.25
X_7^o	4.35	27	1.00	0

Analysis of table 1 shows that the average value of the information criterion after additional sequential optimization of control tolerances according to procedure (8) was equal to $\overline{E}^* = 3.91$, which exceeds the value of this criterion obtained by parallel optimization.

6 DISCUSSION

The obtained results of information-extreme machine learning according to the hierarchical structure of data in the form of a decursive tree open a promising direction for solving the problem of multidimensionality of the alphabet of recognition classes. The possibility of automatic retraining of the system with increasing power of the alphabet of recognition classes, which characterize the relevant technical conditions of the device, is proved on the example of information synthesis of the SFD of a laser printer capable of learning from typical defects of printed material. It is known that the application of a linear algorithm of machine learning at high power of the alphabet leads to a significant reduction in the reliability of recognition by increasing the degree of intersection of recognition classes with constant dimensionality of the space of recognition features. In contrast to the linear algorithm of information-extreme machine learning, which determines the optimal system of control tolerances for all recognition classes, in the proposed method, optimal control tolerances are determined only for the nearest neighboring classes. Building a hierarchical data structure in the form of a binary multi-tiered decursive tree allows the division of the high-power alphabet into strata, which consist of the nearest neighboring recognition classes. As a result, for each stratum in the process of machine learning determines its optimal system of control tolerances as shown in Figures 4 and 6. It is shown that machine learning should be carried out by parallel-sequential optimization of control tolerances. In this case, both the reliability of recognition and the efficiency of machine learning increases, because with consistent optimization, the search for the global maximum of the information criterion is carried out in the work area, which is determined by parallel optimization.

CONCLUSIONS

1. A functional categorical model is proposed, on the basis of which an algorithm of information-extreme machine learning according to the hierarchical data structure is developed and programmatically implemented. At the same time, building a hierarchical data structure in the form of a binary decursive tree allows you to divide a powerful set of recognition classes into pairs of nearest neighbors. As a result, the optimization of machine learning parameters is carried out by a linear algorithm of sufficient depth for the two nearest neighboring recognition classes, which provides high recognition reliability.

2. Decisive rules based on the example of information-extreme machine learning SFD laser printer on images of defects of printed material are not infallible on the training matrix, which requires increasing the depth of machine learning by optimizing other parameters of the system, including parameters of input information description of the system.

REFERENCES

1. Rodgers S. Laser Printer: The Definitive Guide to Laser Printer Wireless, Laser Printer Paper and More. NY, Lulu Press Inc, 2015, 70 p.
2. Lhotka B. P. Hacking the Digital Print. USA, New Riders, 2015, 310 p.
3. Sun W., Yao B., Zeng N. et al. An Intelligent Gear Fault Diagnosis Methodology Using a Complex Wavelet Enhanced Convolutional Neural Network, 2017, Vol. 10, No. 7, P. 790.
4. Henao H., Capolino G. A., et al. Trends in fault diagnosis for electrical machines: A review of diagnostic techniques, IEEE Industrial Electronics Magazine, 2014, Vol. 8, No. 2. pp. 31–42.
5. Engelbrecht A. Computational intelligence: an introduction. Sidney, John Wiley & Sons, 2007, 597 p. DOI: 10.1002/9780470512517
6. Reinartz T. A unifying view on instance selection, *Data Mining and Knowledge Discovery,* 2002, No. 6, pp. 191–210. DOI: 10.1023/A:1014047731786
7. Xu G., Zong Y., Yang Y. Z. Applied Data Mining. CRC Press, 2013, 284 p.
8. Dua Sumeet, Xian Du Data Mining and Machine Learning in Cybersecurity, 1st Edition. Auerbach Publications, 2011, 256 p
9. Aha D. W., Kibler D., Albert M. K. Instance-based learning algorithms, *Machine Learning,* 1991, No. 6, pp. 37–66. DOI: 10.1023/A:1022689900470
10. Petr Dolezel, Pavel Skrabanek, Lumir Gago Pattern recognition neural network as a tool for pest birds detection, *Computational Intelligence (SSCIIEEE Symposium Series on)*, 2016, pp. 1–6.
11. Huang Ching-Lien, Hsu Tsung-Shin, Liu Chih-Ming The Mahalanobis-Taguchi system – Neural network algorithm for data-mining in dynamic environments, *Expert Systems with Applications: An International Journal*, 2009, Vol. 36, Issue 3, pp. 5475–5480.

DOI 10.15588/1607-3274-2022-18

12. Ammour H., Alhichri A., Bazi Y. et al. Deep Learning Approach for Car Detection in UAV Imagery, *Remote Sens*, 2017, Vol. 9, No. 4, pp. 1–15.
13. Dong S., Xu X., Liu J. et al. Rotating Machine Fault Diagnosis Based on Locality Preserving Projection and Back Propagation Neural Network-Support Vector Machine Model, *Measurement and Control*, 2015, Vol. 48, No. 7, pp. 211–216.
14. Gerrit J. J., Burg van den, Groenen P. J. GenSVM: A Generalized Multiclass Support Vector Machine, *Journal of Machine Learning Research*, 2016, Vol. 17, No. 224, pp. 1–42.
15. Shi Y., Mizumoto M. An improvement of neuro-fuzzy learning algorithm for tuning fuzzy rules, *Fuzzy sets and systems*, 2001, Vol. 118, No. 2, pp. 339–350.
16. Subbotin S. A. The neuro-fuzzy network synthesis and simplification on precedents in problems of diagnosis and pattern recognition, *Optical Memory and Neural Networks (Information Optics)*, 2013, Vol. 22, No. 2, pp. 97–103. DOI: 10.3103/s1060992x13020082.
17. Efendigil T. Önüt S., Kahraman C. A decision support system for demand forecasting with artificial neural networks and neuro-fuzzy models: a comparative analysis, *Expert Systems with Applications*, 2009, Vol. 36, No. 3, pp. 6697–6707.
18. Moskalenko V. V., Korobov A. G. Information-extreme algorithm of the system for recognition of objects on the terrain with optimization parameter feature extraction, *Radio Electronics, Computer Science, Control*, 2017, No. 2, pp. 38–45.
19. Moskalenko V. V., Dovbysh A. S., Naumenko I. V. et al. Improving the effectiveness of training the on-board object detection system for a compact unmanned aerial vehicle, *Eastern-European Journal of Enterprise Technologies*, 2018, Vol. 4/9, No. 94, pp. 19–26.
20. Protsenko O., Savchenko T., Myronenko M. et al. Informational and extreme machine learning for onboard recognition system of ground objects, *Dependable Systems, Services and Technologies, XI International Conference, Kyiv, 14–18 May 2020, proceedings.* Kyiv, IEEE, 2020, pp. 213–218.
21. Dovbysh A. S., Budnyk M. M., Piatachenko V. Yu et al. Information-Extreme Machine Learning of On-Board Vehicle Recognition System, *Cybernetics and Systems Analysis*, 2020, Vol. 56(4), pp. 534–543.
22. Simonovskiy J., Piatachenko V., Myronenko N. On-board Geographic Information System of Images' Identification, *Advanced Information Systems and Technologies : VI International Conference, Sumy, 16–18 May 2018, proceedings.* Sumy, Sumy State University, 2018, pp. 115 – 118.
23. Dovbysh A., Zimovets V. Hierarchical Algorithm of the Machine Learning for the System of Functional Diagnostics of the Electric Drive, *Advanced Information Systems and Technologies, VI International Conference, Sumy, 16–18 May 2018: proceedings.* Sumy, Sumy State University, 2018, pp. 85–88.
24. Zimovets V. I., Shamatrin S. V., Olada D. E et al. Functional diagnostic system for multichannel mine lifting machine working in factor cluster analysis mode, *Journal of Engineering Sciences,* 2020, Vol. 7(1), pp. E20–E27. DOI: 10.21272/jes.2020.7(1).e4.
25. Dovbysh A., Piatachenko V. Hierarchical Clustering Approach for Information-Extreme Machine Learning of Hand Brush Prosthesis, *Computational Linguistics and Intelligent Systems, V International Conference, Lviv, 22–23 April 2021, proceedings.* Lviv, CEUR-WS, 2021, pp. 1706–1715.

Received 15.02.2022.
Accepted 20.03.2022.

УДК 681.518:004.93

ІНФОРМАЦІЙНО-ЕКСТРЕМАЛЬНЕ МАШИННЕ НАВЧАННЯ СИСТЕМИ ФУНКЦІОНАЛЬНОГО ДІАГНОСТУВАННЯ З ІЄРАРХІЧНОЮ СТРУКТУРОЮ ДАНИХ

Шелехов І. В. – канд. техн. наук, доцент, доцент кафедри комп'ютерних наук Сумського державного університету, Суми, Україна; докторант кафедри комп'ютерних систем, мереж і кібербезпеки, Національний аерокосмічний університет ім. М.Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Барченко Н. Л. – канд. техн. наук, доцент кафедри комп'ютерних наук Сумського державного університету, Суми, Україна.

Прилепа Д. В. – асистент кафедри комп'ютерних наук Сумського державного університету, Суми, Україна.

Бібик М. В. – асистент Конотопського інституту Сумського державного університету, Конотоп, Україна.

АНОТАЦІЯ

Актуальність. Розглянуто задачу інформаційно-екстремального машинного навчання системи функціонального діагностування на прикладі розпізнавання технічного стану лазерного принтера за типовими дефектами друкованого матеріалу. Об'єктом дослідження є процес ієрархічного машинного навчання системи функціонального діагностування електромеханічного пристрою.

Мета. Підвищення функціональної ефективності машинного навчання системи функціонального діагностування шляхом автоматичного формування нової ієрархічної структури даних при перенавчанні системи через розширення алфавіту класів розпізнавання.

Метод. Запропоновано метод інформаційно-екстремального ієрархічного машинного навчання системи функціонального діагностування лазерного принтеру за типовими дефектами друкованого матеріалу. Метод розроблено в рамках функціонального підходу до моделювання когнітивних процесів природнього інтелекту, що дозволяє надати системі діагностування властивості адаптивності при довільних початкових умовах формування зображень дефектів друку та

DOI 10.15588/1607-3274-2022-18

гнучкості при перенавчанні системи через збільшення потужності алфавіту класів розпізнавання. В основу методу покладено принцип максимізації кількості інформації в процесі машинного навчання. Процес інформаційно-екстремального машинного навчання розглядається як ітераційна процедура оптимізації параметрів функціонування системи функціонального діагностування за інформаційним критерієм. Як критерій оптимізації параметрів машинного навчання розглядається модифікована інформаційна міра Кульбака, яка є функціоналом від точнісних характеристик класифікаційних рішень. Згідно із запропонованою категорійною функціональною моделлю розроблено алгоритм інформаційно-екстремального машинного навчання за ієрархічною структурою даних у вигляді бінарного декурсивного дерева. Застосування такої структури даних дозволяє розбивати велику кількість класів розпізнавання на пари найближчих сусідів, для яких оптимізація параметрів машинного навчання здійснюється за лінійним алгоритмом необхідної глибини.

Результати. Розроблено інформаційне, алгоритмічне і програмне забезпечення системи функціонального діагностування лазерного принтеру за зображеннями типових дефектів друкованого матеріалу. Досліджено вплив параметрів машинного навчання на функціональну ефективність системи функціонального діагностування лазерного принтеру за зображеннями дефектів друкованого матеріалу.

Висновки. Результати фізичного моделювання підтвердили працездатність запропонованого методу інформаційно-екстремального машинного навчання системи функціонального діагностування лазерного принтеру за типовими дефектами друкованого матеріалу і можуть бути рекомендовані для практичного використання. Перспектива підвищення функціональної ефективності інформаційно-екстремального машинного навчання системи функціонального діагностування полягає в збільшенні глибини машинного навчання шляхом оптимізації додаткових параметрів функціонування системи, включаючи параметри формування вхідної навчальної матриці.

КЛЮЧОВІ СЛОВА: інформаційно-екстремальне машинне навчання, категорійна функціональна модель, інформаційний критерій, система контрольних допусків, функціональне діагностування, лазерний принтер.

УДК 681.518:004.93

ИНФОРМАЦИОННО-ЭКСТРЕМАЛЬНОЕ МАШИННОЕ ОБУЧЕНИЕ СИСТЕМЫ ФУНКЦИІОНАЛЬНОГО ДІАГНОСТИРОВАНИЯ С ИЕРАРХИЧЕСКОЙ СТРУКТУРОЙ ДАННЫХ

Шелехов И. В. – канд. техн. наук, доцент кафедры компютерных наук Сумского государственного университета, Сумы, Украина; докторант кафедры компьютерных систем, сетей и кибербезопасности, Национальный аэрокосмический университет им. М.Е. Жуковского «Харьковский авиационный институт», Харьков, Украина.

Барченко Н. Л. – канд. техн. наук, доцент кафедры компютерных наук Сумского государственного университета, Сумы, Украина.

Прилепа Д. В. – асистент кафедры компютерных наук Сумского государственного университета, Сумы, Украина.

Бибик М. В. – асистент Конотопского института Сумского государственного университета, Конотоп, Украина.

АННОТАЦИЯ

Актуальность. Рассмотрена задача информационно-экстремального машинного обучения системы функционального диагностирования на примере распознавания технического состояния лазерного принтера по типовым дефектам печатного материала. Объектом исследования является процесс иерархического машинного обучения системы функционального диагностирования электромеханического устройства.

Цель. Повышение функциональной эффективности машинного обучения системы функционального диагностирования методом автоматического формирования новейшей иерархической структуры данных при переобучении системы через расширение алфавита классов распознавания.

Метод. Предложен метод информационно-экстремального иерархического машинного обучения системы функционального диагностирования лазерного принтера по типовым дефектам печатного материала. Метод разработан в рамках функционального подхода к моделированию когнитивных процессов естественного интеллекта, позволяющего придать системе диагностирования свойства адаптивности при произвольных начальных условиях формирования изображений дефектов печати и гибкости при переобучении системы из-за увеличения мощности алфавита классов распознавания. В основу метода положен принцип максимизации количества информации в процессе машинного обучения. Процесс информационно-экстремального машинного обучения рассматривается как итерационная процедура оптимизации параметров функционирования системы функционального диагностирования по информационному критерию. В качестве критерия оптимизации параметров машинного обучения рассматривается модифицированная информационная мера Кульбака, которая является функционалом от точных характеристик классификационных решений. Согласно предложенной категориальной функциональной модели разработан алгоритм информационно-экстремального машинного обучения по иерархической структуре данных в виде бинарного декурсивного дерева. Применение такой структуры данных позволяет разбивать большое количество классов распознавания на пары ближайших соседей, для которых оптимизация параметров машинного обучения осуществляется по линейному алгоритму требуемой глубины.

Результаты. Разработаны информационное, алгоритмическое и программное обеспечение системы функционального диагностирования лазерного принтера по изображениям типовых дефектов печатного материала. Исследовано влияние параметров машинного обучения на функциональную эффективность системы функциональной диагностики лазерного принтера по изображениям дефектов печатного материала.

Выводы. Результаты физического моделирования подтвердили работоспособность предложенного метода информационно-экстремального машинного обучения системы функционального диагностирования лазерного принтера по типовым дефектам печатного материала и могут быть рекомендованы для практического использования. Перспектива повышения функциональной эффективности информационно-экстремального обучения системы функционального диагностирования заключается в увеличении глубины машинного обучения путем оптимизации дополнительных параметров функционирования системы, включая параметры формирования входной обучающей матрицы.

DOI 10.15588/1607-3274-2022-18

КЛЮЧЕВЫЕ СЛОВА: информационно-экстремальное машинное обучение, категорионная функциональная модель, информационный критерий, система контрольных допусков, функциональное диагностирование, лазерный принтер.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Rodgers S. Laser Printer: The Definitive Guide to Laser Printer Wireless, Laser Printer Paper and More / S. Rodgers. – NY: Lulu Press Inc, 2015. – 70 p.
2. Lhotka B. P. Hacking the Digital Print / B. P. Lhotka – USA: New Riders, 2015. –310 p.
3. An Intelligent Gear Fault Diagnosis Methodology Using a Complex Wavelet Enhanced Convolutional Neural Network / [W. Sun, B. Yao, N. Zeng et al.] // Materials. – 2017. – Vol. 10, №7. – P. 790.
4. Trends in fault diagnosis for electrical machines: A review of diagnostic techniques / [H. Henao, G. A. Capolino, et al.] // IEEE Industrial Electronics Magazine. – 2014. – Vol. 8, №2. – P. 31–42.
5. Engelbrecht A. Computational intelligence: an introduction / A. Engelbrecht. – Sidney: John Wiley & Sons, 2007. – 597 p. DOI: 10.1002/9780470512517
6. Reinartz T. A unifying view on instance selection / T. Reinartz // Data Mining and Knowledge Discovery. – 2002. – №6. – P. 191–210. DOI: 10.1023/A:1014047731786
7. Xu G., Applied Data Mining / G. Xu, Y. Zong, Y. Z. Yang. – CRC Press, 2013. – 284 p.
8. Dua Sumeet. Data Mining and Machine Learning in Cybersecurity / Sumeet Dua, Xian Du. 1st Edition. – Auerbach Publications, 2011. – 256 p
9. Aha D. W. Instance-based learning algorithms / D. W. Aha, D. Kibler, M. K. Albert // Machine Learning. – 1991. – № 6. – P. 37–66. DOI: 10.1023/A:1022689900470
10. Petr Dolezel. Pattern recognition neural network as a tool for pest birds detection / Petr Dolezel, Pavel Skrabanek, Lumir Gago // Computational Intelligence (SSCIIEEE Symposium Series on). – 2016, P. 1–6.
11. Huang Ching-Lien. The Mahalanobis-Taguchi system – Neural network algorithm for data-mining in dynamic environments / Ching-Lien Huang, Tsung-Shin Hsu, Chih-Ming Liu // Expert Systems with Applications: An International Journal. – 2009. Vol. 36, Issue 3. – P. 5475–5480.
12. Deep Learning Approach for Car Detection in UAV Imagery / [H. Ammour, A. Alhichri, Y. Bazi et al.]// Remote Sens. – 2017. – Vol. 9, № 4. – P. 1–15.
13. Rotating Machine Fault Diagnosis Based on Locality Preserving Projection and Back Propagation Neural Network–Support Vector Machine Model / [S. Dong, X. Xu, J. Liu et al.] // Measurement and Control. – 2015.– Vol. 48, № 7. – P. 211–216.
14. Gerrit J. J. GenSVM: A Generalized Multiclass Support Vector Machine / J. J. Gerrit, van den Burg, P. J. Groenen // Journal of Machine Learning Research. – 2016. – Vol. 17, № 224. – P. 1–42.
15. Shi Y. An improvement of neuro-fuzzy learning algorithm for tuning fuzzy rules / Y. Shi, M. Mizumoto // Fuzzy sets and systems. – 2001. – Vol. 118, № 2. – P. 339–350.
16. Subbotin S. A. The neuro-fuzzy network synthesis and simplification on precedents in problems of diagnosis and pattern recognition / S. A. Subbotin // Optical Memory and Neural Networks (Information Optics). – 2013. – Vol. 22, № 2. – P. 97–103. DOI: 10.3103/s1060992x13020082.
17. Efendigil T. A decision support system for demand forecasting with artificial neural networks and neuro-fuzzy models: a comparative analysis / T. Efendigil, S. Önüt, C. Kahraman // Expert Systems with Applications. – 2009. – Vol. 36, № 3. – P. 6697–6707.
18. Moskalenko V.V. Information-extreme algorithm of the system for recognition of objects on the terrain with optimization parameter feature extraction / V.V. Moskalenko, A.G. Korobov // Radio Electronics, Computer Science, Control. – 2017. – №2. – P. 38–45.
19. Improving the effectiveness of training the on-board object detection system for a compact unmanned aerial vehicle / [V. V. Moskalenko, A. S. Dovbysh, I. V. Naumenko et al.] // Eastern-European Journal of Enterprise Technologies. – 2018. – Vol. 4/9, № 94. – P. 19–26.
20. Informational and extreme machine learning for onboard recognition system of ground objects / [O. Protsenko, T. Savchenko, M. Myronenko et al.] // Dependable Systems, Services and Technologies : XI International Conference, Kyiv, 14–18 May 2020 : proceedings. – Kyiv : IEEE, 2020. – P. 213–218.
21. Information-Extreme Machine Learning of On-Board Vehicle Recognition System / [A. S. Dovbysh, M. M. Budnyk, V. Yu Piatachenko et al.] // Cybernetics and Systems Analysis. – 2020. – Vol 56(4). – P 534–543.
22. Simonovskiy J. On-board Geographic Information System of Images' Identification / J. Simonovskiy, V. Piatachenko, N. Myronenko // Advanced Information Systems and Technologies : VI International Conference, Sumy, 16–18 May 2018: proceedings. – Sumy : Sumy State University, 2018. – P. 115 – 118.
23. Dovbysh A. Hierarchical Algorithm of the Machine Learning for the System of Functional Diagnostics of the Electric Drive / A. Dovbysh, V. Zimovets // Advanced Information Systems and Technologies : VI International Conference, Sumy, 16–18 May 2018: proceedings. – Sumy : Sumy State University, 2018. – P. 85–88.
24. Functional diagnostic system for multichannel mine lifting machine working in factor cluster analysis mode / [V. I. Zimovets, S. V. Shamatrin, D. E. Olada et al.] // Journal of Engineering Sciences. – 2020. – Vol. 7(1). – P. E20–E27. DOI:10.21272/jes.2020.7(1).e4.
25. Dovbysh A. Hierarchical Clustering Approach for Information-Extreme Machine Learning of Hand Brush Prosthesis / A. Dovbysh, V. Piatachenko // Computational Linguistics and Intelligent Systems : V International Conference, Lviv, 22–23 April 2021 : proceedings. – Lviv, CEUR-WS, 2021. – P. 1706–1715.

DOI 10.15588/1607-3274-2022-18

УПРАВЛІННЯ У ТЕХНІЧНИХ СИСТЕМАХ

CONTROL IN TECHNICAL SYSTEMS

УПРАВЛЕНИЕ В ТЕХНИЧЕСКИХ СИСТЕМАХ

UDC 519.61:517.97:004

FREQUENCY FEATURES OF THE NUMERICAL METHOD SAMPLING OF DIGITAL CONTROL SYSTEMS

Moroz V. I. – Prof., Dr. Sc., Professor of Institute of Power Engineering and Control Systems, Lviv Polytechnic National University, L'viv, Ukraine.

Vakarchuk A. B. – PhD Student of Institute of Power Engineering and Control Systems, Lviv Polytechnic National University, L'viv, Ukraine.

ABSTRACT

Context. The studies of the frequency properties of the explicit multistep numerical integrators which use for sampling of continuous transfer function in the digital control systems, are conducted in this article. Numerical integrators in such systems implement as an integral parts of the digital regulators.

Objective. The goal of this research is an analysis of the behavior of explicit numerical integrators of different orders, which are used to discretize continuous systems, in order to study their impact on the properties of the synthesized digital system.

Method. Numerical methods of integration are considered as digital filters, the behavior of which is studied by the frequency characteristics method. To do this, the z-transform apparatus was used. Integrators' discrete transfer functions were found for frequency analysis using the Control Systems Toolbox package of the mathematical application MATLAB. For further analysis, two closed feedback test structures were used: with integrators in the forward channel and in the feedback loop. Both variants of structures were studied by the frequency characteristics method for sampling using numerical integrators of 1st–6th orders.

Results. The inefficiency of using high-order numerical integrators for continuous systems' discretization is shown. Given the behavior of the frequency characteristics of test systems, the most rational is the use of low-order integrators, namely – the first and second orders. Establishing the cause of this phenomenon requires additional research, in particular, to identify the possible impact of additional zeros and poles of discrete transfer functions of the numerical integrators.

Conclusions. The use of low-order integrators, namely the first and second orders, is the most rational for sampling of digital control systems and the inefficiency of using high-order numerical integrators to sample continuous systems is proven.

KEYWORDS: Bode diagram, control theory, digital control system, discrete transfer function, linear system, numeric integrators, structure models, z-transform.

ABBREVIATIONS

PID controller is proportional-integral-derivative controllers.

NOMENCLATURE

$X(s)$ is an input signal of the tested structure;

$Y(s)$ is an output signal of the tested structure;

$\frac{1}{s}$ is an ideal integrator's continuous transfer function;

a_k is a k-th denominator's coefficient of the continuous transfer function;

b_k is a k-th numerator's coefficient of the continuous transfer function;

y_{i+1} is a numeric integrator's output variable of i+1-th step (next sample);

y_i is a numeric integrator's output variable of i-th step (current sample);

x_k is an input variable of k-th step (sample) in the recurrent formula of the numeric integrator;

h is a sampling time (integration step);

j is an imaginary unit;

s is an operator in Laplace domain;

z is an operator in Z-domain (z-transform);

ω is an angular frequency;

ω_0 is an angular sampling frequency;

$A(\omega)$ is a magnitude of the continuous transfer function;

DOI 10.15588/1607-3274-2022-2-19

$A^*(\omega)$ is a magnitude of the discrete transfer function;

$\varphi(\omega)$ is a phase of the continuous transfer function;

$\varphi^*(\omega)$ is a phase of the discrete transfer function;

$W(s)$ is a continuous transfer function in Laplace domain;

$W^*(z)$ is a discrete transfer function in Z-domain;

$W_n^*(z)$ is a n-order discrete transfer function of the numeric integrator.

INTRODUCTION

Modern digital control systems can be meet in almost all technological systems, from home appliances to complex technological complexes. Any digital system has two interconnected components: hardware and software, which cannot function without each other. The capabilities of the hardware usually determined by one of its few manufacturers and can be slightly corrected by adding some technical components; otherwise, the software fully meets the digital system requirements and largely determines its capabilities. In particular, the same controller used in home appliances, and industrial controllers, and to control the hard disk drive. Less noticeable, however, the defining part of the software is to provide mathematical – software implementation of numerical methods in control algorithms.

Means of the process automation of developing algorithmic software for digital systems have been widely used in engineering practice. The mathematical applications Mathcad, MATLAB (in particular, together with the Control System Toolbox library) etc. can be examples, which simplify the process of synthesizing the mathematical part of control algorithms for following software implementation in a digital control system. The presence in mathematical applications of ready-made implementations of the discretization typical methods for continuous systems makes it possible to some extent to automate the entire process of the mathematical component synthesis for digital system software. On the one hand, this is good because the developer gets a number of advantages:

– reduction of development time due to the avoidance of a large number of symbolical transformations in the discretization process (synthesis of the control algorithm);

– reducing the number of possible human errors in mathematical expression through the use of mentioned mathematical applications;

– the developer often no longer needs a deep understanding of discretization processes, in particular, in physical processes relation in the designed system, which significantly accelerates the actual development process.

On the other hand, these same advantages are to some extent a “Trojan horse” for the following consideration:

– The developer does not analyze the advantages or disadvantages of a method, and usually uses the default method (this option is available in almost all mathematical applications). This is due to the use of the existing mentioned means of automating the process of continuous systems sampling and it is not always suitable;

– the lack of need to understand the mathematical basis of discretization processes reduces the professional level of the developer, limiting its activities only to ready-made (however proven) standard solutions;

– availability of ready-made automated solutions does not encourage the digital systems developer to look for non-standard or optimal (rational) solution and encourages the use of rather limited standard methods (default methods).

The basic element of the implementation of most control algorithms is the integration operation. Therefore, the use of numerical methods of integration is one of the basic methods of discretization of continuous systems with the subsequent introduction of the obtained dependencies in the software of digital systems. It is clear that the choice of a numerical integrator under such conditions will affect the behavior of the obtained discretized (sampled-data) system. Thus, it is necessary to investigate such an action to improve the efficiency of digital systems.

The object of study is the process of the continuous systems’ sampling.

The subject of study is the properties of the sampling methods that based on the numerical integrators.

The purpose of the work is the studies of the frequency properties of the numeric integration methods for sampling to obtain the digital transfer function and increase the efficiency of the synthesized digital systems.

1 PROBLEM STATEMENT

Suppose given the continuous transfer function $W(s) = \dfrac{b_n s^n + \ldots + b_1 s + b_0}{s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0}$ that can be described by the structure of observer canonical form using n continuous integrators. Such structure used as a prototype for discretization of the digital control systems.

For the continuous transfer function $W(s)$ the problem of their digital transfer function $W^*(z)$ finding can be presented as the problem of finding n-order digital approximation $W_n^*(z)$ of the used continuous integrators $\dfrac{1}{s}$ in observer canonical form. Frequency properties of the transfer functions can be found using substitution $s = j \cdot \omega$ for continuous systems and $z = \exp(j \cdot \omega \cdot h)$ for sampled-data systems by the next expressions:

– for magnitude: $A(\omega) = |W(j \cdot \omega)|$ (for continuous transfer function) and $A^*(\omega) = |W^*(\exp(j \cdot \omega \cdot h)|$ (for discrete transfer function);

– for phase: $\varphi(\omega) = \arg(W(j \cdot \omega))$ (for continuous transfer function) and $\varphi^*(\omega) = \arg(W^*(\exp(j \cdot \omega \cdot h))$ (for discrete transfer function).

Thus, the problem of the finding the best discrete approximation $W_n^*(z)$ of a continuous integrator can be focused to finding the minimum of the integral standard deviation between the frequency characteristics of the continuous system and the sampled by the selected nu-

DOI 10.15588/1607-3274-2022-2-19

merical integrator $\int_0^{\omega_0}\left(A(j\omega)-A^*(j\omega h)\right)^2 d\omega \Rightarrow \min$ and $\int_0^{\omega_0}\left(\varphi(j\omega)-\varphi^*(j\omega h)\right)^2 d\omega \Rightarrow \min$.

2 REVIEW OF THE LITERATURE

The most popular developers' methods of the continuous prototype discretization (for example, an analog regulator) are traditional engineering methods: Tustin's method, z-transform etc., that applicable during the synthesis of the control algorithm of digital systems [1, 2, 3, 4]. This is due, firstly, to the well-known and proven methods of automatic control theory for continuous systems, which, moreover, are well implemented in mathematical applications (it is enough to mention the MATLAB's Control System Toolbox library again [5, 6]). Secondly, simple engineering methods of continuous systems discretization have already been developed and they do not require significant symbolical work from the developer (the same method of Tustin), and are also implemented in the applicable programs. Thus, there are all the prerequisites for the wide application of known traditional methods of discretization continuous systems by a wide range of engineers.

Most mathematical models of control systems can be reduced to block diagrams in which the basic element is an integrator [2]. For example, it applies to such well-known and popular regulators as the PID controller, which, according to the IEEE, used in more than 90% of industrial applications [7]. Conversion to the digital systems in the case of using this method of describing the model of the controller involves the transformation from analog (continuous) integrator to its discrete analog – a numerical integrator, which allows you to leave the controller structure unchanged. Accordingly, in this case, the main difference in the behavior of the obtained digital controller and its continuous prototype will be the difference in the behavior of the numerical integrator compared to the continuous.

One of the main tools for the analysis of control systems and their elements in the classical theory of automatic control is the use the frequency characteristics method, which allows a quite clearly analysis of the system behavior by its frequency response. Thus, considering the numerical integrator as a digital filter, it is possible to analyze its behavior by the control theory methods.

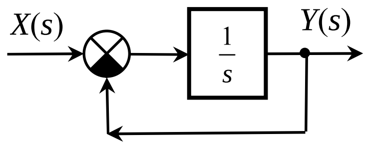
Analysis of the frequency characteristics of traditional numerical integrators using the z-transform method proposed in the classic (old but still actual) works by Elijah Jury [3, 4] and Julius Tou [8], although this method was used to only a few known numerical methods at the time: rectangles, trapezoids and Simpson. At the same time, the use of applied mathematics apparatus of frequency characteristics for the study of numerical methods for integrating ordinary differential equations (as proposed in the above-mentioned publications) has not been used before [9] and is not used in the future [10]. This is due to ignorance, misunderstanding or even non-acceptance by mathematicians the methods of automatic control's classical theory, for which the method of frequency response is basic. This case is because applied mathematics does not involve the consideration of numerical integrators as digital filters, although this method allows to obtain additional information about their behavior and to determine the possible impact on the digital control system [3, 4, 8].

The use of numerical integrators for continuous systems' discretization is not of interest in the case of modern methods of discrete systems synthesis too. This is due to the major use of state space and z-transform methods for this purpose [1, 2, 11]. The use of the simplest digital integrators to discretize continuous integrators in computer systems considered only as a partial case and a potential implementation [12].

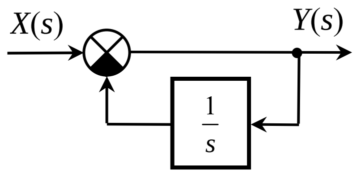
3 MATERIALS AND METHODS

At the first stage of research, the analysis provided using two elementary structure (Fig. 1), that allows investigating the numerical integration method impact on forward channel and feedback of closed-loop systems.

This use, at first look, of primitive structures has its advantages: it allows minimizing the effects of the actual structure and complexity of the test system on the behavior of a continuous prototype discretized by a numerical integrator. This helps to abstract from the possible variants of structural transformations, highlighting only two basic combinations (Fig. 1), and allows us to focus only on the influence of the applied methods of discretization.



a



b

Figure 1 – Block diagrams of the tested structure:
a – integrator in forward channel; b – integrator in feedback channel

The practical implementation of the numerical integration in the real-time control system or real-time digital model (for prediction analysis of operating mode for power and energy systems [13] or electromechanical systems [14]) is possible for using explicit multi-step formulas only, that is due to the following factors:

– It is not possible to obtain information about the value of a function or controlled coordinate in the interval between the samples (reason to exclude from review the single-step methods).

DOI 10.15588/1607-3274-2022-2-19

– It is not possible to obtain information of the next (future) sample of controlled coordinate (reason to exclude from review the multi-step implicit methods).

At present, Adam's formulas are still the most effective among the whole family of the explicit multi-step formulas [9, 10], so which was their choice for further analysis.

Obtaining process of the discrete transfer function for the digital integrator and fixed sampling time (integration step) h shown by this example of the 3rd-order explicit Adams formula [9, 10]

$$y_{i+1} = y_i + \frac{h}{12}\left(23x_i - 16x_{i-1} + 5x_{i-2}\right)$$

using method [3, 4, 15].

By the shifting theorem [3, 4, 8] $\begin{cases} y_i z = y_{i+1}; \\ y_i z^{-1} = y_{i-1}; \end{cases}$ a discrete transfer function of this integrator has a form

$$W_3^*(z) = \frac{\frac{h}{12}\left(23 - 16z^{-1} + 5z^{-2}\right)}{z-1} = \frac{\frac{h}{12}\left(23z^2 - 16z + 5\right)}{z^3 - z^2}$$

and may use for next analysis. Applying mentioned methods [3, 4, 8, 15], we can find discrete transfer functions for all of 1st–6th order digital integrators based on continuous integration by explicit Adams formulas. Obtained discrete transfer functions summarized in Table 1.

4 EXPERIMENTS

The founded discrete transfer functions (see Table 1) investigated by means of Control System Toolbox (MATLAB) [5, 6] for further analysis of frequency responses using standard function **bode**. The resulted frequency characteristics (Bode plots) are shown in Fig. 2 for mentioned 1st–6th orders explicit Adams formulas and sampling time $h = 0.1$ s with the continuous ideal

Table 1 – Discrete transfer functions of numerical integration operators

Integrator's order	Numerical integrator / Integrator's digital transfer function
1	$y_{i+1} = y_i + hx_i$
	$W_1^*(z) = \frac{h}{z-1}$
2	$y_{i+1} = y_i + \frac{h}{2}\left(3x_i - x_{i-1}\right)$
	$W_2^*(z) = \frac{\frac{h}{2}\left(3z-1\right)}{z^2 - z}$
3	$y_{i+1} = y_i + \frac{h}{12}\left(23x_i - 16x_{i-1} + 5x_{i-2}\right)$
	$W_3^*(z) = \frac{\frac{h}{12}\left(23z^2 - 16z + 5\right)}{z^3 - z^2}$
4	$y_{i+1} = y_i + \frac{h}{24}\left(55x_i - 59x_{i-1} + 37x_{i-2} - 9x_{i-3}\right)$
	$W_4^*(z) = \frac{\frac{h}{24}\left(55z^3 - 59z^2 + 37z - 9\right)}{z^4 - z^3}$
5	$y_{i+1} = y_i + \frac{h}{720}\left(1901x_i - 2774x_{i-1} + 2616x_{i-2} - 1274x_{i-3} + 251x_{i-4}\right)$
	$W_5^*(z) = \frac{\frac{h}{720}\left(1901z^4 - 2774z^3 + 2616z^2 - 1274z + 251\right)}{z^5 - z^4}$
6	$y_{i+1} = y_i + \frac{h}{1440}\left(4277x_i - 7923x_{i-1} + 9982x_{i-2} - 7298x_{i-3} + 2877x_{i-4} - 475x_{i-5}\right)$
	$W_6^*(z) = \frac{\frac{h}{1440}\left(4277z^5 - 7923z^4 + 9982z^3 - 7298z^2 + 2877z - 475\right)}{z^6 - z^5}$

DOI 10.15588/1607-3274-2022-2-19

integrator to comparing. Note, that ideal continuous integrator has a descending magnitude characteristic with – 20 dB/decade and constant phase –90 deg.

It is worth noting two things:

1. The big difference in the frequency characteristics (note, both magnitude and phase shift) of high-order digital integrators compared to the ordinary continuous integrator on highest frequency especial.

2. The form of frequency characteristics is practically independent of the sampling period (see Fig. 3, Fig. 4).

The conclusions of the second point are quite expected, but the first point (regarding the behavior of higher-order methods) came as a surprise, as it is traditionally believed that the higher order of the integration formula causes the higher the accuracy of such an operation. However, the analysis of the obtained frequency characteristics shows the opposite – the higher order of the numerical integrator has the greater the amplitude and phase errors at high frequencies. Moreover, the nature of such errors becomes more and more nonlinear, with increasing order of the integration method. This does not give possibility add correction.

The next stage of the research is to study the behavior of numerical integrators using the method of frequency characteristics in the case of their use of their digital equivalents instead of the continuous integration for two case of test structural models. They show in Fig. 1 – to place the integrator in the direct channel of the closed system and in the case of placing the integrator in the feedback circuit. In this part of the researches influence of the feedback control system's structure and the location of the integrator on the frequency characteristics of a closed system with a digital integrator is studied.

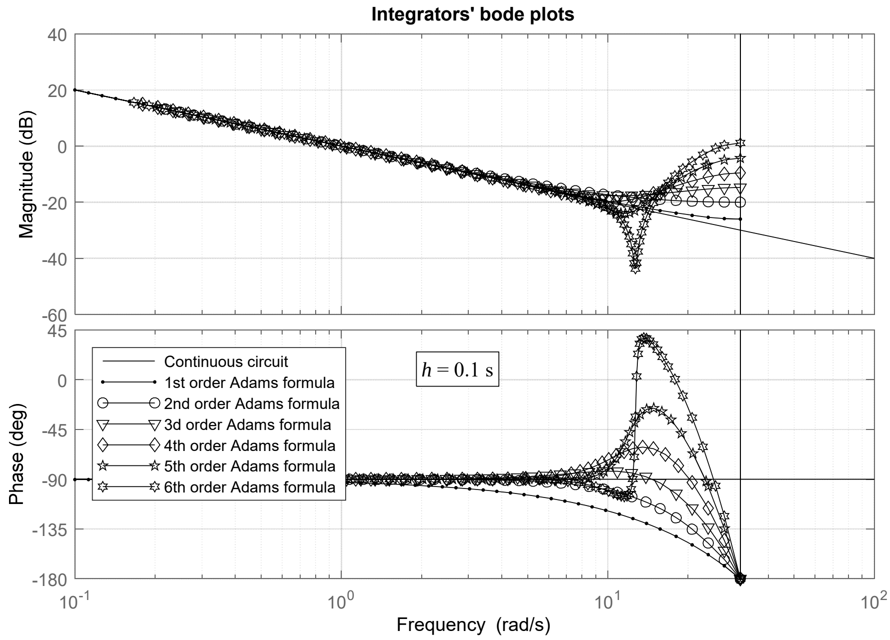


Figure 2 – Bode plots for 1st–6th-order numerical explicit integrators and sample time h = 0.1 s

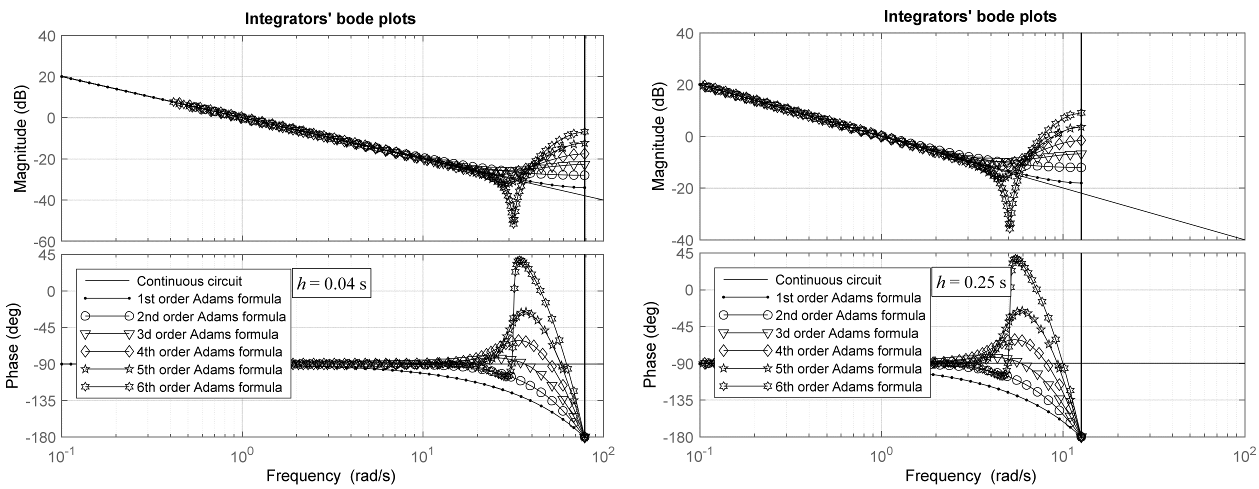


Figure 3 – Bode plots for 1st–6th-order numerical explicit integrators and sample times h = 0.04 s and h = 0.25 s

DOI 10.15588/1607-3274-2022-2-19

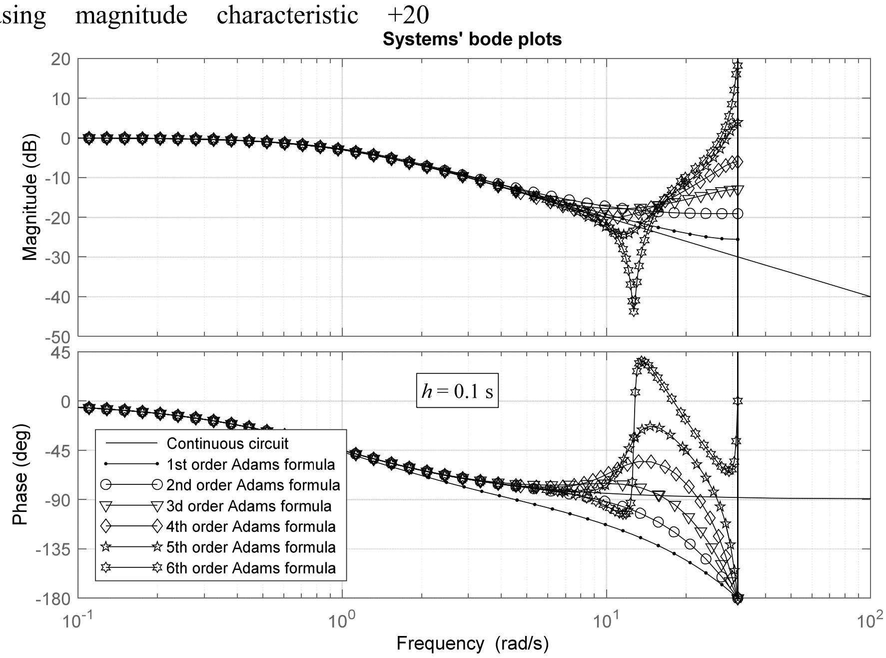
5 RESULTS

The obtained discrete transfer functions of integrators from Table 1 implemented to the digital models of structures Fig. 1 using again Control System Toolbox (MATLAB) [5, 6] for further analysis of frequency responses. Bode plots build for frequency workspace of the digital systems (1/10 of the sampling frequency [4, 16]).

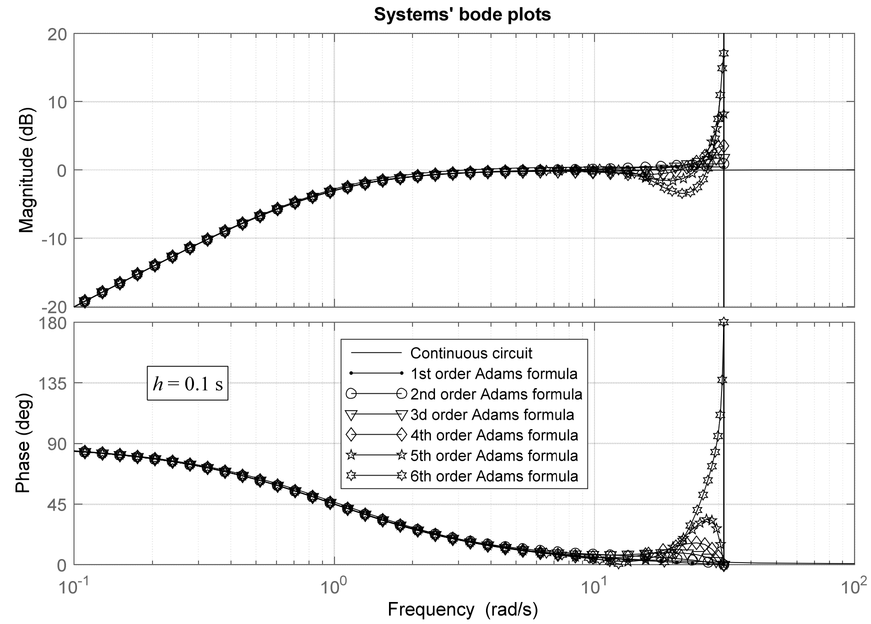
From Fig. 1, a – numerical integrator placed in forward channel. This is correspond to ordinary first-order inertial circuit with a descending magnitude characteristic with –20 dB/decade after the cutting frequency and smooth varying phase from zero to –90 deg.

Form Fig. 1, b – numerical integrator placed in feedback loop, that correspond to real differential operation with an increasing magnitude characteristic +20 dB/decade before the cutting frequency and smooth varying phase from +90 deg. to zero. Note that in this case, the negative effect of numerical integrators' high-order is unexpectedly reduced.

It is important that in the case of the second structure (Fig. 1, b) – the inclusion of a digital integrator in the feedback loop, the amplitude and phase errors in the use of higher-order formulas are smaller than in the case of placing a digital integrator in a direct channel. In addition, as noted earlier, it is possible to note a rather unexpected fact that given the behavior of both types of frequency response characteristics of test systems (Fig. 1) it is the formulas of high-order integration bring in errors in a closed system.



a



b

Figure 4 – Frequency characteristics for circuit Fig. 1:
a – using numerical integrators; b – using numerical integrators

DOI 10.15588/1607-3274-2022-2-19

5 DISCUSSION

A somewhat unexpected result is that high-order numerical integrators make larger errors at higher frequencies range after discretization of continuous system. To some point, this opposes our understanding from applied mathematics about the higher accuracy of the high-order methods. Moreover, the use of low-order integrators (first and second orders) surprise turned out to be the most rational given the frequency errors.

What is the next step of research? The digital transfer functions of the synthesized digital systems get additional discrete zeros and poles comparing to the continuous systems (analog prototype). This is caused as a result of sampling continuous transfer function by digital integrator [17, 18]. In this case, additional zeros and poles from discrete transfer functions of numeric integrators add to obtained discrete transfer functions of discretized continuous system. It is clear, that a system with more zeros and poles (digital system) will behave differently than a system with fewer zeros and poles (continuous system).

CONCLUSIONS

Studies using the frequency response have shown:

– The behavior of the frequency characteristics of test systems (Fig. 1) showed that the use of low-order integrators, namely the first and second orders, is the most rational. In this case, the amplitude and phase's errors by discretization process will be the smallest, regardless of the structure of the synthesized digital system and the location of the numerical integrator.

– The inefficiency of using high-order numerical integrators to sample continuous systems is proven. Establishing the cause of this phenomenon requires additional research, in particular, to identify the possible impact of additional zeros and poles of the transfer functions of discrete integrators.

The scientific novelty of obtained results is the based on two simple circuits the researches of frequency properties of the numerical integrators in the digital control systems was made.

The practical significance of obtained results is the possibility to improve efficiency of the synthesized digital control systems.

Prospects for further research are the researches of the impact of the zeros and poles of the numerical integrators causes to additional zeros and poles of the obtained discrete transfer function.

REFERENCES

1. Åström K., Wittenmark B. Computer-Controlled Systems: Theory and Design, Third Edition. New York, Published by Dover Books on Electrical Engineering, 2013, 578 p. DOI 10.1108/ir.1998.04925fae.003
2. Dorf R. C., Bishop R. H. Modern Control Systems. 12th Edition. New Jersey, Pearson, 2010, 1104 p. DOI 10.1002/rnc.1054
3. Jury E. Sampled-data control systems. New York, John Wiley & Sons, Inc., 1958, 453 p. DOI: 10.2307/3007623
4. Jury E. Theory and Application of the Z-Transform Method. Melbourne, Krieger Pub Co, 1973, 330 p.
5. MATLAB Environment. [Electronic resource] ©1994–2021. The MathWorks, Inc. Access mode: https://www.mathworks.com/products/matlab.html
6. Control System Toolbox: Design and analyze control systems. [Electronic resource] ©1994–2021. The MathWorks, Inc. Access mode: https://www.mathworks.com/products/control.html?s_tid=srchtitle
7. Johnson M., Moradi M. (Editors)PID Control: New Identification and Design Methods. London, ©Springer-Verlag London Limited, 2005, 544 p. DOI: 10.1007/1-84628-148-2
8. Tou J. Digital and Sampled-Data Control System (McGraw-Hill Electrical and Electronic Engineering Series). New York, McGraw Hill Book Co, January 1959, 631 p.
9. Chua L., Pen-Min Lin Computer-aided analysis of electronic circuits: algorithms and computational techniques. Englewood Cliffs, N. J., Prentice-Hall, 1975, 737 p.
10. Hairer E., Nørsett S., Wanner G. Solving Ordinary Differential Equations I: Nonstiff Problems. Second Edition. Berlin, Heidelberg, Springer, 2008, 528 p. DOI: 10.1007/978-3-540-78862-1
11. Ogata Katsuhiko. Discrete-Time Control Systems, 2nd edition. Englewood Cliffs, N. J.: Prentice-Hall, 1995, 760 p.
12. Kuo B. Digital Control Systems, 2nd Edition (The Oxford Series in Electrical and Computer Engineering. Oxford, Oxford University Press, 1995, 751 p.
13. Khaitan S., Gupta A. High Performance Computing in Power and Energy Systems, *Power Systems Series*. Berlin, Heidelberg, Springer-Verlag, 2013, 384 p. DOI 10.1007/978-3-642-32683-7_2
14. Lozynskyi O., Paranchuk Ya., Moroz V., Stakhiv P. Computer Model of the Electromechanical System of Moving Electrodes of an Arc Furnace with a Combined Control Law, *2019 IEEE 20th International Conference on Computational Problems of Electrical Engineering (CPEE). September 15–18, 2019, proceedings*. Lviv, Ukraine. DOI: 10.1109/CPEE47179.2019.8949136
15. Moroz V. The Numerically-Analytic Method for the Real-Time Computer Simulation, 9th International Workshops "*Computational Problems of Electrical Engineering", September 16–20, 2008, proceedings, Volume 1.* Ukraine, Alushta (Crimea), pp. 162–164.
16. Smith J. Mathematical Modeling and Digital Simulation for Engineers and Scientists. Second Edition. New Jersey, Wiley-Interscience, 448 p. DOI: 10.2307/2531888
17. Moroz V., Vakarchuk A. Numerical Integrators on Electrical Circuits' Transient Calculation, *22nd International Conference "Computational Problems of Electrical Engineering" (CPEE-2021), September 15–17th, 2021 : proceedings.* Šumava, Czech Republic. DOI: 10.1109/CPEE54040.2021.9585266
18. Moroz V., Vakarchuk A. Why High-Order Integrators Not Rational on Electrical Systems' Computer Calculation, *IEEE 20th International Conference on Modern Electrical and Energy System September 21–24, 2021 : proceedings. Kremenchuk Mykhailo Ostrohradskyi National University,* Ukraine. DOI: 10.1109/MEES52427.2021.9598791

Received 25.01.2022.
Accepted 15.02.2022.

DOI 10.15588/1607-3274-2022-2-19

УДК 519.61:517.97:004

ЧАСТОТНІ ХАРАКТЕРИСТИКИ ЧИСЛОВИХ МЕТОДІВ ДИСКРЕТИЗАЦІЇ ЦИФРОВИХ СИСТЕМ КЕРУВАННЯ

Мороз В. І. – д-р техн. наук, професор кафедри електромехатроніки та комп'ютеризованих електромеханічних систем Національного університету «Львівська політехніка», Львів, Україна.

Вакарчук А. Б. – аспірантка кафедри електромехатроніки та комп'ютеризованих електромеханічних систем Національного університету «Львівська політехніка», Львів, Україна.

АНОТАЦІЯ

Актуальність. У статті проведено дослідження частотних властивостей явних багатокрокових числових інтеграторів, які використовують для дискретизації неперервних передавальних функцій в цифрових системах керування. Числові інтегратори в таких системах виступають як складові частини цифрових регуляторів.

Метою дослідження є аналіз поведінки явних числових інтеграторів різних порядків, які використовують для дискретизації неперервних систем, з метою вивчення їхнього впливу на властивості синтезованої цифрової системи.

Метод. Методи числового інтегрування розглянуто як цифрові фільтри, поведінку яких досліджено методом частотних характеристик. Для цього з використанням апарату z-перетворення знайдено їхні дискретні передавальні функції для частотного аналізу з використанням пакету Control Systems Toolbox математичного застосунку MATLAB. Для подальшого аналізу використано дві замкнені зворотним зв'язком тестові структури: з інтеграторами в прямому каналі та в колі зворотного зв'язку. Обидва варіанти структур досліджено методом частотних характеристик для дискретизації за допомогою числових інтеграторів 1–6 порядків.

Результати. Показана неефективність застосування числових інтеграторів високого порядку для дискретизації неперервних систем. З огляду на поведінку частотних характеристик тестових систем найраціональнішим є використання інтеграторів невисокого порядку, а саме – першого і другого. Встановлення причини такого явища потребує додаткових досліджень, зокрема, виявлення можливого впливу додаткових нулів та полюсів дискретних передавальних функцій числових інтеграторів.

Висновки. Використання інтеграторів низького порядку, а саме – першого та другого порядків, є найбільш раціональним для вибірки цифрових систем керування, також доведена неефективність використання чисельних інтеграторів високого порядку для дискретизації неперервних систем.

КЛЮЧОВІ СЛОВА: дискретні передавальні функції, лінійні системи, структурні моделі, теорія автоматичного керування, цифрові системи керування, частотні характеристики, числові інтегратори, z-перетворення.

УДК 519.61:517.97:004

ЧАСТОТНІ ХАРАКТЕРИСТИКИ ЧИСЛОВИХ МЕТОДІВ ДИСКРЕТИЗАЦІЇ ЦИФРОВИХ СИСТЕМ КЕРУВАННЯ

Мороз В. І. – д-р техн. наук, профессор кафедры электромехатроники и компьютеризированных электромеханических систем Национального университета «Львовская политехника», Львов, Украина.

Вакарчук А. Б. – аспирантка кафедры электромехатроники и компьютеризированных электромеханических систем Национального университета «Львовская политехника», Львов, Украина.

АННОТАЦИЯ

Актуальность. В статье проведено исследование частотных свойств явных многошаговых численных интеграторов, которые используются для дискретизации непрерывных передаточных функций в цифровых системах управления. Численные интеграторы в таких системах выступают как составные части цифровых регуляторов.

Целью исследования является анализ поведения явных численных интеграторов разных порядков, которые используют для дискретизации непрерывных систем, с целью изучения их влияния на свойства синтезируемой цифровой системы.

Метод. Методы численного интегрирования рассмотрены как цифровые фильтры, поведение которых исследовано методом частотных характеристик. Для этого с использованием аппарата z-преобразования найдены дискретные передаточные функции для частотного анализа с использованием пакета Control Systems Toolbox математического приложения MATLAB. Для дальнейшего анализа использованы две замкнутые обратной связью тестовые структуры: с интеграторами в прямом канале и в цепи обратной связи. Оба варианта структур исследованы методом частотных характеристик для дискретизации с помощью численных интеграторов 1–6 порядков.

Результаты. Показана неэффективность использования численных интеграторов высокого порядка для дискретизации непрерывных систем. Учитывая поведение частотных характеристик тестовых систем, наиболее рациональным является использование интеграторов невысокого порядка, а именно – первого и второго. Установление причины такого явления требует дополнительных исследований, в частности, выявления возможного влияния дополнительных нулей и полюсов дискретных передаточных функций численных интеграторов.

Выводы. Использование интеграторов низкого порядка, а именно – первого и второго порядков, наиболее рационально для выборки цифровых систем управления, также доказана неэффективность использования численных интеграторов высокого порядка для дискретизации непрерывных систем.

КЛЮЧЕВЫЕ СЛОВА: дискретные передаточные функции, линейные системы, структурные модели, теория автоматического управления, цифровые системы управления, частотные характеристики, численные интеграторы, z-преобразование.

DOI 10.15588/1607-3274-2022-2-19

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Åström K. Computer-Controlled Systems: Theory and Design, Third Edition / Karl Åström, Björn Wittenmark. – New York : Published by Dover Books on Electrical Engineering, 2013. – 578 p. DOI 10.1108/ir.1998.04925fae.003
2. Dorf R. Modern Control Systems. 12th Edition / Richard C. Dorf, Robert H. Bishop. – New Jersey : Pearson, 2010. – 1104 p. DOI 10.1002/rnc.1054
3. Jury E. Sampled-data control systems / Elijah Jury. – New York : John Wiley & Sons, Inc., 1958. – 453 p. DOI: 10.2307/3007623
4. Jury E. Theory and Application of the Z-Transform Method / Elijah Jury. – Melbourne : Krieger Pub Co, 1973. – 330 p.
5. MATLAB Environment. [Electronic resource] ©1994–2021. The MathWorks, Inc. – Access mode: https://www.mathworks.com/products/matlab.html
6. Control System Toolbox: Design and analyze control systems. [Electronic resource] ©1994–2021. The MathWorks, Inc. – Access mode: https://www.mathworks.com/products/control.html?s_tid=srchtitle
7. Johnson M. PID Control: New Identification and Design Methods / Michael A. Johnson, Mohammad H. Moradi (Editors). – London: ©Springer-Verlag London Limited, 2005. – 544 p. DOI: 10.1007/1-84628-148-2
8. Tou J. Digital and Sampled-Data Control System (McGraw-Hill Electrical and Electronic Engineering Series) / Julius T. Tou. – New York : McGraw Hill Book Co, January 1959. – 631 p.
9. Chua L. Computer-aided analysis of electronic circuits: algorithms and computational techniques / Leon O. Chua, Pen-Min Lin. – Englewood Cliffs, N. J.: Prentice-Hall, 1975. – 737 p.
10. Hairer E. Solving Ordinary Differential Equations I: Nonstiff Problems. Second Edition / E. Hairer, S. Nørsett, G. Wanner. – Berlin, Heidelberg: Springer, 2008. – 528 p. DOI: 10.1007/978-3-540-78862-1
11. Ogata Katsuhiko. Discrete-Time Control Systems, 2nd edition / Katsuhiko Ogata. – Englewood Cliffs, N. J.: Prentice-Hall, 1995. – 760 p.
12. Kuo B. Digital Control Systems, 2nd Edition (The Oxford Series in Electrical and Computer Engineering / Benjamin C. Kuo. – Oxford : Oxford University Press, 1995. – 751 p.
13. Khaitan S. High Performance Computing in Power and Energy Systems / Siddhartha Kumar Khaitan, Anshan Gupta // Power Systems Series. – Berlin, Heidelberg: Springer-Verlag, 2013. – 384 p. DOI 10.1007/978-3-642-32683-7_2
14. Computer Model of the Electromechanical System of Moving Electrodes of an Arc Furnace with a Combined Control Law / [O. Lozynskyi, Ya. Paranchuk, V. Moroz, P. Stakhiv] // 2019 IEEE 20th International Conference on Computational Problems of Electrical Engineering (CPEE). September 15–18, 2019 : proceedings. Lviv, Ukraine. DOI: 10.1109/CPEE47179.2019.8949136
15. Moroz V. The Numerically-Analytic Method for the Real-Time Computer Simulation / V. Moroz // 9th International Workshops "Computational Problems of Electrical Engineering". – September 16-20, 2008 : proceedings, Volume 1. – Ukraine, Alushta (Crimea). – P. 162–164.
16. Smith J. Mathematical Modeling and Digital Simulation for Engineers and Scientists. Second Edition / J. M. Smith. – New Jersey : Wiley-Interscience. – 448 p. DOI: 10.2307/2531888
17. Moroz V. Numerical Integrators on Electrical Circuits' Transient Calculation / Volodymyr Moroz, Anastasia Vakarchuk // 22nd International Conference "Computational Problems of Electrical Engineering" (CPEE-2021), September 15–17th, 2021 : proceedings. Šumava, Czech Republic. DOI: 10.1109/CPEE54040.2021.9585266
18. Moroz V. Why High-Order Integrators Not Rational on Electrical Systems' Computer Calculation / Volodymyr Moroz, Anastasia Vakarchuk // IEEE 20th International Conference on Modern Electrical and Energy System September 21–24, 2021 : proceedings. Kremenchuk Mykhailo Ostrohradskyi National University, Ukraine. DOI: 10.1109/MEES52427.2021.9598791

DOI 10.15588/1607-3274-2022-2-19

UDC 658.51.012

SYNTHESIS OF THE ALGORITHM FOR THE FLOW PARAMETERS OPTIMAL CONTROL OF THE REVERSIBLE CONVEYOR

Pihnastyi O. M. – Dr. Sc., Professor of the Department of Distributed Information Systems and Cloud Technologies, National Technical University "Kharkov Polytechnic Institute", Kharkiv, Ukraine.

Ivanovska O. V. – PhD, Assistant Professor of the Department of Composite Structures and Aviation Materials, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine.

Sobol M. O. – PhD, Senior Lecturer of the Department of Computer Science and Intellectual Property, National Technical University "Kharkov Polytechnic Institute", Kharkiv, Ukraine.

ABSTRACT

Context. The problem of optimal control of flow parameters of a conveyor-type transport system containing sections with reversible conveyors is considered. The object of the stady was an analytical model of a reversible transport conveyor for synthesizing an algorithm for optimal control of the flow parameters of a reversible transport conveyor.

Objective. The goal of the work is to develop a synthesis technique for an algorithm for optimal control of the flow parameters of a reversible transport conveyor based on an analytical model of a conveyor section containing a transport delay.

Method. An analytical model of a reversible conveyor has been developed for the case of a constant speed of a conveyor belt, which makes it possible to determine the values of the output flows from the reverse section with known values of material flows coming to the input of the conveyor section. To build a model of the reversible section of the conveyor, an analytical model of the section of the conveyor in partial derivatives, containing the transport delay, was used. When constructing the model, the assumption was made about the instantaneous switching of the direction of movement of the conveyor belt, and it is also assumed that the interval between switching the direction of the belt speed exceeds the values of the transport delay for the conveyor section. To synthesize an algorithm for optimal control of the reversible conveyor, a control quality criterion was introduced. The formulation of the problem of optimal control of the flow parameters of the reversible conveyor is given, based on the Pontryagin maximum principle. The Hamilton function for the controlled system is written, taking into account the criterion of the quality of control of the reversible conveyor. A technique for synthesizing an algorithm for optimal control of the material output flow of a section of a reversible conveyor is demonstrated. The conditions for switching the direction of the speed of the conveyor belt are determined.

Results. The developed model of the reversible conveyor section is used to synthesize an algorithm for optimal control of the material output flow of the reversible conveyor section.

Conclusions. A method for the synthesis of algorithms for optimal control of the flow parameters of a transport system with sections containing reversible conveyors has been developed. The construction of an analytical model opens up new perspectives for the design of transport conveyor control algorithms, which can be used to reduce the specific energy costs for material transportation in the mining industry.

KEYWORDS: reversible conveyor, PiKh-conveyor model, transport delay, conveyor belt speed, transport system, conveyor control.

ABBREVIATIONS

PDE-model is a model of continuous representation of the movement of material along the technological route of the production line, using equations in partial derivatives;

PiKh-model is an analytical model of a conveyor line that allows you to determine the density of the material and the material flow at an arbitrary point on the conveyor belt;

RC (reversible conveyor) is a conveyor whose belt is capable of changing the direction of speed to the opposite in order to move the material in the opposite direction.

NOMENCLATURE

S_d is a conveyor line length;

T_d is a characteristic time for the material to pass the transport route;

$[\chi]_0(t,S)$ is a linear density of the material at the moment of time t at the point of the transport route with the coordinate $S \in [0, S_d]$;

$[\chi]_1(t,S)$ is a material flow at the moment of time t at the point of the transport route with the coordinate $S \in [0, S_d]$;

$\Psi(S)$ is an initial distribution of material along the technological route;

Θ is a limit value of the linear density of the material for the conveyor section;

$\lambda_i(t)$ is a material flow from the i-th bunker incoming to the input of the conveyor section;

$\lambda_{i\max}$ is a maximum allowable value of the material flow from the i-th bunker incoming to the input of the conveyor section, $0 \le \lambda_1(t) \le \lambda_{i\max}$;

$\sigma_i(t)$ is a planned value of the output flow from the conveyor section, determined by the input flow from the i-th bunker;

$a(t)$ is a conveyor belt speed;

G^{-1} is a function inverse to the function $G(\tau)$;

$H(S)$ is a Heaviside function;

DOI 10.15588/1607-3274-2022-2-20

$\delta(S)$ is a Dirac delta function;

τ_{um} is a dimensionless time of switching the direction of the belt speed, $m = 0,1,2,3...$;

τ_{u0} is a dimensionless value of the start time of the transport conveyor belt;

τ_{uk} is a dimensionless value of the transport conveyor completion time, $m = 0$;

$\Delta\tau_{u(m+1)} = \tau_{u(m+1)} - \tau_{um}$ is a dimensionless time interval between switching the direction of the belt speed;

$\Delta\tau_{\xi}$ is a dimensionless value of the transporting delay at the route point, determined by the value ξ;

$\Delta\tau_1$ is the dimensionless value of the transporting delay at the route point, determined by the value $\xi = 1$.

INTRODUCTION

The conveyor is one of the most effective ways to transport material in the mining industry [1, 2]. The length of the transportation route for modern conveyor-type transport systems has reached one hundred kilometers [3, 4] and continues to increase. With a conveyor belt fill factor of 50–70% with material [5], transportation costs reach 20% of the material mining cost [6, 7]. Reducing transport costs is achieved by increasing the load factor of the conveyor belt material [8, 9]. To do this, control systems for belt speed [10, 11, 12], the output flow of material from the accumulating bunker [3, 13, 14], and energy management methodology [15, 16, 17] are used.

The division of the transport conveyor into sections increases the efficiency of managing a section of the transport route within a separate section and the reliability of the functioning of the transport system as a whole [18, 19]. Technological trajectories of individual elements of the material within the section are similar, do not intersect, and are displaced relative to each other [20]. The displacement of technological trajectories is determined by the value of the speed of the conveyor belt.

Increasing the material load factor of the conveyor belt can also be achieved by changing the route of material transportation. Such control is carried out using reversible conveyors, which allow changing the direction of material movement within the section to the opposite direction [21, 22, 23]. The present study is devoted to the synthesis of optimal control algorithms for the flow parameters of a reversible conveyor.

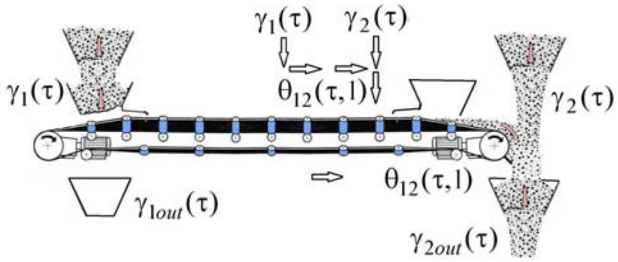
The object of study is an analytical model of a transport reversible conveyor.

The subject of study is analytical methods for designing a transport reversible conveyor control system.

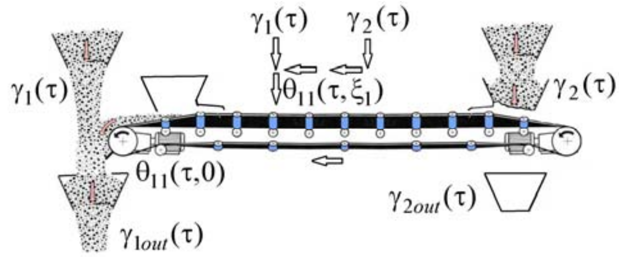
The purpose of the work is analytical methods for designing a transport reversible conveyor control system.

1 PROBLEM STATEMENT

The reversible conveyor (RC) is used to ensure material is transported in both forward and reverse directions (Fig. 1). This method of designing a conveyor-type transport system provides a more uniform loading of branched transport routes as a result of redirecting material flows from a more loaded transport route to a less loaded route.



a



b

Figure 1 – Schematic diagram of the functioning of the transport reversible conveyor:
a – the direct moving belt; b – the reverse moving belt

The transport reversible conveyor is a complex dynamic distributed system with a transport delay. An analytical solution to the problem of the main conveyor, which makes it possible to calculate the value of the output flow for a given initial distribution of material along the transport route, was obtained in [1]. The problem of synthesizing the optimal control of the flow parameters of the transport main conveyor is considered in [2, 3].

For a reversible conveyor, the problem of synthesizing optimal control can be represented as successive algorithms for optimal control of the material flow between the switching points of the direction of the conveyor belt speed. The initial conditions for the equation of the transport conveyor [1] at the point of switching the direction of movement are determined by the current distribution of material along the transport route.

When synthesizing algorithms for optimal material flow control, let us assume:

a) there is no control over the flow of material incoming the reversible conveyor from the input accumulating bunker;

b) belt speed between switching intervals is constant;

c) the change of speed direction is instantaneous;

d) the time interval $\Delta\tau_{um}$ between two adjacent switching of the direction of speed exceeds the time $\Delta\tau_1$ ($\xi = 1$) of the passage of the material along the transport path of the conveyor section.

DOI 10.15588/1607-3274-2022-2-20

The accepted assumption about the instantaneous switching of the speed of the belt implies the absence of restrictions on the amount of change in the speed of the conveyor belt, due to the occurrence and propagation of dynamic stresses along the conveyor belt. The assumption of the absence of material flow control at the input and the assumption of a constant belt speed makes it possible to simplify the problem of synthesizing algorithms for optimal material flow control by considering at the initial stage a model of a reversible conveyor with a constant transport delay in the presence of relay control. Separate studies will be devoted to the synthesis of algorithms for optimal control of the speed of the reversible conveyor belt and the flow of material coming from the accumulation bunker.

2 REVIEW OF THE LITERATURE

To build a model of a separate section of the transport conveyor, the finite element method is used [24, 25, 26]; finite difference method [27]; Lagrange method; method using the aggregated equation of state [11]; equations of system dynamics [14]. The methods are based on various numerical schemes for calculating the flow parameters of the transport system. Also, models based on neural networks [4, 28, 29] and regression equations [30, 31, 32] are widely used to describe the state of the transport conveyor. The synthesis of an optimal algorithm for controlling the flow parameters of a transport multi-section conveyor using a model that includes a neural network is presented in [33]. Among the existing models used to calculate the flow parameters of the transport conveyor section, it should be noted the analytical PiKh-model (PDE-model) [34], which is used to synthesize algorithms for optimal control of the flow parameters of the conveyor, taking into account the energy management methodology [6], to synthesize the optimal speed control algorithm movement of the conveyor belt [8], as well as for generating a training data set in a model based on a neural network [33] and on a linear regression equation [32]. The analytical PiKh-model also proved to be good in describing the change in the flow parameters of a multi-section main conveyor and modeling a conveyor with an input/output accumulating bunker. In this study, the scope of the analytical PiKh-model of the transport conveyor will be expanded, using it to build a model of a reversible conveyor.

The principle of operation of a multi-section transport system containing reversible conveyors is described in [21] when simulating transport flows in the "Rudna" mine (Poland). Later, the "Rudna" mine transport system was considered during research in [22, 23]. Interest in the use of reversible conveyors is associated, on the one hand, with the use of a reversible conveyor to change the route of material transportation, and on the other hand, with the use of a reversible conveyor as an accumulation bunker in the transport system. The principle of operation of the reversible conveyor section described in [21] is used to develop a reversible conveyor model based on the analytical PiKh-model.

DOI 10.15588/1607-3274-2022-2-20

3 MATERIALS AND METHODS

To build a model of a transport reversible conveyor that determines the state of the flow parameters of a section along the transportation route, we will use the equation PiKh–model of the conveyor in a dimensionless form [34]

$$\frac{\partial\theta_0(\tau,\xi)}{\partial\tau}+g(\tau)\frac{\partial\theta_0(\tau,\xi)}{\partial\xi}=\delta(\xi)\gamma(\tau), \quad (1)$$

$$\theta_0(0,\xi)=\mathrm{H}(\xi)\psi(\xi). \quad (2)$$

The state of the flow parameters of the reversible conveyor section is described by dimensionless variables:

$$\tau=\frac{t}{T_d},\ \xi=\frac{S}{S_d}, \quad (3)$$

$$\theta_0(\tau,\xi)=\frac{[\chi]_0(t,S)}{\Theta},\ \psi(\xi)=\frac{\Psi(S)}{\Theta}, \quad (4)$$

$$\gamma_i(\tau)=\lambda_i(t)\frac{T_d}{S_d\Theta},\ \gamma_{i\max}=\lambda_{i\max}\frac{T_d}{S_d\Theta},\ i=1,2, \quad (5)$$

$$\Theta=\max\left\{\Psi(S),\frac{\lambda_i(t)}{a(t)}\right\},\ \vartheta_i(\tau)=\sigma_i(t)\frac{T_d}{S_d\Theta} \quad (6)$$

$$g(\tau)=a(t)\frac{T_d}{S_d},\ [\chi]_1(t,S)=a(t)[\chi]_0(t,S) \quad (7)$$

$$\delta(\xi)=S_d\delta(S),\ H(\xi)=H(S). \quad (8)$$

The solution of equation (1) with initial conditions (2) has the form [34]

$$\theta_0(\tau,\xi)=\left(1-H(\xi-G(\tau))\right)\frac{\gamma_1(G^{-1}(G(\tau)-\xi))}{g(G^{-1}(G(\tau)-\xi))}+$$
$$+\mathrm{H}(\xi-G(\tau))\psi(\xi-G(\tau)), \quad (9)$$

$$G(\tau)=\int_0^\tau g(\alpha)d\alpha, \quad (10)$$

$$\theta_1(\tau,\xi)=g(\tau)\theta_0(\tau,\xi). \quad (11)$$

The presented solution makes it possible to determine the density of the material $\theta_0(\tau,\xi)$ and the flow of the material $\theta_1(\tau,\xi)$ at an arbitrary point in time τ for each point ξ of the transport route. In this study, let us focus on building a model of a transport reversible conveyor, the belt speed of which is constant and equal g_0 (with the exception of the moment of switching the direction of movement of the conveyor belt)

$$g(\tau)=g_0,\ G(\tau)=g_0\tau, \quad (12)$$
$$0\le\tau\le\tau_{u1}.$$

For a constant belt speed, solution (9)–(11) can be written in the following form

$$\theta_0(\tau,\xi) = \left(1 - H(\xi - g_0\tau)\right)\frac{\gamma_1(\tau - \Delta\tau_\xi)}{g_0} + \tag{13}$$

$$+\mathrm{H}(\xi - g_0\tau)\psi(\xi - g_0\tau),$$

$$\theta_1(\tau,\xi) = g_0\theta_0(\tau,\xi), \tag{14}$$

$$\Delta\tau_\xi = \xi / g_0, \tag{15}$$

$$0 \le \tau \le \tau_{u1}.$$

The resulting solution (9)–(11) makes it possible to determine the output flow of material from the conveyor section

$$\theta_1(\tau,1) = \left(1 - H(1 - g_0\tau)\right)\gamma_1(\tau - \Delta\tau_1) + \\ +\mathrm{H}(1 - g_0\tau)\psi(1 - g_0\tau)g_0, \tag{16}$$

$$\Delta\tau_1 = 1/g_0.$$

Solution (13)–(16) of equation (1) was obtained for the case of material movement only in the forward direction (Fig. 1a) without speed switching.

If there are points of switching the direction of the flow at the instants of time τ_{um}, the values of the output flows $\gamma_{1out}(\tau)$, $\gamma_{2out}(\tau)$ of the reversible conveyor, taking into account the solution (16), take the form

$$\gamma_{n\,out}(\tau) = \sum_{m=0}^{M} F_{n,m}(\tau)\left(\gamma_{n1}(\tau) + \gamma_{n2,m}(\tau) + \gamma_{n3,m}(\tau)\right), \tag{17}$$

$$\gamma_{n1}(\tau) = \gamma_n(\tau), \quad n = (1,2), \tag{18}$$

$$\gamma_{12,m}(\tau) = \left(1 - H(1 - g_0\Delta\tau_{m\tau})\right)\gamma_2(\tau - \Delta\tau_1), \tag{19}$$

$$\gamma_{22,m}(\tau) = \left(1 - H(1 - g_0\Delta\tau_{m\tau})\right)\gamma_1(\tau - \Delta\tau_1), \tag{20}$$

$$\gamma_{n3,m}(\tau) = H(1 - g_0\Delta\tau_{m\tau})\gamma_n(\tau_{um} - \Delta\tau_{m\tau}), \tag{21}$$

$$\Delta\tau_{m\tau} = (\tau - \tau_{um}), \tag{22}$$

$$F_{1,m}(\tau) = \frac{1 - (-1)^m}{2}\left(H(\tau - \tau_{um}) - H(\tau - \tau_{u(m+1)})\right), \tag{23}$$

$$F_{2,m}(\tau) = \frac{1 + (-1)^m}{2}\left(H(\tau - \tau_{um}) - H(\tau - \tau_{u(m+1)})\right), \tag{24}$$

$$\tau_m = \infty, \; m > M.$$

The flow of material into the bunker occurs with the forward direction of the conveyor belt (Fig. 1a), and the flow of material into the bunker $\gamma_{1out}(\tau)$ occurs with the reverse direction of the conveyor belt (Fig. 1b).

Functions $F_{1,m}(\tau)$, $F_{2,m}(\tau)$ determine the time interval $\Delta\tau_{u(m+1)}$ between switching the direction of movement of the material along the conveyor belt. The function $F_{2,m}(\tau)$ is equal to one for the case if the conveyor moves in the forward direction (Fig. 1a) and the inequality $\tau_{um} \le \tau < \tau_{u(m+1)}$, (m is even) is fulfilled. Similarly, the function $F_{2,m}(\tau)$ is equal to one for the case if the conveyor moves in the opposite direction (Fig. 1b) and the inequality $\tau_{um} \le \tau < \tau_{u(m+1)}$, ($m$ is odd) is satisfied. The function $\gamma_{22,m}(\tau)$ determines the flow of material from the bunker $\gamma_1(\tau)$ to the bunker $\gamma_{2out}(\tau)$ with a transport delay (Fig. 1a) in the time interval $\tau_{um} \le \tau < \tau_{u(m+1)}$. The function $\gamma_{12,m}(\tau)$ determines the flow of material from bunker $\gamma_2(\tau)$ to bunker $\gamma_{1out}(\tau)$ with the same transport delay $\Delta\tau_1$ (Fig. 1b).

The function $\gamma_{23,m}(\tau)$ determined by the flow of material from the conveyor during the time interval $\Delta\tau_1$ from the moment of switching τ_{um}. The flow of material $\gamma_{23,m}(\tau)$ is formed by the distribution of material $\psi_m(\xi)$ along the conveyor belt at a time τ_{um}

$$\gamma_{23,m}(\tau) = \gamma_{23,m}(\tau_{um} + \Delta\tau_{m\tau}) = \psi_m(1 - g_0\Delta\tau_{m\tau}). \tag{25}$$

Taking into account the assumption $\Delta\tau_{um} > \Delta\tau_1$, the distribution of material along the conveyor belt is completely determined by the material flow $\gamma_2(\tau)$. This dependence at a constant speed of the belt within the time interval $\Delta\tau_{um}$ can be represented in the following form

$$\gamma_2(\tau_{um} - \Delta\tau_{m\tau}) = \psi_m(1 - g_0\Delta\tau_{m\tau}), \tag{26}$$

whence for the time interval $\Delta\tau_1$ from the moment of the time of switching τ_{um}, the expression is obtained for the output flow from the conveyor belt in the forward direction of motion

$$\gamma_{23,m}(\tau) = \gamma_{23,m}(\tau_{um} + \Delta\tau_{m\tau}) = \\ = \gamma_2(\tau_{um} - \Delta\tau_{m\tau}) = \gamma_2(2\tau_{um} - \tau). \tag{27}$$

For the reverse direction of movement of the belt, the distribution of material $\psi_m(\xi)$ along the conveyor belt at the moment of time τ_{um} is given by the flow of material $\gamma_1(\tau)$

$$\gamma_1(\tau_{um} - \Delta\tau_{m\tau}) = \psi_m(g_0\Delta\tau_{m\tau}). \tag{28}$$

Taking into account the relationship between the output flow $\gamma_{13,m}(\tau)$ and the distribution of material $\psi_m(\xi)$ along the conveyor belt for the period of time $\Delta\tau_1$ from the time of switching τ_{um}

$$\gamma_{13,m}(\tau) = \gamma_{13,m}(\tau_{um} + \Delta\tau_{m\tau}) = \psi_m(g_0\Delta\tau_{m\tau}), \tag{29}$$

the value of the material flow $\gamma_{13,m}(\tau)$ is obtained when the conveyor moves in the opposite direction

DOI 10.15588/1607-3274-2022-2-20

$$\gamma_{13,m}(\tau)=\gamma_{13,m}(\tau_{um}+\Delta\tau_{m\tau})= \qquad (30)$$
$$=\gamma_1(\tau_{um}-\Delta\tau_{m\tau})=\gamma_1(2\tau_{um}-\tau)\ .$$

At given times of switching τ_{um} the direction of movement of the belt, expressions (17) determine the flow of material in the transport system in the presence of a reverse mode of operation of the conveyor.

4 EXPERIMENTS

To carry out numerical experiments, the software has been developed that makes it possible to calculate the values of the flow parameters of the transport conveyor in accordance with the RC model (17)–(26). Test values of material flows $\gamma_1(\tau)$, $\gamma_2(\tau)$, incoming the section of the reversible conveyor from the accumulation bunkers, as well as the value of the planned output flow $\vartheta_2(\tau)$ from the section of the conveyor represented by periodic functions (Fig. 2):

$$\gamma_1(\tau)=2.0+\sin(0.4\pi\tau),\quad (31)$$
$$\gamma_2(\tau)=2.0+\sin(0.2\pi\tau),$$
$$\vartheta_2(\tau)=2.0+2.0\sin(0.2\pi\tau+\pi).$$

Periodic functions in the form (31) are used in the qualitative analysis of the flow parameters of transport and production systems [26, 35, 36], the production process of which is periodic. This approach makes it possible to reveal the qualitative features of the model and the relationship between flow parameters [37]. When carrying out numerical experiments, it was assumed that at the initial time the conveyor section is fully loaded with material

$$\psi(\xi)=1\ . \quad (32)$$

In the absence of reversible control, the material flows $\gamma_1(\tau)$, $\gamma_2(\tau)$, incoming the section of the reversible conveyor from the accumulation bunkers, form the output material flow $\gamma_{2out}(\tau)$ from the conveyor section (Fig. 3) in accordance with the RC model (17)–(26). The type of function $\psi(\xi)$, which specifies the initial distribution of material along the RC section, affects the value of the output material flow only in the initial period of time $\tau<1$. For the time moments of the transport system operation $\tau\geq 1$, the initial distribution of the material does not affect the state of the output flow parameters of the conveyor section (Fig. 3). In the absence of reversible control, the output flow of material from the conveyor section is determined by the expression

$$\gamma_{2out}(\tau)=\gamma_2(\tau)+\gamma_1(\tau-1)\ . \quad (33)$$

which contains the transport delay $\Delta\tau_1=1$. The superposition of material flows from the accumulation bunkers $\gamma_1(\tau)$, $\gamma_2(\tau)$, that form the output flow $\gamma_{2out}(\tau)$, leads to the fact that in the allocated time intervals the output flow $\gamma_{2out}(\tau)$ deviates significantly from the planned material flow $\vartheta_2(\tau)$, required to maintain a continuous production process (Fig. 3). With the reversible movement of the belt, the flow of material changes direction, and therefore, $\gamma_{2out}(\tau)=0$. The condition (Fig. 4) was used to calculate the switching points of the belt movement direction

$$\Delta\gamma_2(\tau)=\gamma_{2out}(\tau)-2\vartheta_2(\tau)>0\ . \quad (34)$$

The function $\Delta\gamma_2(\tau)$, on the basis of which the switching points are numerically calculated, is shown in Fig. 4. When $\Delta\tau_{m\tau}>>1$, to improve the performance of calculations, the RC model (17)–(26) can be replaced by the approximate model (33).

The method for calculating switching points in accordance with condition (34) was used to synthesize the algorithm for controlling the output flow from the conveyor section.

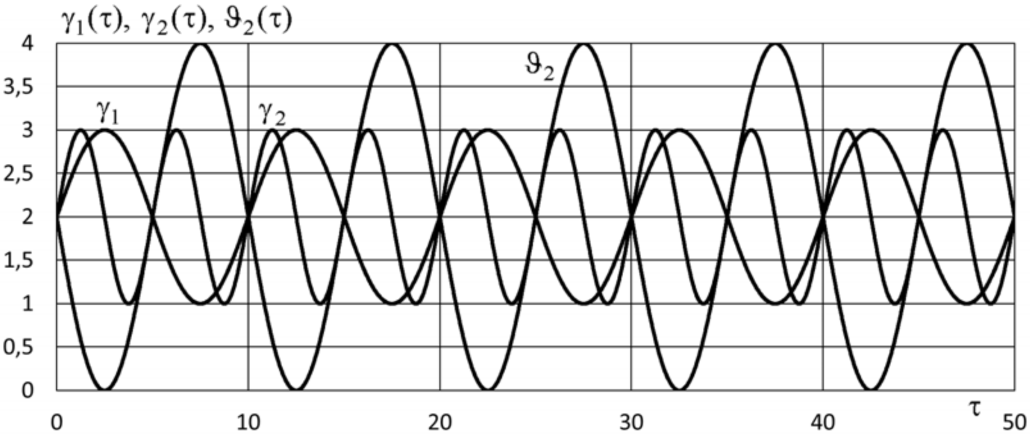


Figure 2 – Dynamics of material flows $\gamma_1(\tau)$, $\gamma_2(\tau)$ from the accumulation bunkers incoming the section of the reversible conveyor and the plan material flow $\vartheta_2(\tau)$ from RC

DOI 10.15588/1607-3274-2022-2-20

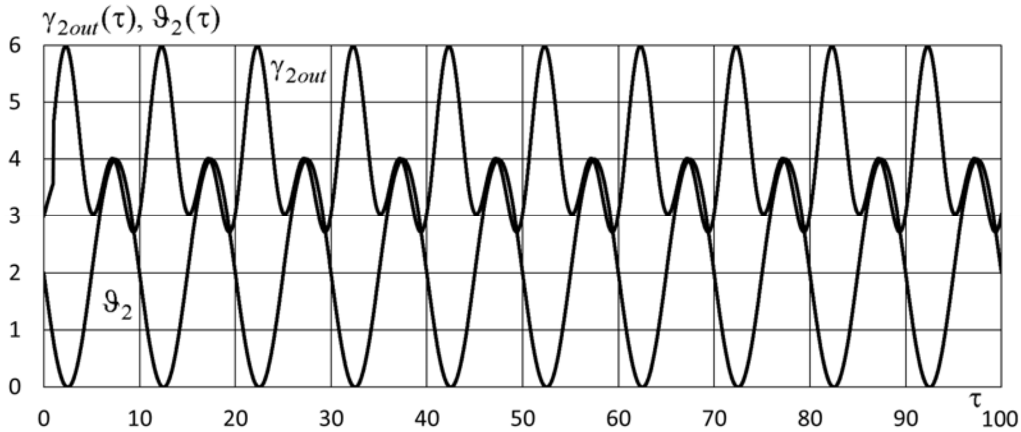


Figure 3 – Comparison of the material flow $\gamma_{2out}(\tau)$ from the conveyor in the absence of reverse control with the value of the planned material flow $\vartheta_2(\tau)$ from RC

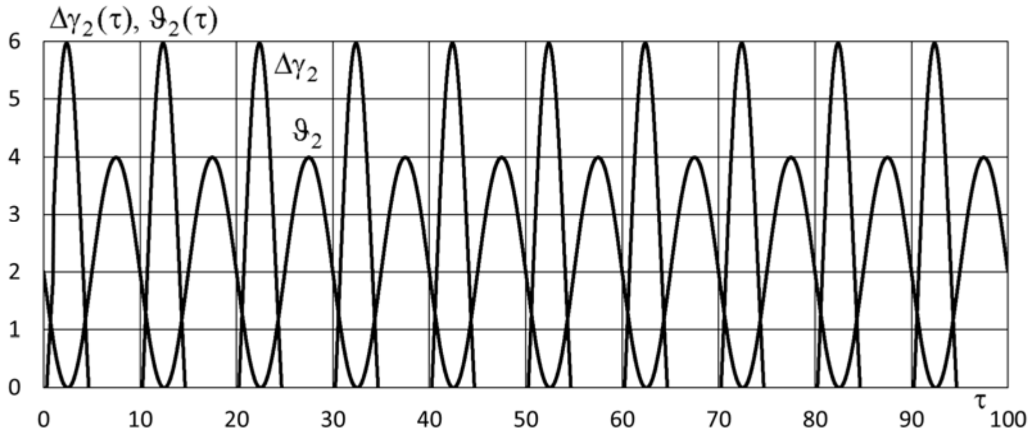


Figure 4 – A function $\Delta\gamma_2(\tau)$ for constructing points for switching the reversible mode of a conveyor section for a given planned value of the output flow $\vartheta_2(\tau)$

5 RESULTS

Let us formulate the problem of constructing an optimal program for controlling the flow of material $\gamma_{2out}(\tau)$, coming out of the reversible conveyor to meet the needs of the processing industry in the material. The transport conveyor will be controlled by switching the direction of material movement. Let us determine the value of the switching points τ_{um} of the direction of material movement during a period of time $\tau = [0, \tau_{uk}]$ with continuous control $u(\tau) = [0; \gamma_{2out}(\tau)]$ of the output flow of material from the reverse conveyor, which lead to a minimum of the functional

$$J(\tau_{uk}) = \int_0^{\tau_{uk}} (u(\tau) - \vartheta_2(\tau))^2 d\tau \to \min , \qquad (35)$$

with a limitation on the value of material flow

$$u(\tau) = [0; \gamma_{2out}(\tau)], \qquad (36)$$
$$\infty > \gamma_{2out}(\tau) > 0 .$$

The control value $u(\tau)$ is equal to $\gamma_{2out}(\tau)$ for forward material movement the control value $u(\tau)$ is zero for reverse material movement. To build a control system, this paper uses a very simple criterion of control quality, which makes it possible to demonstrate the features of control of a reversible conveyor. It is assumed that there are no restrictions on the maximum permissible value of the linear density of the material along the conveyor belt.

The Pontryagin function for control problem (35), (36) has the form:

$$H = -(u(\tau) - \vartheta_2(\tau))^2 \to \max . \qquad (37)$$

From the condition of the maximum of the Pontryagin function, the optimal control of the reversible conveyor is determined $u(\tau)$

$$\frac{\partial H}{\partial u(\tau)} = -2(u(\tau) - \vartheta_2(\tau)) = 0 . \qquad (38)$$

DOI 10.15588/1607-3274-2022-2-20

Since the control $u(\tau)$ takes one of the values $[0;\gamma_{2out}(\tau)]$, and in the general case

$$u(\tau) \neq \gamma_{2out}(\tau),$$

then equality (38) cannot be used to construct the optimal control of the reversible conveyor. Taking this into account, the conditions for the proposed switching of the conveyor operation mode are determined by the inequalities

$$\gamma_{2out}(\tau) - \vartheta_2(\tau) > \vartheta_2(\tau),\ u(\tau) = 0,$$
$$\gamma_{2out}(\tau) - \vartheta_2(\tau) \leq \vartheta_2(\tau),\ u(\tau) = \gamma_{2out}(\tau),$$

for which the Pontryagin function has a minimum. Thus, for a finite interval $\Delta\tau_1 = 1$ the point of switching the direction of movement at the moment of time τ_{um0}, defined by the condition

$$\gamma_{2out}(\tau_{um0}) = 2\vartheta_2(\tau_{um0}), \quad (39)$$
$$\Delta\gamma_2(\tau) = \gamma_{2out}(\tau) - 2\vartheta_2(\tau),$$

For switching points when the condition is satisfied

$$I(\tau) > 0, \quad (40)$$

the conveyor line operates in reversible mode, $u(\tau) = 0$. As a rule, for existing conveyor systems, the condition $\Delta\tau_{um} >> \Delta\tau_1$ is satisfied, and the switching points are determined by equation (39).

A numerical experiment demonstrating the synthesis of an algorithm for the material output flow control for boundary and initial conditions (31), (32) is presented in Fig. 5. The presence of peak values of the output flow is explained by the fact that starting from the moment of switching the direction of movement and during the time interval $\Delta\tau = \Delta\tau_1 = 1$ the output flow of material $\gamma_{2out}(\tau)$ determined only by the input flow of material $\gamma_2(\tau)$, and during the time interval for which the condition $\Delta\tau \geq 1$ is satisfied, the output flow of material $\gamma_{2out}(\tau)$ is determined by the input flows of material $\gamma_1(\tau)$ and $\gamma_2(\tau)$, which and leads to a jump in the function $u(\tau) = [0;\gamma_{2out}(\tau)]$ at $\Delta\tau = 1$. An analysis of the results of a numerical experiment shows that the initial distribution of material (32) does not affect the value of the output flow at $\tau >> 1$.

6 DISCUSSION

One of the significant difficulties that researchers encounter when designing control systems for a transport system containing reversible conveyors is building a model of a reversible conveyor section. Let us consider one of the ways in which these difficulties can be overcome.

One such way is to use an approximate model for the section of the conveyor in which the transport delay $\Delta\tau_1 = 0$ is assumed. This case may correspond to a simplified model of the reversible conveyor section in the following form

$$\gamma_{n\,out}(\tau) = \sum_{m=0}^{M} F_{n,m}(\tau)(\gamma_1(\tau) + \gamma_2(\tau)). \quad (41)$$

For a conveyor section of small length ($S_d \approx 200$ meters [23]), at a belt speed of one meter at the second, the transport delay is several minutes. For conveyor sections of medium length ($S_d \approx 2000$ meters [23]), the transport delay can be about one hour. If there are several reversible sections through which the flow of material moves in the transport system, then the total transport delay of the

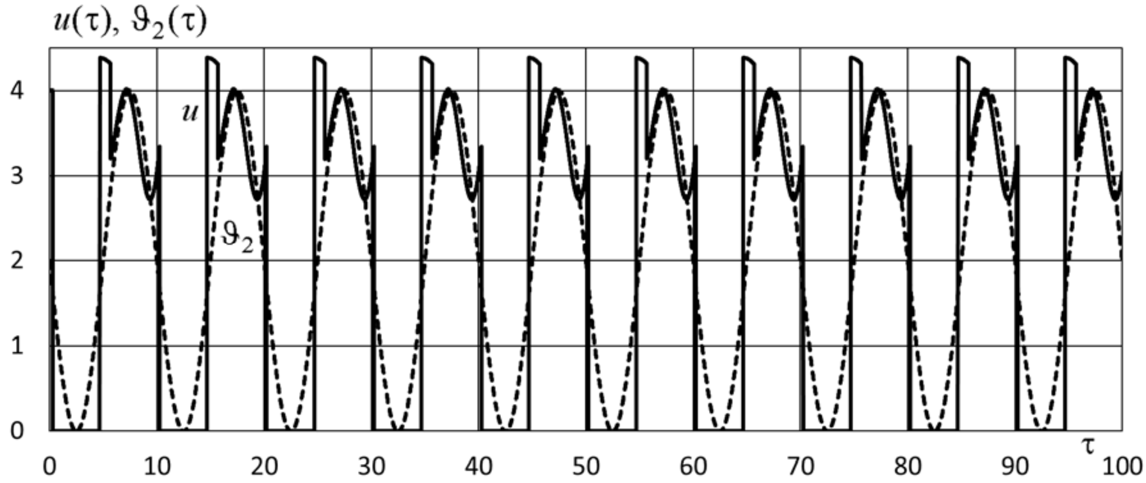


Figure 5 – Optimal control $u(\tau)$ of the RC section for a given planned value of the output flow $\vartheta_2(\tau)$

DOI 10.15588/1607-3274-2022-2-20

conveyor system during the sequential movement of material can be obtained as a result of adding the transport delays of individual sections. Thus, the value of the transport delay can be significant in the value. Neglecting the transport delay in the model of the conveyor section can lead to significant errors in the calculation of the flow parameters of the transport system, and the model itself, accordingly, should not be used to build algorithms for optimal control of the flow parameters of the transport system.

The use of model (41) implies not only an approximate calculation of the values of the flow parameters of the conveyor section, but also the fact that the specific energy costs for the movement of material are not optimized for the reversible sections of the transport system. The reduction in energy costs for moving the mined material along the transport route makes the problem of building accurate analytical models of reversible sections that can be used to synthesize algorithms for optimal control of the output flow of a conveyor-type transport system relevant.

When constructing the model and synthesizing material flow control algorithms, a number of assumptions are made in this paper. The purpose of these assumptions is to simplify as much as possible the mathematical transformations necessary to build the model, demonstrating the general methodology for creating models of reversible conveyor sections and the features of synthesizing the algorithm for optimal material flow control.

CONCLUSIONS

The actual problem of synthesizing algorithms for optimal control of the flow parameters of a conveyor-type transport system containing sections with reversible conveyors is considered. An analytical model of a reversible conveyor for the design of transport conveyor control systems is proposed.

The scientific novelty of obtained results is that for the first time an analytical model of a reversible conveyor section has been proposed for conveyor-type transport systems. This model, under the assumptions of a constant speed of the conveyor belt, of instantaneous switching of the direction of movement of the conveyor belt and of the value of the time interval between two adjacent switching of the direction of speed $\Delta\tau_{um} \geq \Delta\tau_1$, makes it possible to calculate the output flows of material $\gamma_{1out}(\tau)$, $\gamma_{2out}(\tau)$ from the section of the reversible conveyor with known values of the input flows of material $\gamma_1(\tau)$, $\gamma_2(\tau)$. The construction of an analytical model of a reversible conveyor section allows, for a given control quality criterion, to synthesize simple algorithms for optimal control of the flow parameters of a transport system containing sections with reversible conveyors.

The practical significance of obtained results is that a technique has been developed for constructing algorithms for optimal control of the flow parameters of a transport system with sections containing reversible conveyors, which can be used to reduce the specific energy costs for transporting material at mining enterprises.

Prospects for further research is to develop systems for controlling the belt speed of the reversible conveyor.

REFERENCES

1. Alspaugh M. Longer Overland Conveyors with Distributed Power, *Rockwell Automation Fair*, 2005. http://www.overlandconveyor.cn/uploadfile/pdf/13-Longer_Overland_Conveyors_with_Distributed_Power[1].pdf
2. Cornet J. Head and tail controls in long overland conveyors, *Bulk Materials Handling by Conveyor Belt*, 2002, No. 4, pp. 55–67. https://cvdyn.com/wp-content/uploads/2020/01/JLC-SME-2002-Conveyor-Head-Tail.pdf
3. Pihnastyi O., Kozhevnikov G., Khodusov V. Conveyor Model with Input and Output Accumulating Bunker, *In IEEE 11th International Conference on Dependable Systems, Services and Technologies (DESSERT)*, 2020, pp. 253–258. http://doi.org/10.1109/DESSERT50317.2020.9124996
4. Pihnastyi O., Khodusov V. Neural model of conveyor type transport system, *Proceedings of The Third International Workshop on Computer Modeling and Intelligent Systems*, 2020. http://ceur-ws.org/Vol-2608/paper60.pdf
5. Jeftenić B. Ristić L., Bebić M., Štatkić S., Mihailović I., Jevtić D. Optimal utilization of the bulk material transportation system based on speed controlled drives, *The XIX International Conference on Electrical Machines, ICEM,* 2010, pp. 1–6. https://ieeexplore.ieee.org/document/5608055
6. Pihnastyi O., Khodusov V. Development of the controlling speed algorithm of the conveyor belt based on TOU-tariffs, *Proceedings of the 2nd International Workshop on Information-Communication Technologies & Embedded Systems*, 2020, Vol. 2762, pp. 73–86. http://ceur-ws.org/Vol-2762/paper4.pdf
7. Stadnik M., Semenchenko D., Semenchenko A., Belytsky P., Virych S., Tkachov V. Improving energy efficiency of coal transportation by adjusting the speeds of a combine and a mine face conveyor, *Eastern-european Journal of Enterprise Technologies*, 2019, No. 1, pp. 60–70. http://doi.org/10.15587/1729-4061.2019.156121
8. Pihnastyi O. Control of the belt speed at unbalanced loading of the conveyor, *Scientific bulletin of National Mining University*, 2019, No. 6, pp. 122–129. https://doi.org/10.29202/nvngu/2019-6/18
9. Semenchenko A., Stadnik M., Belitsky P., Semenchenko D., Stepanenko O. The impact of an uneven loading of a belt conveyor on the loading of drive motors and energy consumption in transportation, *Eastern-European Journal of Enterprise Technologies,* 2016, No. 82, pp. 42–51. https://doi.org/10.15587/1729-4061.2016.75936
10. Halepoto I., Uqaili M. Design and Implementation of Intelligent Energy Efficient Conveyor System Model Based on Variable Speed Drive Control and Physical Modeling, *International Journal of Control and Automation,* 2016, No. 9 (6), pp. 379–388. http//dx.doi.org/10.14257/ijca.2016.9.6.36
11. Reutov A. Simulation of load traffic and steeped speed control of conveyor, *IOP Conference Series: Earth and Environmental*, 2017, No. 87, pp. 1–6. https://doi.org/10.1088/1755-1315/87/8/082041
12. Lauhoff H. Speed Control on Belt Conveyors–Does it Really Save Energy? *Bulk Solids Handling*, 2005, No. 25(6),

DOI 10.15588/1607-3274-2022-2-20

pp. 368–377. http://synergy-eng.com/pdf/BSH-2005_Beltspeed_Lauhoff.pdf
13. Bardzinski P., Walker P., Kawalec W. Simulation of random tagged ore flow through the bunker in a belt conveying system, *International Journal of Simulation* Modelling, 2018, No. 4, pp. 597–608. https://doi.org/10.2507/IJSIMM17(4)445
14. Wolstenholm E. Designing and assessing the benefits of control policies for conveyor belt systems in underground mines, *Dynamica*, 1980, No. 6 (2), pp. 25–35. https://www.systemdynamics.org/assets/dynamica/62/6.pdf
15. Pihnastyi O., Kozhevnikov G., Glavchev M. Energy Management Strategy in the Synthesis of an Algorithm for Multi-step Conveyor Belt Speed Control, *Lecture Notes in Mechanical Engineering*, 2022, pp. 33–42. http://doi.org/10.1007/978-3-030-91327-4_4
16. Marais J., Mathews E., Pelzer R. Analysing DSM opportunities on mine conveyor systems, *Industrial and commercial use of energy conference. Cape Town*, 2008.
17. Granell R., Axon C. J., Wallom D. Predicting winning and losing businesses when changing electricity tariffs, *Appl. Energy*, 2014, No. 133, pp. 298–307. https://doi.org/10.1016/j.apenergy.2014.07.098
18. Pihnastyi O., Khodusov V. Calculation of the parameters of the composite conveyor line with a constant speed of movement of subjects of labour, *Scientific bulletin of National Mining University,* 2018, No. 4 (166), pp. 138–146. https://doi.org/10.29202/nvngu/2018-4/18
19. Antoniak J. Energy-saving belt conveyors installed in polish collieries, *Transport Problems,* 2010, No. 5(4), pp. 5–14. http://transportproblems.polsl.pl/pl/Archiwum/2010/zeszyt4/2010t5z4_01.pdf
20. Pihnastyi O. Analytical methods for designing technological trajectories of the object of labour in a phase space of states *Scientific bulletin of National Mining University,* 2017, No. 4, pp. 104–111. http://nvngu.in.ua/index.php/en/component/jdownloads/viewdownload/69/8679
21. Koman M., Laska Z. The constructional solution of conveyor system for reverse and bifurcation of the ore flow, Rudna mine KGHM Polska Miedź SA, *CUPRUM,* 2014, No. 3(72), pp. 69–82. http://www.czasopismo.cuprum.wroc.pl/journal-articles/download/113
22. Burduk A., Więcek D., Zajačko I., Jurdziak L., Błażej R. Analysis and risk assessment of the supply of copper ore in the belt conveyor system in an underground mine, *Acta Montanistica*, 2020, No. 25(2), pp. 236–249. https://doi.org/10.46544/AMS.v25i2.10
23. Bajda M., Błażej R., Jurdziak L. Analysis of changes in the length of belt sections and the number of splices in the belt loops on conveyors in an underground mine, *Engineering Failure Analysis*, 2019, No. 101, pp. 436–446. https://doi.org/10.1016/j.engfailanal.2019.04.003
24. Alspaugh M. Latest developments in belt conveyor technology, *In: MINExpo,* 2004.
25. Karolewski B., Ligocki P. Modelling of long belt conveyors, *Maintenance and reliability,* 2014, No. 16 (2), pp. 179–187. http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-ce355084-3e77-4e6b-b4b5-ff6131e77b30
26. Pascual R., Meruane V., Barrientos G. Analysis of transient loads on cable-reinforced conveyor belts with damping consideration, *In: the XXVI Iberian Latin-American Congress on Computational Methods in Engineering (CILAMCE-2005)*, 2005, pp. 1–15. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.494.34&rep=rep1&type=pdf
27. Mathaba T., Xia X. A parametric energy model for energy management of long belt conveyors, *Energies,* 2015, No. 8(12), pp. 13590–13608, https://doi.org/10.3390/en81212375
28. Kirjanów A. The possibility for adopting an artificial neural network model in the diagnostics of conveyor belt splices, *Interdisciplinary issues in mining and geology,* 2016, No. 6. pp. 1–11.
29. Więcek D., Burduk A., Kuric I. The use of ANN in improving efficiency and ensuring the stability of the copper ore mining process, *Acta Montanistica Slovaca*, 2019, No. 24(1). – P. 1–14. https://actamont.tuke.sk/pdf/2019/n1/1wiecek.pdf
30. Andrejiova M., Marasova D. Using the classical linear regression model in analysis of the dependences of conveyor belt life, *Acta Montanistica Slovaca,* 2013, No. 18(2), pp. 77–84. https://actamont.tuke.sk/pdf/2013/n2/2andrejiova.pdf
31. Grincova A., Li Q. A regression model for prediction of idler rotational resistance on belt conveyor, *Measurement and Control,* 2019, No. 52(5), pp. 441–448. https://doi.org/10.1177/0020294019840723
32. Pihnastyi O., Khodusov V., Subbotin S. Linear Regression Model of the conveyor type transport system, *Proceedings of the 9th International Conference "Information Control Systems & Technologies"*, 2020, Vol. 2711, pp. 468–481
33. Pihnastyi O., Kozhevnikov G. Control of a Conveyor Based on a Neural Network, *2020 IEEE International Conference on Problems of Infocommunications. Science and Technology (PIC S&T)*, 2020, pp. 295–300, https://doi.org/10.1109/PICST51311.2020.9467934
34. Pihnastyi O., Khodusov V. Model of conveyer with the regulable speed, *Bulletin of the South Ural State University. Ser.Mathematical Modelling, Programming and Computer Software*, 2017, No. 10(4), pp. 64–77. https://doi.org/10.14529/mmp170407
35. Hlaing N., Htwe E., Htay M. Dynamic analysis of the belt conveyor system for detergent industry, *International journal of scientific and research publications*, 2018, No. 8 (9), pp. 633–638. http://dx.doi.org/10.29322/IJSRP.8.10.2018.p8279
36. He D., Pang Y., Lodewijks G., Liu X. Determination of acceleration for belt conveyor speed cont-rol in transient operation, *International journal of engineering and technology*, 2016, No. 8 (3), pp. 206–211. http://dx.doi.org/10.7763/IJET.2016.V8.886
37. Pihnastyi O., Azarekov N., Khodusov V. To the question of similarity of technological processes of the industrial technical systems, *Reports of the National Academy of Sciences of Ukraine*, 2011, No. 2, pp. 29–35. http://dspace.nbuv.gov.ua/handle/123456789/37227

Received 15.01.2022.
Accepted 20.03.2022.

DOI 10.15588/1607-3274-2022-2-20

УДК 658.51.012

СИНТЕЗ АЛГОРИТМУ ОПТИМАЛЬНОГО УПРАВЛІННЯ ПОТОЧНИМИ ПАРАМЕТРАМИ РЕВЕРСИВНОГО КОНВЕЄРА

Пігнастий О. М. – д-р техн. наук, професор, професор кафедри розподілених інформаційних систем і хмарних технологій Національного технічного університету «Харківський політехнічний інститут», м Харків, Україна.

Івановська О. В. – канд. техн. наук, доцент, доцент кафедри композиційних конструкцій і авіаційного матеріалознавства Національного аерокосмічного університету ім. М. Є. Жуковського «Харківський авіаційний інститут», м. Харків, Україна.

Соболь М. О. – канд. техн. наук, старший викладач кафедри інформатики та інтелектуальної власності Національного технічного університету «Харківський політехнічний інститут», м. Харків, Україна.

АНОТАЦІЯ

Актуальність. Розглянуто проблему оптимального управління потоковими параметрами транспортної системи конвеєрного типу, що містить секції з реверсивними конвеєрами. Об'єктом дослідження була аналітична модель транспортного реверсивного конвеєра для синтезу алгоритму оптимального керування потоковими параметрами транспортного реверсивного конвеєра. Мета роботи – розробка методики синтезу алгоритму оптимального керування потоковими параметрами транспортного реверсивного конвеєра, що базується на аналітичній моделі конвеєрної секції, що містить транспортну затримку.

Метод. Розроблено аналітичну модель реверсивного конвеєра для випадку постійної швидкості конвеєрної стрічки, що дозволяє визначити значення вихідних потоків з реверсивної секції при відомих значень потоків матеріалу, що надходять на вхід секції конвеєра. Для побудови моделі реверсивної секції конвеєра використано аналітичну модель секції конвеєра у приватних похідних, що містить транспортну затримку. При побудові моделі введено припущення про миттєве перемикання напрямку руху стрічки конвеєра, а також передбачається, що інтервал між перемиканнями напрямку швидкості руху стрічки перевищує значення транспортної затримки для секції конвеєра. Для синтезу алгоритму оптимального управління реверсивним конвеєром запроваджено критерій якості управління. Дана постановка задачі оптимального управління потоковими параметрами реверсивного конвеєра, заснована на принципі максимуму Понтрягіна. Записано функцію Гамільтона для керованої системи, яка враховує критерій якості керування реверсивним конвеєром. Продемонстровано методику синтезу алгоритму оптимального управління вихідним потоком матеріалу секції реверсивного конвеєра. Визначено умови перемикання напрямку швидкості руху стрічки конвеєра.

Результати. Розроблена модель секції реверсивного конвеєра використана синтезу алгоритму оптимального управління вихідним потоком матеріалу секції реверсивного конвеєра.

Висновки. Розроблено методику синтезу алгоритмів оптимального керування потоковими параметрами транспортної системи з секціями, що містять реверсивні конвеєри. Побудова аналітичної моделі відкриває нові перспективи для проектування алгоритмів керування транспортним конвеєром, які можуть бути використані для зниження питомих енергетичних витрат на транспортування матеріалу на підприємствах гірничодобувної промисловості.

КЛЮЧОВІ СЛОВА: реверсивний конвеєр, PiKh-модель конвеєра, транспортна затримка, швидкість стрічки конвеєра, транспортна система, керування конвеєром.

УДК 658.51.012

СИНТЕЗ АЛГОРИТМА ОПТИМАЛЬНОГО УПРАВЛЕНИЯ ПОТОКОВЫМИ ПАРАМЕТРАМИ РЕВЕРСИВНОГО КОНВЕЙЕРА

Пигнастый О. М. – д-р техн. наук, профессор, профессор кафедры распределенных информационных систем и облачных технологий Национального технического университета «Харьковский политехнический институт», г. Харьков, Украина.

Ивановская О. В. – канд. техн. наук, доцент, доцент кафедры композиционных конструкций и авиационного материаловеденья Национального аэрокосмического университета им. Н. Е. Жуковского «Харьковский авиационный институт», г. Харьков, Украина.

Соболь М. О. – канд. техн. наук, старший преподаватель кафедры информатики и интеллектуальной собственности Национального технического университета «Харьковский политехнический институт», г. Харьков, Украина.

АННОТАЦИЯ

Актуальность. Рассмотрена проблема оптимального управления потоковыми параметрами транспортной системы конвейерного типа, содержащей секции с реверсивными конвейерами. Объектом исследования являлась аналитическая модель транспортного реверсивного конвейера для синтеза алгоритма оптимального управления потоковыми параметрами транспортного реверсивного конвейера. Цель работы – разработка методики синтеза алгоритма оптимального управления потоковыми параметрами транспортного реверсивного конвейера, основанной на аналитической модели конвейерной секции, содержащей транспортную задержку.

Метод. Разработана аналитическая модель реверсивного конвейера для случая постоянной скорости конвейерной ленты, позволяющая определить значения выходных потоков с реверсивной секции при известных значений потоков материала, поступающих на вход секции конвейера. Для построения модели реверсивной секции конвейера использована аналитическая модель секции конвейера в частных производных, содержащая транспортную задержку. При построении модели вве-

DOI 10.15588/1607-3274-2022-2-20

дены допущение о мгновенном переключении направления движения ленты конвейера, а также предполагается, что интервал между переключениями направления скорости движения ленты превышает значения транспортной задержки для секции конвейера. Для синтеза алгоритма оптимального управления реверсивным конвейером введен критерий качества управления. Дана постановка задачи оптимального управления потоковыми параметрами реверсивного конвейера, основанная на принципе максимума Понтрягина. Записана функция Гамильтона для управляемой системы, учитывающая критерий качества управления реверсивным конвейером. Продемонстрирована методика синтеза алгоритма оптимального управления выходным потоком материала секции реверсивного конвейера. Определены условия переключения направления скорости движения ленты конвейера.

Результаты. Разработанная модель секции реверсивного конвейера использована для синтеза алгоритма оптимального управления выходным потоком материала секции реверсивного конвейера.

Выводы. Разработана методика синтеза алгоритмов оптимального управления потоковыми параметрами транспортной системы с секциями, содержащими реверсивные конвейера. Построение аналитической модели открывает новые перспективы для проектирования алгоритмов управления транспортным конвейером, которые могут быть использованы для снижения удельных энергетических затрат на транспортировку материала на предприятиях горнодобывающей промышленности.

КЛЮЧЕВЫЕ СЛОВА: реверсивный конвейер, PiKh-модель конвейера, транспортная задержка, скорость ленты конвейера, транспортная система, управление конвейером.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Alspaugh M. Longer Overland Conveyors with Distributed Power / M. Alspaugh // Rockwell Automation Fair. – 2005. http://www.overlandconveyor.cn/uploadfile/pdf/13-Longer_Overland_Conveyors_with_Distributed_Power[1].pdf
2. Cornet J. Head and tail controls in long overland conveyors / J.Cornet// Bulk Materials Handling by Conveyor Belt. – 2002. – № 4. – P. 55–67. https://cvdyn.com/wp-content/uploads/2020/01/JLC-SME-2002-Conveyor-Head-Tail.pdf
3. Pihnastyi O. Conveyor Model with Input and Output Accumulating Bunker / O. Pihnastyi, G. Kozhevnikov, V. Khodusov// In IEEE 11th International Conference on Dependable Systems, Services and Technologies (DESSERT). – 2020. – P. 253–258. http://doi.org/10.1109/DESSERT50317.2020.9124996
4. Pihnastyi O. Neural model of conveyor type transport system / O. Pihnastyi, V. Khodusov // Proceedings of The Third International Workshop on Computer Modeling and Intelligent Systems. – 2020. http://ceur-ws.org/Vol-2608/paper60.pdf
5. Optimal utilization of the bulk material transportation system based on speed controlled drives / [B. Jeftenić, L. Ristić, M. Bebić et al.] // The XIX International Conference on Electrical Machines, ICEM – 2010. – P. 1–6. https://ieeexplore.ieee.org/document/5608055
6. Pihnastyi O. Development of the controlling speed algorithm of the conveyor belt based on TOU-tariffs / O. Pihnastyi, V. Khodusov // Proceedings of the 2nd International Workshop on Information-Communication Technologies & Embedded Systems. – 2020. – Vol. 2762. – P.73–86. http://ceur-ws.org/Vol-2762/paper4.pdf
7. Improving energy efficiency of coal transportation by adjusting the speeds of a combine and a mine face conveyor / [M. Stadnik, D. Semenchenko, A. Semenchenko, et al.] // Eastern-european Journal of Enterprise Technologies. – 2019. – № 1. – P. 60–70. http://doi.org/10.15587/1729-4061.2019.156121
8. Pihnastyi O. Control of the belt speed at unbalanced loading of the conveyor / O. Pihnastyi // Scientific bulletin of National Mining University. – 2019. – № 6. – P. 122–129. https://doi.org/10.29202/nvngu/2019-6/18
9. Semenchenko A. The impact of an uneven loading of a belt conveyor on the loading of drive motors and energy consumption in transportation / [A. Semenchenko, M. Stadnik, P. Belitsky et al] // Eastern-European Journal of Enterprise Technologies. – 2016. – № 82. – P. 42–51. https://doi.org/10.15587/1729-4061.2016.75936
10. Halepoto I. Design and Implementation of Intelligent Energy Efficient Conveyor System Model Based on Variable Speed Drive Control and Physical Modeling / I. Halepoto, M. Uqaili // International Journal of Control and Automation. – 2016. – № 9 (6). – P. 379–388. http//dx.doi.org/10.14257/ijca.2016.9.6.36
11. Reutov A. Simulation of load traffic and steeped speed control of conveyor / A. Reutov // IOP Conference Series: Earth and Environmental. – 2017. – № 87. – P. 1–6. https://doi.org/10.1088/1755-1315/87/8/082041
12. Lauhoff H. Speed Control on Belt Conveyors-Does it Really Save Energy? / H. Lauhoff // Bulk Solids Handling. – 2005. – № 25(6). – P. 368–377. http://synergy-eng.com/pdf/BSH-2005_Beltspeed_Lauhoff.pdf
13. Bardzinski P. Simulation of random tagged ore flow through the bunker in a belt conveying system / P. Bardzinski, P. Walker, W. Kawalec// International Journal of Simulation Modelling. – 2018. – № 4. – P. 597–608. https://doi.org/10.2507/IJSIMM17(4)445
14. Wolstenholm E. Designing and assessing the benefits of control policies for conveyor belt systems in underground mines / E. Wolstenholm // Dynamica. – 1980. – № 6(2). – P. 25–35. https://www.systemdynamics.org/assets/dynamica/62/6.pdf
15. Pihnastyi O. Energy Management Strategy in the Synthesis of an Algorithm for Multi-step Conveyor Belt Speed Control / O. Pihnastyi, G. Kozhevnikov, M. Glavchev // Lecture Notes in Mechanical Engineering. – 2022. – P. 33–42. http://doi.org/10.1007/978-3-030-91327-4_4
16. Marais J. Analysing DSM opportunities on mine conveyor systems / J. Marais, E. Mathews, R. Pelzer // Industrial and commercial use of energy conference. Cape Town. – 2008.
17. Granell R. Predicting winning and losing businesses when changing electricity tariffs / R. Granell, C. J. Axon, D. Wallom // Appl. Energy. – 2014. – № 133. – P. 298–307. https://doi.org/10.1016/j.apenergy.2014.07.098
18. Pihnastyi O. Calculation of the parameters of the composite conveyor line with a constant speed of movement of subjects of labour / O. Pihnastyi, V. Khodusov // Scientific bulletin of National Mining University. – 2018. – № 4 (166). – P. 138–146. https://doi.org/10.29202/nvngu/2018-4/18
19. Antoniak J. Energy-saving belt conveyors installed in polish collieries / J. Antoniak //Transport Problems. – 2010. – № 5(4). – P. 5–14. http://transportproblems.polsl.pl/pl/Archiwum/2010/zeszyt4/2010t5z4_01.pdf

DOI 10.15588/1607-3274-2022-2-20

20. Pihnastyi O. Analytical methods for designing technological trajectories of the object of labour in a phase space of states / O. Pihnastyi // Scientific bulletin of National Mining University. – Dnipro: State Higher Educational Institution "National Mining University". – 2017. – № 4. – P. 104–111. http://nvngu.in.ua/index.php/en/component/jdownloads/viewdownload/69/8679
21. Koman M. The constructional solution of conveyor system for reverse and bifurcation of the ore flow, Rudna mine KGHM Polska Miedź SA / M. Koman, Z. Laska // CUPRUM. – 2014. – № 3(72). – P. 69–82. http://www.czasopismo.cuprum.wroc.pl/journal-articles/download/113
22. Burduk A. Analysis and risk assessment of the supply of copper ore in the belt conveyor system in an underground mine / [A. Burduk, D. Więcek, I. Zajačko et al] // Acta Montanistica. – 2020. – № 25(2). – P. 236–249. https://doi.org/10.46544/AMS.v25i2.10
23. Bajda M. Analysis of changes in the length of belt sections and the number of splices in the belt loops on conveyors in an underground mine / M. Bajda, R. Błażej, L. Jurdziak // Engineering Failure Analysis. – 2019. – № 101. – P. 436–446. https://doi.org/10.1016/j.engfailanal.2019.04.003
24. Alspaugh M. Latest developments in belt conveyor technology / M. Alspaugh // In: MINExpo. – 2004.
25. Karolewski B. Modelling of long belt conveyors / B. Karolewski, P. Ligocki // Maintenance and reliability. – 2014. – № 16 (2). – P. 179–187. http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-ce355084-3e77-4e6b-b4b5-ff6131e77b30
26. Pascual R. Analysis of transient loads on cable-reinforced conveyor belts with damping consideration / R. Pascual, V. Meruane, G. Barrientos // In: the XXVI Iberian Latin-American Congress on Computational Methods in Engineering (CILAMCE-2005). – 2005. – P. 1–15. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.494.34&rep=rep1&type=pdf
27. Mathaba T. A parametric energy model for energy management of long belt conveyors / T. Mathaba, X. Xia // Energies. – 2015. – № 8(12). – P. 13590–13608, https://doi.org/10.3390/en81212375
28. Kirjanów A. The possibility for adopting an artificial neural network model in the diagnostics of conveyor belt splices / A. Kirjanów // Interdisciplinary issues in mining and geology. – 2016. – № 6. – P. 1–11.
29. Więcek D. The use of ANN in improving efficiency and ensuring the stability of the copper ore mining process / D. Więcek, A. Burduk, I. Kuric // Acta Montanistica Slovaca. – 2019. – № 24(1). – P. 1–14. https://actamont.tuke.sk/pdf/2019/n1/1wiecek.pdf
30. Andrejiova M. Using the classical linear regression model in analysis of the dependences of conveyor belt life / M. Andrejiova, D. Marasova // Acta Montanistica Slovaca. – 2013. – №18 (2). – P. 77–84. https://actamont.tuke.sk/pdf/2013/n2/2andrejiova.pdf
31. Grincova A. A regression model for prediction of idler rotational resistance on belt conveyor / A. Grincova, Q. Li // Measurement and Control. – 2019. – № 52(5). – P. 441–448. https://doi.org/10.1177/0020294019840723
32. Pihnastyi O. Linear Regression Model of the conveyor type transport system / O. Pihnastyi, V. Khodusov, S. Subbotin // Proceedings of the 9th International Conference "Information Control Systems & Technologies". – 2020. – Vol. 2711. – P. 468–481
33. Pihnastyi O. Control of a Conveyor Based on a Neural Network / O. Pihnastyi, G. Kozhevnikov // 2020 IEEE International Conference on Problems of Infocommunications. Science and Technology (PIC S&T). – 2020. – P. 295–300, https://doi.org/10.1109/PICST51311.2020.9467934
34. Pihnastyi O. Model of conveyer with the regulable speed / O. Pihnastyi, V. Khodusov // Bulletin of the South Ural State University. Ser.Mathematical Modelling, Programming and Computer Software. – 2017. – № 10(4). – P. 64–77. https://doi.org/10.14529/mmp170407
35. Hlaing N. Dynamic analysis of the belt conveyor system for detergent industry / N. Hlaing, E. Htwe, M. Htay // International journal of scientific and research publications. – 2018. – № 8(9). – P. 633–638. http://dx.doi.org/10.29322/IJSRP.8.10.2018.p8279
36. Determination of acceleration for belt conveyor speed control in transient operation / [D. He, Y. Pang, G. Lodewijks, X. Liu] // International journal of engineering and technology. – 2016. – №8 (3). – P. 206–211. http://dx.doi.org/10.7763/IJET.2016.V8.886
37. Pihnastyi O. To the question of similarity of technological processes of the industrial technical systems / N. Azarekov, O. Pihnastiy, V. Khodusov // Reports of the National Academy of Sciences of Ukraine. – 2011. – № 2. – P. 29–35. http://dspace.nbuv.gov.ua/handle/123456789/37227

DOI 10.15588/1607-3274-2022-2-20

Наукове видання

Радіоелектроніка,

інформатика,

управління

№ 2/2022

Науковий журнал

Головний редактор – д-р техн. наук С. О. Субботін

Заст. головного редактора – д-р техн. наук Д. М. Піза

Комп'ютерне моделювання та верстання С. В. Зуб
Редактор англійських текстів С. О. Субботін

Оригінал-макет підготовлено у редакційно-видавничому відділі НУ «Запорізька політехніка»

Свідоцтво про державну реєстрацію
КВ № 24220-14060 ПР від 19.11.2019.

Підписано до друку 07.06.2022. Формат 60×84/8.
Папір офс. Різогр. друк. Ум. друк. арк. 25,81.
Тираж 300 прим. Зам. № 384.

69063, м. Запоріжжя, НУ «Запорізька політехніка», друкарня, вул. Жуковського, 64

Свідоцтво суб'єкта видавничої справи
ДК № 6952 від 22.10.2019.